Renewable Energy Cannot Sustain A Consumer Society

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For summaries and documentary material on themes dealt with in this book, intended for use by critical global educators, see The Simpler Way website
http://socialwork.arts.unsw.edu.au/tsw/

CHAPTER 1

THE CONTEXT

In the last three decades considerable concern has emerged regarding limits to the future availability of energy in the quantities required by industrial-affluent societies. More recently Campbell (1997) and others have argued that the energy source on which industrial societies are most dependent, petroleum, is more scarce than had previously been thought, and that supply will probably peak between 2005 and 2015 (Fleay, 1995, Ivanhoe, 1995, Gever, et al., 1991, Hall, Cleveland and Kaufman, 1986, Laherrere, 1995, Duncan, 1997, Bentley, 2002, Youngquist, 1997). Some of these people argue that the world discovery rate is currently about 25% of the world use rate, and that non-conventional sources such as tar sands and shale oil will not make a significant difference to the situation. The USGS (2000) has recently arrived at a much higher estimate for ultimately recoverable petroleum, but this would only delay the peak by some 10 years.

If the discussion is expanded to take into account the energy likely to be required by the Third World, the situation becomes much more problematic. If the present world population were to consume energy at the rich-world per capita rate, world supply would have to be five times its present volume. World population is likely to reach 9.4 billion by 2070. If all these people were to consume fossil fuels at present, rich-world per capita consumption rates, all probably recoverable conventional, oil, gas, shale oil, uranium (through burner reactors), and coal (2000 billion tonnes assumed as potentially recoverable), would be totally exhausted in about 20 years (Trainer, 1985, Ch.4).

What is not well understood is the magnitude of the overshoot, the extent to which our present consumer society has exceeded sustainable levels of resource use and environmental impact. This is made clear by a glance at the greenhouse problem. The Inter-governmental Panel on Climate Change (IPCC 2001, 2005, see also Enting, et al., 1994) has given a range of emission rates and the associated levels that the carbon dioxide concentration in the atmosphere would rise to.

- Perhaps the most quoted graph shows that if the concentration is to be stabilised at 550 ppm, twice the pre-industrial level, emissions must be cut to 2.5 Gt/y by 2040 and to 0.2 Gt/y by about 2200. The present level from fossil fuel burning (i.e., not including land clearing) is over 6 GT/y.

- To keep the concentration below 450 ppm, emissions must be cut to about 1 + Gt/y by 2100, and to about 0.3 Gt/y by 2200. This target is much too high because the atmospheric concentration is now at about 380 ppm and many disturbing climatic effects are becoming apparent.
- The limit now often referred to as the maximum before catastrophic effects are risked, such as the cessation of the Gulf Stream, is 400 ppm, associated with a 2 degree rise in temperature.
- If we were to stabilise the concentration at about the present level we would have to cut emissions to about 0.5Gt/y by around 2040, and for some decades after 2070 we would have to extract more carbon from the atmosphere than we added.

It would seem clear therefore that our target should be at most 2 Gt/y, but a more sensible target would be closer to 0.5 Gt/y. Yet what is the input that the Australian Bureau of Agricultural and Resource Economics estimates we are heading for by 2050? An alarming 15 Gt/y.

If world population reaches 9+ billion, a global carbon use budget of 1 Gt would provide us all with *about 150 kg of fossil fuel per year*, which is around 2–3% of our present rich-world per capita use of fossil fuels (in GHGe terms). Alternatively only about 170 million people, 2.5% of the world's present population, could live on the present rich-world per capita fossil fuel use of over 6 tonnes of fossil fuel per year.

These figures define the enormous magnitude of the sustainability problem we confront. Consumer-capitalist society has overshot viable levels of production and consumption by a huge amount. In effect we have to give up fossil fuels altogether. That is, we have to live almost entirely on renewables. This book argues that these very high levels of production and consumption and therefore of energy use that we have in today's consumer-capitalist society cannot be sustained by renewable sources of energy.

However the foregoing numbers only define the magnitude of the *present* problem. This is nothing like the magnitude of the problem set when our commitment to growth is also taken into account. As will be detailed in Chapter 10, if 9.4 billion people are to have the "living standards" we in rich countries will have by 2070 given 3% economic growth, total world economic output every year would then be *60 times* as great as it is now.

The question of whether we can run our society on renewable energy is therefore not about whether it can meet present demand, and this book concludes that it cannot do that, it is about whether it can meet the vastly increased demand that will be set by the pursuit of limitless increase in production and consumption.

There is an overwhelmingly powerful, never questioned, assumption that all these problems can and will be solved by moving to renewable energy sources. That is, it is generally believed that sources such as the sun and the wind can replace fossil fuels, providing the quantities of energy that consumer society will need, in the forms and at the times that they are needed. Surprisingly, almost no literature has explored whether this is possible. Wildly optimistic and highly challengeable claims are often encountered. "Hydrogen is abundant. All we need is water."[1] "It is estimated that renewable energy has the potential of meeting the energy demand of the human race well into the future." (Lewis, 2003). " . . . existing renewable energy resources are capable of substituting for coal-fired power stations . . ." (Diesendorf, 2005, p. 1). "Renewable energy and energy efficiency can deliver the power we need, without the problems." (ACF, 2005). " . . . energy crops can provide ample biofuel feedstock." (Lovins, et al., 2005, p. 107). "All observers of energy seem to agree that various energy alternatives are virtually inexhaustible." (Gordon, 1981, p. 109). "An entirely renewable and thus sustainable electricity supply is possible using existing technologies." (Czisch, 2004). "Solar energy can replace fossil and nuclear fuels over the next 50 years thus creating a truly sustainable energy supply system." (Blakers, 2003).

Unfortunately in the task of assessing the validity of this dominant assumption we have not been helped by the people who know most about the field, the renewable energy experts. They have a strong interest in boosting the potential of their pet technology and in not drawing attention to its weaknesses, difficulties and limits. Exaggerated, misleading, questionable and demonstrably false claims are often encountered in the promotional literature. Minor technical advances which might or might not become significant in the long run are announced as miraculous solutions. Doubts regarding the potential of renewable technologies are rarely if ever heard from within these fields.

This enthusiasm is understandable in view of the need to attract public support and research funding, but it means that contributions by those most familiar with these fields to the critical assessment of the potential and limits of renewables are quite rare. In developing the following review, considerable difficulty has been encountered from people hostile to having attention drawn to the weaknesses in their technologies and proposals (including threats of legal action if data they have provided in personal communications is used). Sources eager to provide information tend to dry up when they realise that limits are being explored. In addition some of the crucial information will not be made public by the private firms developing the new systems. For example it is almost impossible to get information on actual windmill output in relation to mean wind speeds at generating sites. Where commercial interest might be threatened by critical inquiry, prickly reactions, including harassment, can be encountered.

Unfortunately these difficulties have meant that at times it has not been possible to get access to information that would settle an issue and that must exist somewhere, and that at times one has to attempt an indirect estimation using whatever scraps of information one has been able to find. Ideally this study would have been carried out by someone more expert in renewable energy technology than I am, but it is understandable that the task has been left for an outsider to take up.

This is not an exhaustive examination of all the various renewable energy sources but it attempts to be a sufficient analysis, i.e., to deal well enough with the crucial issues which seem to enable a persuasive case. A number of technologies which might make a significant difference some day have not been examined closely because there are not persuasive reasons to think they can rival the main four options, wind, solar thermal, photovoltaics and biomass.

1.1. THE TWO CORE PROBLEMS

There are two vital problems for renewable energy, the provision of electricity and of liquid fuels. Renewable energy can meet various needs very well, or perfectly in many regions, such as heating and cooling space via simple "solar passive" designs whereby the structure captures and stores solar energy. However renewables face formidable problems with respect to the two forms of energy which consumer society demands in enormous quantities, viz. electricity and liquid fuels. The fundamental issue in both cases has to do with the quantity of energy that can be delivered reliably, not dollar cost or "energy return".

The situation is clearest with respect to liquid fuel (i.e., oil plus gas). Chapter 5 seems to show quite conclusively that there is no possibility of getting the quantity we take for granted, no matter what plausible assumptions are made regarding technical advances. There are only two possible sources of renewable liquid fuels, biomass and hydrogen. Even wild optimism about potential land and energy yields cannot provide the world's future 9.4 billion people with more than perhaps 10% of the per capita liquid fuel consumption we now average in rich countries.

The situation concerning electricity is less clear cut. Some regions such as north-east Europe and the US will be able to derive a lot of electricity from the wind in winter (although the situation in summer is much more problematic). Yet even if the quantity of wind and solar electricity was not a problem, very difficult problems remain having to do with making these highly variable forms of energy available at the times when they are needed.

It is quite misleading to focus on the contribution a renewable source can make when it is merely augmenting supply largely derived from coal or nuclear sources. In that situation the significant problems set by the variability of renewables can be avoided. When the sun is not shining or the wind is not blowing, a little more coal can be burned. However the problem this book is concerned with is the development of systems in which almost all energy used comes from renewables, and that means we would have to provide for large fluctuations in energy production, and thus for the storage of large quantities of energy. At this point in time there is no satisfactory solution in sight for this problem, on the scale that would be required.

Electricity is more or less impossible to store in very large quantities, so it has to be transformed into something that can be stored, such as hydrogen or pumped water, then transformed back to electricity when it is needed. However these processes involve significant difficulties and costs, as Chapters 6 and 7 will discuss. The best option, using electricity to pump water into high dams and then using its power to generate electricity when there is insufficient wind, involves the problem of limited hydro-capacity. Less than 10% of world electricity is generated by hydro-electric generating power, so this source cannot carry anywhere near the full load when there is little wind or sun.

In other words the biggest difficulties for solar and wind energy are set by their *variability*, especially the occurrence of nigh time and winter for solar, and the fact that winds can be down for days at a time. Many sites with quite satisfactory summer PV or solar thermal performance are almost useless right through winter, especially in Europe. Winds tend to be low in summer and autumn. Even more problematic for wind are the large variations from day to day as gales and calms occur.

At present it seems that the variability of wind means that it probably cannot provide more than 25% of demand in the best wind regions, and perhaps no more than 10 to 15% in most good wind regions. Variability also seems to mean that if we build a lot of windmills we might also have to build almost as much coal or nuclear generating capacity, to use when the winds are down.

The belief that the world will soon run on a "hydrogen economy" is very common. Chapter 6 will explain why this is not likely. The first challenge to this faith-based assumption is the question of a source for the huge quantities of hydrogen that will be required. Chapters 2, 3 and 4 explain why we are not likely to get enough energy from solar or wind sources to meet electricity demand, let alone have any left over to convert into hydrogen. But even if we had a lot of hydrogen, there are coercive arguments as to why we still could not have a hydrogen economy. These involve the difficulties posed by the physical nature of the very small and light hydrogen atom. Large volumes of hydrogen have to be pumped or stored before much energy arrives at the destination, and this consumes a lot of energy. In fact according to one estimate, pumping hydrogen from the Sahara to northern Europe would use up the equivalent of 65% of the energy pumped. Then there would be other losses and energy costs in moving the hydrogen into fuel tanks, and especially driving motors and generating electricity. Finally fuel cells are likely to deliver at most 50% to 60% of the energy that reaches them as hydrogen after all those pumping losses.

If the losses are combined, we find that to provide electricity or run vehicles from wind power via hydrogen would require 3 or 4 times as much wind-generated energy as there is in the petrol we are trying to replace. Similar losses would be involved in storing wind-generated power in hydrogen and using it to regenerate electricity later. The capital cost of such a generating system could be 12 to 15 times as much as that of the coal-fired generating system, not including the cost of the hydrogen production, pumping, storage and fuel cell systems.

This poses the question of what multiple of present electricity cost could be tolerated. Our economy might survive if electricity cost five times as much as it does now, but could it survive a 10-fold increase?

What about using solar energy in summer and autumn when the winds tend to be low, and wind in the winter when there's little sun? This would mean constructing two very expensive systems in addition to the one we have now. We would have the wind system, the solar system and the coal-fired system for use when the other two are not working.

These are brief indications of the significant difficulties and costs that lie along the renewable paths, and especially the hydrogen, path. Chapters 2 to 7 provide detailed supporting evidence for the validity of these concerns. Chapter 8 briefly summarises the reasons for concluding that the four main renewable sources cannot sustain the resource-extravagant society we have in rich countries today. Chapter 9 briefly explains the reasons why nuclear energy cannot solve the problem.

The general conclusions arrived at will probably not offend most advocates of the technologies examined because it is recognised that each of them can supply a significant amount of energy. Most enthusiasts have claimed that wind alone for instance can meet 20–25% of demand and the discussion in Chapter 2 suggests that something like this could be possible in many regions. What this book denies however are claims and assumptions that renewable sources are so abundant and prolific that they will be able to fuel a society committed to affluence and growth for all.

1.2. THE WIDER CONTEXT: A GROSSLY UNSUSTAINABLE AND UNJUST SOCIETY

Chapter 10 puts energy into the wider perspective of the "limits to growth" analysis of our global predicament. For forty years the argument has been accumulating that our resource consuming and environmentally expensive way of life is grossly unsustainable, for many reasons besides energy difficulties. The rich-world per capita "footprint" is about ten times that which could ever be extended to all people. In addition our way of life is built on a grotesquely unjust global economy. We in rich countries could not have such high "living standards" if we were not taking most of the world's resource wealth and condemning the Third World to a form of "development" which benefits us and our corporations but not the mass of Third World people.

Most people assume that although some of our resource and ecological problems are very serious, they can be solved by strategies like greater recycling efforts and the development of better technology. Chapter 10 will argue that this "tech-fix" position is quite mistaken because the overshoot is already far too big for this to be possible. Reductions possibly of the order of 90% are required in rich-world per capita resource use. It is not at all plausible that more recycling and more energy efficiency and better technology can make such a difference while we all to go on merrily pursuing energy-affluent living standards.

Most importantly, Chapter 10 will focus attention on the absurdity of the fundamental commitment to economic growth. All our problems will rapidly become worse if we continue to be obsessed with constantly increasing production and consumption, living standards and the GDP. Yet these are the fierce and supreme commitments of just about all governments, economists and people, and we have an economic system that cannot work without them.

The crucial, studiously avoided conclusion detailed in Chapter 10, is that a global consumer-capitalist society cannot be made sustainable or just. We cannot solve the big global problems such a society generates unless we face up to transition to a very different kind of society. Salvation cannot be achieved by changes within consumer-capitalist society –- there must be change from it to very different social, economic, geographical, political and cultural systems.

It should be stressed that this book is not an argument against the development of renewable energy sources. For some forty years I have argued that renewable energy sources are ideal, that we must move to them, and that we can live very well on them –- but not at the level of energy use we take for granted today in consumer-capitalist society. Far from being hostile to them, I have always relied on renewable energy forms. Our homestead has a wood fire for space heating, for decades our cooking was by wood stove (not at present), we pump our water by windmills, and for thirty years have had PV panels on the roof and no grid connection. In several previous publications I have argued that in a sustainable world we must live on renewables and that we can live well on them, but only after radical transition from consumer-capitalist society to "The Simpler Way" sketched in Chapter 11.

1.3. APOLOGIES TO 'GREEN' PEOPLE

Obviously this book's message is not a pleasant one for people in the Green Movement and I am acutely aware of the damage it would do the general environmental cause if it were taken seriously. Environmental activists have great difficulty getting the public in general to respond to environmental issues, even when they pose no significant challenges to the lifestyles and systems of consumer society.

Almost all environmental activists seem to be oblivious to the contradiction built into their thinking. They are in effect saying, "Please help us save the planet by calling for a switch to the use of renewable energy sources — which can sustain consumer society and will pose no threat to our obsession with affluent lifestyles and economic growth." Even getting people to attend to such unthreatening messages is very difficult. So how much more difficult would it be to get people to listen to the claim that to save the environment we have to cut consumption by perhaps 90%, and give up fossil fuels – and renewables cannot substitute for them?

Given that I have been part of the Green Movement for decades, I realise that green goals could be significantly undermined if the theme of this book became widely discussed, let alone generally accepted. The most immediate effect would be a surge in support for nuclear energy (despite the case against it given in Chapter 9).

As Chapter 10 will make clear, the Green Movement in general is deeply flawed. It is for the most part, only light green. Most environmental gurus and agencies never go beyond seeking reforms within consumer-capitalist society. They do not consider the possibility that environmental and other major global problems cannot be solved without radical change to a very different kind of society.

Chapter 10 explains why a sustainable and just society cannot be a consumer society, it cannot be driven by market forces, it must have relatively little international trade and no economic growth at all, it must be made up mostly of small local economies, and its driving values cannot be competition and acquisitiveness. Whether or not we are likely to achieve such a transition is not crucial here (. . . and I am quite pessimistic about achieving it). The point is that when our "limits to growth" situation is understood, a sustainable and just society cannot be conceived in any other terms. Discussion of these themes is of the utmost importance, but few if any green agencies ever even mention them.

The "tech-fix optimists", who are to be found in plague proportions in the renewable energy field, are open to the same criticism. If the position underlying this book is valid, then despite the indisputably desirable technologies all these people are developing, they are working for the devil. If it is the case that a sustainable and just world cannot be achieved without transition from consumer society to a Simpler Way of some kind, then this transition is being thwarted by those who reinforce the faith that technical advances will eliminate any need to even think about such a transition.

Chapter 11 includes a brief quantitative indication of the kind of energy economy we might have in the new settlements of The Simpler Way. It explains how we could easily have an extremely low per capita rate of energy consumption, and footprint, based on local resources –- but only if we undertake vast and radical change in economic, political, geographical and cultural systems. The chapter also offers a brief discussion of the way people might best work for the transition.

1.4. THE SPIRIT OF THE BOOK

The renewable energy field is strewn with dogmatic, challengeable, and unexamined assertions and assumptions. It reveals many strongly held and unquestioned beliefs. Hardly anyone has published even a brief critical analysis of the field, the notable exception being Howard Hayden's *The Solar Fraud* (2003, 2004).

This book presents the results of an attempt to look carefully at the crucially important and almost completely neglected question of what the limits to renewable energy sources might be. It attempts to clearly and succinctly describe evidence and arguments extracted from the literature and from discussions with active researchers.[2] These have been at times incomplete, conflicting and unsatisfactory, and a number of important issues are not as clearly delineated as one would wish. Especially worrying is the fact that we are dealing with a situation where uncertain information can lead to either underestimation or overestimation of the potential of a renewable source technology. I have been quite anxious to avoid this, but given the complexity of the issues involved, it is possible that confusion will be reflected in the following pages. The reader should also be aware that information has been accumulated over several years, meaning that some cost figures could now be less reliable due to inflation.

Nevertheless this book, I believe, leads to some rather convincing conclusions. Although its major findings might turn out to have been incorrect, what is important at this point in time is the book's contribution to identifying the difficulties, clarifying the situation, pointing to questions that need to be answered, presenting evidence and arguments, attempting to interpret the situation, and getting the issue more centrally onto the agenda of public discussion. It offers an attempt to sort the issues out, which others can critically assess and then build on. It offers arguments and interpretations and it identifies challenges which need to be dealt with satisfactorily. What matters is not so much whether its conclusions are correct, as whether it contributes to the eventual establishment of the correct conclusions.

The importance of the task cannot be exaggerated. There is a widespread assumption that a consumer-capitalist society, based on the determination to increase production, sales, trade, investment, “living standards” and the GDP as fast as possible and indefinitely, can be run on renewable energy. Indeed the almost total lack of literature or public discussion on the topic shows that no need is felt to even think about this taken-for-granted conviction. But if this assumption is wrong, we are in for catastrophic problems in the very near future and we should be exploring radical social alternatives urgently. Clearly therefore it is of the utmost importance that critical discussion of this crucial assumption should be moved onto the public agenda.

CHAPTER 2

WIND ENERGY

As with other renewable sources, claims about wind energy potential vary considerably and confident conclusions about quantities and limits are usually elusive. Many very optimistic claims are often encountered. For instance the American Wind Association has said that three times present US electricity use could be derived from wind. Some argue that wind energy is so abundant that just about everything could be run on it. Nevertheless this review seems to show that in general, even in good wind areas, wind will not be able to provide more than a rather small fraction of electricity demand over the whole year, primarily due to its variability.

Most people in the wind industry will probably be quite content with this conclusion, having seen wind as an important potential contributor but not having claimed that it can largely or totally replace fossil fuel generation. The main purpose of this chapter is to become clearer about limits to the proportion of total energy demand that wind could meet in a fully renewable energy economy.

There is a great deal of energy in the planet's winds and in many regions the potentially harvestable amount is much greater than demand. However it is necessary to distinguish between this quantity and the proportion of it that can be used due to the fact that wind is an intermittent energy source. Firstly however, the factors determining how much energy could be harvested from the wind if variability was not a problem will be considered.

2.1. CAPACITY AND INFEED FACTORS

It is usually assumed that windmills will perform at better than 30% capacity on average; i.e., that a mill that can generate 750 kW in its optimum or "peak" conditions will have an average output of 225 MW. However a mill's capacity is mainly a function of its location, and a key question therefore becomes how many good sites are there, and what will capacity fall to if there is very large development of wind energy requiring use of less than ideal sites?

"Infeed" refers to the actual amount of energy fed into the grid from the windmill. Sometimes wind energy is available but cannot be accepted by the dispatchers, for instance because coal or nuclear power stations are already meeting demand and cannot be phased down quickly. It can take 12 or 24 hours to “ramp up” a big coal, gas or nuclear power station to be fully on line and this sets serious difficulties for the integration of wind sources into a national electricity supply system. (For convenience from here on the term coal-fired will stand for these three kinds of power station.)

Infeed averaged over a year can be well below the quantity indicated by windmill capacity. Given that very good sites enable a mill to average over a long period 35% or more of the peak output it is capable of generating, it might come as a surprise that average capacity in the UK in 2003 was 24% (Renewable Energy Foundation, 2004, p. 53, Department of Trade and Industry, 2004). Over a two year period the capacity for the Netherlands, Denmark, Sweden and Germany was about 22% (Ferguson, 2003, and Windstats, n.d.). In 1997 and 1998 UK capacity averaged between 24% and 26.7%. The average capacity achieved by Californian mills in 1990 was 18.6% (Elliott, Wendell and Gower, 1991, p. 56). Sharman (2005a) reports a surprising infeed factor of 17% for Denmark in 2003, and the reports by E.ON Netz (2004, 2005) puts the German figures at a similarly remarkable 16% in 2003 and 19% in 2004.

Denmark has been regarded as the leader in wind energy development, producing electricity equal to about 18% of national electricity use. Germany has developed far more wind energy than any other country, having about one-third of all European installed capacity. The E.ON Netz company operates around 44% of this, spread over an area 880 km across. Their recent reports are therefore important, providing data based on a great deal of actual experience. Their system infeed factor for half the year averaged 11%, meaning that in the worst months it was even lower. Thus even though the German wind system is still only contributing some 4.7% of the nation’s electrical demand, it is having serious difficulties integrating even that small amount of wind energy into the system. This indicates that we should be cautious about optimistic claims regarding capacity and the amount of wind energy that can be conveniently used.

Because the sites first used when a region begins to install wind power will tend to be the best ones, we could expect average capacity to decline over time as less ideal sites have to be used. The reports on Germany and especially Denmark raise concerns on this issue. Czisch (2004) says suitable sites in Germany are becoming limited.

2.2. EXCLUSION FACTORS

Surprisingly large proportions of the areas with good wind-generating potential have to be excluded from use for a variety of reasons, primarily pre-existing use, national parks, military use, state forests, endangered species (e.g., migrating birds), water catchment and distance from electricity grids. Also land owners might not wish to host wind farms, and there can be strong opposition from local people and the tourist industry.

The exclusion factor is likely to be greater in Europe than in the US because the US area is 3.5 times that of Europe and the population density of European countries is 4 to 12 times as high (Sorenson, 2000, p. 484). For other evidence on the issue see Note 1 which suggests that in general three quarters or more of a suitable area might be unusable.

2.3. THE QUANTITY PROBLEM: THE AREAS REQUIRED AND AVAILABLE

It is useful to have an estimate of the wind farm area that would correspond to the output of a 1000 MW coal-fired station, operating at 0.8 capacity. Hayden's discussion (2003) of seven cases where he has been able to obtain data on actual farm spacing and output indicates an area of c. 813 square km, corresponding to 1.2 W/m.

There is uncertainty regarding the best assumptions on which this kind of figure is based. The size and power of the mill assumed make a difference, as do the spacing and array loss assumptions.[2] The main source of uncertainty concerns the capacity factor assumed. Annual capacities of over 35% are often achieved, but only at excellent wind sites, and it has been noted above that, for whole systems, capacity can be less than half this figure.

For six of Hayden's cases the mill capacity was around 36%, far above that typical of wind systems as a whole as the references in Note 2 show. For one case with capacity of 34% the corresponding "power station" area was quite large, 1,970 square km. If a 25% capacity is assumed in the cases Hayden discusses, close to the European average, then the corresponding area rises to approximately 1,170 square km. (It also seems from the figures given that the spacing in his cases averaged more like 10 × 2.5 diametres.)

However the 17% infeed figure reported by Sharman and by E.On Netz (2004) for the Danish and German wind systems makes a further significant difference to this calculation. If it is representative of the figure that is going to be attached to use of very large areas, then the area derived from Hayden becomes 1,828 square km.

Thus the issue is complicated and unsettled, but the following discussion will take 1,170 square km for a power station equivalent, as a loose indicator of probable harvestable wind energy over very large areas. If we combine this figure with a 40% exclusion factor, then a wind system capable of long term aggregate output equivalent to that of a 1000 MW coal-fired power station would occupy about 2,200 square km.

2.4. THE MEANING OF 'MEAN'

There are difficulties in applying the above figure to areas with different means on large-scale wind maps to draw conclusions about how many power stations worth of wind power could be developed there. A figure of 6 m/s for instance written on most of NSW in a large-scale map of Australia is not saying that at every point in that area the wind speed will average 6 m/s. The winds at a relatively few ridges and hill tops within that very large area will be over 8 m/s and viable mills could operate there.

So what we need to focus on is the wind speed *at a mill or farm site* and how this relates to mill output or capacity, not on the mean for the region in which we find that site on a large-scale map. This is the issue of mapping “resolution”. Ideally we would have maps which state the mean for every single square km, i.e., maps of very high resolution.

The trap is evident when a large-scale map for Germany is examined. The large area means are remarkably low. The map at www.Winddata.com shows almost half the country at 3–4 m/s, almost half at 2–3 m/s and hardly any over 5 m/s. Yet Germany has a lot of windmills. This might appear to show that wind is viable in regions where means are quite low, so the world can look forward to abundant wind energy output from its many areas with similarly low means. The point however is that the German mills have all been located at the best available sites within those large regions with low means on the big map, and what matters is what the means at those sites are.

On the large-scale maps Denmark seems to have a mean under 7.5 m/s, but a 12.5 MW farm, Norre, and a 4 MW farm, Delabole, were at sites which had means over 9 m/s in 2005 (Hansen, 2005).

Also relevant here is the fact that there will be many good sites that are too small to build a sufficiently large farm. Mills (2002) estimates that at least five mills must be built to lower cost per kW sufficiently. Many ridges and hills with good wind speeds would have an area of less than the necessary, perhaps, 2 square km. Again this means that some of the area that might seem useful on the large-scale map cannot be used.

Unfortunately it is difficult, indeed usually impossible, to get public data that would enable estimation of the significance of the numbers on the large-scale maps, i.e., data on actual mill output, the actual mean wind speed at its site and the value given on the map. Wind companies do not want to give their competitors access to this kind of data.[3]

This lack of information makes it difficult to clarify two important issues. The first is the area over which mills equal in output to a 1000 MW power station would have to be spread, because this depends on (the capacity assumed and thus on) the wind speed. So we cannot just take the area on a large-scale map labelled 8 m/s and divide it by 1,170 square km to find the number of coal-fired power station equivalents that region could equate to if covered by windmills. That would give an overestimate because many small areas within that large region will have mean speeds too low for viable wind power.

The second issue left unsettled is the relationship between speed and output at lower wind speeds, and thus the minimum wind speed at which wind power generation would cease to be economic. (Discussed further below.)

The following sections grapple with large area maps without being able to take this resolution factor into account well, but it should be kept in mind that to do so would result in lower estimates for wind potential.

2.5. EUROPE

From the European Wind Energy Atlas (1991) it can be estimated that Europe, excluding Scandinavia probably has 450,000 square km of land with 6.5 m/s or better average wind speed. (However Grubb and Meyer, 1993, p. 193–4, indicate a much lower figure for good European wind area; 90,000 square km of Class 6 wind.) If the areas given in the Atlas at different speeds are roughly transformed into the equivalent area of 8 m/s wind speed, the total is 270,000 square km. If 10% of this can be used (doubtful in densely populated Europe), it would equate to 25 power stations of 1,000 MW size operating at 0.8 capacity. European electricity supply at present is equivalent to some 350 power stations of 1000 MW capacity operating at 0.8.

This derivation is very approximate but it seems to indicate that although European wind potential is considerable it is far from abundant, and indeed much less than could meet present electricity demand. This conclusion aligns with that of the Commission of the European Communities (1994, p. 34) which concluded that "...realisable on-shore technical potential is...about 350 TWh, 23% of the Communities' total electricity demand in 1990." Czisch (2004) refers to a Danish study which concluded that on-shore wind could provide 25% of European electricity. Czisch quotes an estimate that the German limit would be about 17%, and quotes two other studies, one concluding that the figure is 29% and the other that it is 25%.

The Energy Technology Support Unit (1999) at Harwell estimates that available onshore sites with 7 m/s or better winds in the UK might provide 58,000 GWh/y, and offshore sites might add 100,000 GWh/y. Together these come to about 40% of UK demand. These possible quantities are considerable fractions of present demand, but do not promise a super abundance of energy.

2.6. THE USA

Although the US has quite a large wind energy potential, the common assumption that that the potential will be far greater than demand for electricity would seem to be mistaken. An inspection of the wind maps given by the US National Renewable Energy Laboratory (NREL, 2004) indicates that the annual average is indeed large. The annual average map (2–01) gives a broad brush picture of the regions with various mean wind speeds (at 50 m height). By visual estimate the areas are very approximately,

Class 3 winds, (6–7 m/s) or better,	2.4 million square km.
Class 4 winds, (7–7.5 m/s) or better,	0.75 million square km.
Class 5 winds, (7.5 + m/s) or better,	0.3 million square km.

It will be assumed that a site must have a mean of over 8 m/s before it becomes economically viable even with a 100% subsidy (explained below). For the moment the Class 3 area above will therefore be regarded as not viable.

Now we again have to deal with the issue of mapping "resolution", i.e., the fact that the label 6–7 m/s on a very large area does not indicate that this is the average wind speed at every site within this area, and the fact that only some of the sites within the 7.5+ m/s area will have high enough means. Fortunately some of the NREL maps provide information on the issue.

Map (2–11) tells us that 36% of the 0.75 million square km labelled Class 4 or better does not have a mean that reaches 7 m/s. Let us then take 0.55 million ha as the area of the many little locations where a mill would actually get winds with a mean of 7 m/s or better (and let's ignore the question of what capacity will be achieved in these areas and how much will be in pockets too small for say five mills). At 1,170 square km per power station equivalent, this area would equate to 500 power stations.

If we assume a 40% exclusion factor we would end up with the equivalent of 300 power stations, about 50%+ of US electricity system capacity, which is approximately equal to 600 1000 MW stations operating at 0.8 capacity (UN *Statistical Abstract*, 2000). Total system capacity has to be considerably higher, given the need to be able to cope with occasional extreme demand peaks.

Now what about the Class 3 area? As noted above much of this area will not reach 6m/s, but if the whole of it is weighted in proportion to the ratio of energy in 6 m/s wind to 8 m/s wind, i.e., 0.54, then this indicates about 1000 power stations. Applying an exclusion assumption suggests very roughly that Class 3 areas could conceivably enable another 600 power stations, although the number could be far less. Precision is not important here; the general picture is of a total wind potential something like two times the present generating capacity. This is not that far from various other estimates, including those of NREL.

However as will be detailed below, for the renewable energy sources variability is the main problem. The NREL maps do not give information on wind speed distributions and variances or the occurrence of long periods with low or no wind, but seasonal maps are given (2–6). A glance shows that most of the year's wind comes in winter, and far less comes in summer. For summer the areas are approximately,

Class 3 winds, (6–7 m/s) or better,	0.64 million square km.
Class 4 winds, (7–7.5 m/s) or better,	0.32 million square km.
Class 5 winds, (7.5 + m/s) or better,	0.05 million square km.

If we take the 0.32 million square km figure for class 4 or better winds, completely ignore the mapping resolution issue, and apply the 40% exclusion factor again, we have a wind system which in summer equates to about 140 power stations. Adding the Class 3 area (weighted for the lower mean speed) would increase the number to about 284.

Sorenson (2000, p. 461) refers to the Batelle "moderate" estimate which takes 6 m/s or better areas and assumes a 50% exclusion factor, finding that 45,000 square km could produce 27% of US electricity. (This is an implausibly high output from such an area, corresponding to 300 square km per 1000 MW power station.) This is an annual average, so Sorenson's estimate of the summer output would be much lower.

The US maps show that the winter winds are well distributed to the west and the east, reducing transmission distances, but in summer they are confined to the middle of the continent, imposing 1,500 km transmission to where most people live.

Archer and Jacobson (2003) have given an enthusiastic estimate of US wind resources simulated for 80 m hub heights from 10 m data. They conclude that one-fifth of the US could have annual means over 6.9 m/s. This is about twice the NREL area but the summer contribution would still be under US electricity demand. The areas their maps show for 8.1 m/s or better is roughly similar to that given by the NREL maps discussed above, i.e., about 5% of the US land area. The study makes the common assumption that having a large number of mills over a large area will overcome the variability and integration problems. Its conclusions 5 and 6 make the indisputable point that large-scale systems can reduce these problems, but there is no discussion of how large the reduction might be. The discussion of variability below argues that the problems will remain substantial.

The above derivations are very approximate, but the general magnitude is important. It looks as if wind is capable of meeting perhaps half or more of US electricity demand in summer, ignoring intermittency problems, and for the year as a whole it would not be capable of meeting electricity demand and also generating large amounts of hydrogen for transport. Fortunately in summer solar sources are at their best, and the prospects of combining the two are considered later.

2.7. AUSTRALIA

Australia's total electricity demand in the late 1990s was 700 PJ, or on average 22 GW. This is equivalent to the output of 28 1000 MW power stations functioning at 0.8 capacity, although actual generating capacity has to be considerably larger to cover peaks in demand.

In 2005 the Sustainable Energy Development Authority's website (SEDA, 2005) gave the estimate that, in NSW, 1 GW could be derived from wind. However the State's demand in 2004 reached around 12.5 GW.

The Australian CSIRO Wind Research Unit says that in NSW sites must have at least 8 m/s average wind speeds, and must receive a Federal Renewable Energy subsidy of 4 c/kWh, before generation becomes economically viable. This is surprising given that wind is usually thought to be economically viable in areas with over 7 m/s winds.

CSIRO modelling for NSW (Coppin, Ayotte and Steggle, 2003, p. 29, and SEDA *NSW Wind Atlas*, 2005) indicates that within the best 90,000 square km of the state there are only 134 square km with wind means over 8 m/s. At 1,170 square km per power station this would correspond to 0.12 power stations of 1000 MW capacity, ignoring exclusion factors.

The areas with lower means are given as follows. Between 8 and 7.5 m/s, 336 square km, between 7.5 m/s and 7 m/s, 2,175 square km, and between 7 m/s and 6.5 m/s, 7,761 square km. If these areas are given weights according to the energy in winds of these speeds, the total is roughly equivalent to 6,706 square km at 8m/s, corresponding to about six power stations, or 3.6 assuming a 40% exclusion factor.

NSW peak power demand corresponds to about 14.4 power stations operating at 0.8 capacity. There would be additional suitable area outside the 90,000 square km strip along the Great Dividing Range surveyed, but probably not very much as this area was taken as the most promising area for wind generation.

In June 2004 the *Victorian Wind Atlas* was published (Sustainable Energy Authority Victoria, 2004). The state of Victoria lies in the region of 40 degrees South, so has been expected to have large wind potential. The 15% of the state in National Parks has better than average winds but by law this land cannot host windmills. One third of the state is not within 30 km of the grid, but this factor will be ignored here. The state mean is 6.5 m/s, but the distribution plot shows only a small proportion of wind at higher speeds. The areas with various mean speeds are, at 6.5 m/s 106,000 square km, at 7m/s 23,000, at 7.5 m/s 7000, at 8 m/s 2,000 and over 8.5 m/s 1,000 square km. In other words, despite a mean of 6.5 m/s, only 14% of the state's area has winds of 7 m/s or over, and only 1.7% over 8 m/s. Note again that generation in NSW, the state on Victoria's Northern border, is only economic at sites over 8 m/s even with a subsidy of 4c kWh, which doubles the normal price paid to generators. Thus little of Victoria, approximately 3,000 square km, could generate wind electricity "economically" today even with a 100% subsidy. This area represents about 2.7 power stations. However estimation of future potential should take into account use of lower winds and acceptance of higher prices.

An attempt to assess the potential in the lower wind areas might be made as follows. Because the power in wind varies as the cube of its speed, the power in a 7.5 m/s wind is 82% of that in an 8 m/s wind. For 7 m/s, 6.5 m/s, and 6 m/s winds the percentages are 67%, 54% and 43%. If the Victorian areas are given these weights, then the area over 7 m/s yields the very approximate equivalent of 19,000 square km of 8 m/s wind. Taking the above figure of 1,170 square km of windmills to equate to a single 1000 MW power station operating at 0.8 capacity, this area would equate to 19 power stations. If we then take into account the fact that the national park areas that can't be considered are of higher wind speeds than average, and exclude 40% of the remainder, we arrive at around 10 power stations.

By the same reckoning the 106,000 square km at 6.5 m/s equates to 57,000 square km and thus another 26 power stations, but see below on whether harvesting winds that low is likely to be viable, and remember from above that much of this area will be under 6 m/s.

These very approximate conclusions indicate that the quantity of electricity derivable from wind in Victoria plus NSW, at 8c/kWh, would fall far short of meeting present demand. If we assume use of speeds down to 7 m/s the potential quantity might roughly approximate present demand. Again precision is not important here; the point is that harvestable potential seems to be considerable in relation to electricity demand but not abundant.

The southwest corner of Western Australia might have the country's best wind potential, but the 3,000–4,000 km distance from the Eastern states where most of the Australian population resides rules out national supply from the region.

The role Tasmania might play is not easily seen. The Western half of the state has strong winds, but the centre seems to have relatively low winds (Hutchinson, Kalma and Johnson, 1984, Fig. 7). The promising area totals only about 1.5 times Victoria's relatively small good wind area, but the wind speeds are higher. The exclusion factor is difficult to estimate as, although the state is not densely populated, 40% of the entire island is in National Parks and therefore not useable for wind generation. Most of the park land is in the most windy Western region. Supply to mainland users would involve a 400–2,500 km transmission task.

The South Australian resource appears to be excellent although publicly available mapping does not enable clear conclusions. Although not that great, the distance to pumped storage within the Snowy Mountains hydro-scheme has been seen as causing problems regarding possible contribution to national supply (Personal communication). A proposal for pumped storage using the cliffs along the Great Australian Bight was dropped, apparently because the geology would have led to salt seepage and contamination of the surrounding land.

The above figures and derivations are imprecise and uncertain but they suggest some broad generalisations about the quantity harvestable. It would seem unlikely that the sheer quantity of wind energy potentially derivable in the US, Europe and Eastern Australia could be more or less as large as electrical demand, and possibly considerably larger. In other words a lot of electricity could be produced but it is not likely to be many times present demand. Nor is there likely to be such vast quantities of surplus wind energy that we could fuel transport via hydrogen after meeting electricity demand. Note again that the picture changes dramatically when we take into account the problems set by variability (below).

2.8. OFFSHORE WIND POTENTIAL

There is large wind energy potential in regions of shallow sea, especially off the coasts of Europe. Windmills in these areas are more expensive to construct and maintain, but winds tend to be higher, more constant and not disturbed by rough terrain. Offshore regions suffer fewer exclusion factors, although shipping needs can make a significant difference.

Enthusiastic predictions are sometimes made but, as few commercial offshore systems were under development in 2005, it could be too early to draw firm conclusions regarding potential. Easily overlooked is the fact that in areas of high wind, mills will more often have to be shut down for safety. It is noteworthy that the infeed factor for Scottish mills is about the same as for Wales, despite having probably the highest winds in Europe. The American Wind Energy Association (2001) estimates US offshore potential as 15% that of onshore potential. Wind maps for the UK show that despite very high means almost everywhere in winter (10–13+ m/s), in summer areas with 7 m/s means are not within 100 km of the coast except in the North and Baltic seas. Waters so far from the coast are likely to be too deep.

In general, offshore areas are much smaller than onshore areas. At present the maximum depth of water for construction of offshore mills is only about 18 metres *(Windstats Newsletter*, 2004). For most of Europe water under 50 metres depth is mostly confined to within 10–30 km of the coast, except for the North Sea, Baltic and Irish seas. Ireland for instance has negligible areas under 20 metres deep. Britain probably has the highest ratio of offshore to onshore sites in Europe and one-third of Europe's offshore potential (BWEA, 2005). European offshore potential has been estimated at about 22% of electricity demand. Czisch (2001) states a much higher figure, 500,000 square km for the North and Baltic seas, however this assumes mills in water up to 55 metres deep, three times the present depth. If the whole of this area could be tapped, perhaps twice Europe's electricity consumption could be produced. The implications of such depths for costs are unknown. Offshore mills at present depths can cost almost twice as much as onshore mills. Trebling depth would surely mean far more than trebling materials, energy and dollar costs of construction.

It would seem therefore that, although large, the offshore wind resource is not abundant in relation to European electricity demand. It is also subject to the large inter-seasonal variability discussed below. According to Czisch (2001) summer wind energy in Europe is about one-fifth that in February.

2.9. CONCLUSIONS ON THE GROSS WIND RESOURCE

FIrm conclusions are elusive but the foregoing discussion indicates that in many regions the sheer quantity of wind energy available to be harvested might be more or less equivalent to demand, and it might be considerably more but is not abundantly greater than electricity demand. The possibility of tapping low winds is discussed below but it will be concluded that a fairly sudden limit will be encountered and that this option will not dramatically alter the situation. Chapter 6 will discuss the large energy losses involved in use of hydrogen to store electrical energy or run transport. Even if surplus wind energy was far in excess of electrical demand, the losses would seem to disqualify these options. The general conclusion then seems to be that in some important regions the amount of wind that is potentially harvestable is enough to meet electrical demand, but is not likely to be so abundant as to be able to also run our transport via electric motors or hydrogen.

We should note that this has been a discussion of regions close to or within the 40 degree latitudes where winds are best. Most of the world's people do not live close to these latitudes. Finally we should note that electricity demand is increasing so fast that the supply target will probably be more than four times as high by 2050 (See Chapter 10). For instance Australian peak capacity is rising at 2.9% p.a., doubling every 24 years.

2.10. THE PROBLEMS OF VARIABILITY, PENETRATION AND INTEGRATION

Renewable energy sources can fit well into national supply systems while they are only meeting a small fraction of demand, because it is easy to make small adjustments to the non-renewable sources as the output from the renewables fluctuates. There is then no need to provide for storing large amounts of the renewable energy for use later in calm periods. But the concern in this book is with whether renewables could meet the total energy demand. For wind, great difficulties are set here by its variability; sometimes there are gales and sometimes there is no wind at all. "There are times when the wind is calm *everywhere*." (Hayden, 2004, p. 150).

Thus the foregoing discussion of the sheer quantity of energy derivable over a period might tell us little about the actual contribution wind could make. The question is, given the variability, how much can be conveniently "integrated" into the power supply system and with what costs and consequences. One consequence is that the costly renewable components of the system will be largely or totally idle some of the time, and therefore that a number of separate systems each capable of meeting demand could be needed. Another is that it is difficult to increase or decrease output from other generating sources, as required to adjust their output to the fluctuations in the intermittent source. Except for the limited hydro sources, and to a lesser extent gas, these adjustments cannot be made quickly.

In the past it has been commonly assumed that in good wind regions wind might be able to supply 20% or more of electrical energy provided by the system before a penetration problem arises. A number of studies and reports conclude that this is likely to be too optimistic and that problems can arise under 10% wind penetration of the electricity supply system. Kelly and Weinberg (1993) say Europe is not a good location for intermittent energy sources and the limit would probably be 18% of power demand. Spanish authorities have recently stated 17% as the limit (*Windpower Monthly*, Dec., 2003, Feb. 2004, p., 36). Grubb and Meyer (1993, p. 205) say most studies before the early 1990s conclude that production can only reach 5–15% of demand before difficulties arise, and they note that in Denmark penalties become prohibitive at 10% penetration. The UKERC report (2006) says that there need be no problems with 20% penetration of the UK electricity supply system. (See critical comment below.) However most impressive are the recent reports on Germany and Denmark (below) which discuss the significant integration difficulties that have arisen in systems supplying only about 5% of national electricity demand.

It might seem that Denmark had not run into these problems until its wind electrical output reached 18% of its consumption. This often quoted figure is misleading because most of the output is exported and the amount that can be taken into the Danish grid is closer to 4%. Consequently much energy has to be dumped at certain times, and much has to be sold at low prices. (*Country Guardian*, 2002). These problems are said to have arisen regarding 34–45% of the wind power generated in Denmark in 2000. Denmark sometimes has to give away up to 40% of its surplus power (Ferguson, 2004, Sharman, 2005a, p. 7). Duguid, et al. (2004) say, "A couple of years ago we even had to pay Sweden to take it." "Germany . . . is approaching the same threshold. . . . it's buying balance power on the market . . . at up to 20 times the wholesale cost – and selling surplus power very cheaply."

Denmark's extensive development of wind energy has been facilitated firstly by the fact that its neighbours have made much less investment in wind and have therefore been able to buy Denmark's surplus when it was available. In a renewable energy world there would be less scope for this. Secondly the region has much hydro-power power and this can be switched on and off quickly to accommodate fluctuations in wind power. Third, Denmark is a very small country, with 5.4 million people, so the quantity of surplus wind it needs to export to large neighbours is a relatively small amount for them to accommodate.

One important factor here is the period of time in advance in which a wind generating company has to commit to delivering an amount of power, or face penalties; the "gate". The shorter this is the less likely wind energy will not be wasted because of over-cautious predictions. The UK gate is now 1 hour but when it was 4.5 hours some 15% of energy that could have been generated might not have been forwarded (Ferguson, 2003, p. 3). The period can be short in good wind regions, but in Germany where winds are not ideal it is many hours and it could be that the gate problem cannot easily be overcome there precisely because it is partly due to having to make use of poorer winds.

These introductory summary comments indicate that the variability or integration problem sets fairly savage limits on the contribution wind can make, especially when the question is whether wind can be a major element in a wholly renewable system. In the next section some of the more detailed evidence is considered.

2.11. EVIDENCE ON VARIABILITY

Records from wind farms typically show extremely spiky output distributions over time, with many short periods of high and low generation. Outhred (2003, p. 8) reports performance for October from the Lake Benton wind farm in the US showing that for about 14 days output was 60–90% of peak capacity, but for the rest it was only around 10%. On four separate days output was almost zero.

In addition to these rapid fluctuations there are the large variations in wind from summer to winter. In Denmark, Germany, the Netherlands and Sweden the winter capacity of windmills in 2000 averaged 33% but the summer capacity averaged 15%. In August 2000, German and Netherlands capacities were actually down to 8% and 7%, after averaging 38% and 35% in February. For Denmark in 1998 the following capacities were recorded; May 18%, June 14%, July 12%, August 12%, September 15%, November 13% and the annual mean for the whole national system was 22%. For the Netherlands in 1998 the figures were lower; March 15%, April 15%, May 15%, June 13%, July 12%, August 9%, September 12%, for an annual mean of 18% (Ferguson, 2003).

Most surprising are the reports from the large German wind energy company, E.On Netz, accounting for 44% of German wind energy. Serious integration problems have been encountered, although less than 5% of German electricity supply comes from wind (Duguid, et al., 2004, E.On Netz 2004, 2005, Sharman, 2005b, p. 167). The report refers to the “ . . . high costs and serious engineering difficulties . . .” in integrating wind into the German grid. A summary of the 2005 Report (Constable, 2005) concludes, “Wind energy cannot replace conventional power stations to any significant degree.” (The DENA Grid Study, by the German Energy Agency, 2005, seems to contradict this view, but for critical commentary on it see Note 4.)

The output of the E.On Netz system fell to around 4% of peak capacity on 30.4.2003 and 2.8.2003. For the seven days after 3.8.2003 and the seven after 9.2.2003 output did not reach 16% of capacity. The extremely important whole year plot of output (see also Schneller, n.d.) is a deeply jagged pattern of high needles and plunging slots, clearly showing the need for a great deal of backup generation.

The 2004 E.On Netz report says that for half of 2003 the German output averaged only 11%, meaning that in some months it would have been even lower. The report states (p. 9) that winds were above average that year.

Figure 6 from the 2005 E.On Netz Report graphically represents the dispatcher’s problem. Output from the 5.5 GW system was at 100% of capacity on one day but two days later it was at 0%. In one short period capacity was lost at the rate of 16 MW per minute. The Report points out that this variability has implications for grid structure, since it means that much power has to be sent long distances and in various directions, as the regions in which winds are strong change. Grids therefore have to have maximum capacities enabling these larger transfers and more complex despatching paths and arrangements. These are not required for coal or nuclear systems. E.On Netz stress the way that variability destabilises supply systems, causing headaches for electricity dispatchers.

What is most significant about the reports is that they are for a large area wind power system, not just for a single mill or farm. They reflect the negative effects of factors beyond the farm gate, especially the problems in integrating input from many farms, and they include the positive effects of low correlations between mill output over a large area. Again a glance at Schiller’s plot shows that for this 880 Km, almost 6 GW system, infeed is highly erratic and requires much back up capacity.

A recent report in South Australia (Planning Council, 2005) where wind resources are very good concluded that significant integration problems were likely if the wind energy supply was raised from around 10% of demand to about 19% (i.e., 800 MW). This level “ . . . would significantly increase the difficulty of forecasting future scheduled generating requirements” and” . . . would make it difficult to ensure that appropriate generators are available.” (p. iv). Davy and Coppin (2003, p.20) show that in South Australia for five days in a row during February 2003 there was almost no wind at all.

Sharman (2005b) argues that the UK will not be able to increase wind power to more than 10% of electricity generating capacity, well below the government’s stated target. His report on Denmark (2005a) points out that in 2002 the Danish wind system ran at under 5% of capacity for many weeks and the average for the month of June was 3%. Remarkably, for 54 days in the year it produced no electricity at all.

For two of the years reported there was *on average* almost no wind between midnight and 6 am–2.30 am.

According to Grubb and Meyer (1993, p. 170), the US has a 2.5 to 1 variation in wind speeds from winter to summer, with a higher range in the UK. For Australia the variation is between 1 to 1.4 and 1 to 1.8 (Kassel, 2004). The variation in the energy in the wind is much greater than that for wind speed. Figiure 5 from Czisch and Ernst (2003) represents the average aggregate energy in the wind for Europe in February as 4.7 times the May figure, and for the four warmest months of the year as under 18% of the February figure. However, what such statements about means do not make clear is the variation around these monthly averages. What proportion of the time is output well below the summer mean capacity of 12.5% given by Czisch?

In addition there can be significant variation in wind averages from year to year, up to 25% according to the World Energy Council (1994, p. 152). The South Australian study (ECOSA, 2005, 4.1) reported that in some years the average wind power at 12 noon throughout January was 15% lower than that in other years. The Australian CSIRO reports that annual wind speed averages at a location can vary by a factor of two. (www.csiro.au/weru.) Mills (2002, says La Nina and El Nino differences can vary mean speeds by 1 m/s.

Modelling in the South Australian ESCOSA study (Planning Council, 2005) found that in a fairly large system (500 MW) the standard deviation of wind power produced would be 125 MW. This is a surprisingly large variation given that the mean output was expected to be 250 MW during the day. (This is a questionably generous figure, implying a 0.5 capacity factor) and 100 MW at night. Therefore about one third of the time during the day output would be 125 MW below the average output of about 165 MW (i.e., assuming mill output averages 0.3 of peak capacity). Thus output would be about 8% of peak capacity. What then might the nighttime output be one-third of the time? Again it is easy to be misled by plots showing only mean wind speeds for each month of the year, such as that given by Czisch.

The recent report by the UK Energy Research Centre (UKERC, 2006) proceeds as if it has shown that variability is not a problem, after reviewing 212 studies. It states, “None of the studies reviewed . . . suggest that intermittency is a major obstacle to the entry of renewable sources of electricity supply.” (p. 59), i.e., to 20% penetration. However the key analyses in the report are challengeable, and even if its main conclusions are accepted they are not very reassuring. The report says the backup needed to ensure “system balancing”, is 5–10% of wind capacity, (pp. vi, 59) and to ensure “reliability”, 15.2–21.1% of wind capacity, (pp. vi, 46). However this means that the amount of thermal backup plant needed must be capable of *delivering* 56–96% of the amount of electricity the added wind plant would provide. In other words if wind capacity capable of generating 1 MW is added, the same amount of thermal backup capacity might have to be added.[5] (In addition UKERC’s conclusions assume a doubtful 0.35 wind system capacity, perhaps 50% higher than at present. Sharman believes the UK system cannot exceed 0.27 even with a large offshore investment.

The above evidence from Denmark, often claimed to be the most advanced wind nation and in the best region, and Germany with the world’s biggest commitment, is puzzling, and disturbing for wind enthusiasts. It indicates capacity factors for very large systems at less than half those one might assume given the commonly quoted performance of a windmill at a typical ideal site. The causal factors are not obvious. Are there remediable economic, political, managerial etc. reasons why those figures are so low? Is it that when you build a large number of mills you begin to use decreasingly favourable sites? Is the German figure due to the fact that the winds there are poor? But this cannot be the explanation for the Danish figure. Is it that system capacity is inevitably well below average mill capacity? If so this cautions against taking the commonly quoted 35%+ mill capacity factor into expectations re wind potential. To what extent is Denmark's figure due to having previously built much combined heat and power capacity, meaning that fossil fuel generation cannot be phased down now because district heating would also go down? Or is it that in the real world there are more serious limits to how much wind can be integrated than the theoreticians foresaw?

2.12. EVIDENCE ON VARIABILITY AND CORRELATION IN SOUTH EAST AUSTRALIA

The study of wind potential across South East Australia by Davy and Coppin (2003) is especially valuable in being a rare source of detailed publicly available data on these issues. Their account shows that these problems of variability and correlation are quite formidable. The study is especially important in discussing the effect combining mills across the large 1,500 km region would have on a large-scale integrated wind power system. The area is recognised as favourable for wind energy and superior to much of Europe.

Low wind events were found to last a long time.[6] Calms make up a considerable fraction of the time, sometimes lasting 10 or more days even in winter, the best wind season. Long duration events tend to occur all across the three states at the same time. That is, sometimes there are long calm periods extending across the whole 1,500 km. “ . . . variations are well correlated across states.” This tendency for positive correlation between winds at different sites means that in these times it would not be possible for one state to rely on increased supply of wind electricity from another. Especially problematic is the fact that the lulls associated with the cold fronts common in winter are correlated in their occurrence across the three states, and tend to last several days. NSW in particular suffers from a high frequency of low wind events.[7] Low wind events where the average mill capacity falls to 15%, 10% and 5% last on average for 4+, 3.5 and 2.5 hours respectively in the three states. One calm in South Australia, in which output fell to 1/3 of the average, lasted 2.5 days. Similarly very high winds when mills must be shut down, last 1 to 3.5 hours on average.

The example plot given by Davy and Coppin in their Fig. 16 shows that aggregating output for a month from the three states reduced variation, but it remained remarkably wide, and total output fell to quite low levels at times. During one lull average capacity fell to under 10% for four days, and to 4% on one day. Aggregating across the three states would increase the system capacity during extremely low wind events to only 9%. Note that all this is for the input from right across the three state regions, and the plots for the separate (large) states are more varied. The graphs show that NSW would have been at under 5% capacity about 25% of the time and under 10% about 40% of the time, in winter, the best wind season. High wind events across the whole region are also a problem for wind energy producers, although less significant than low events.

In addition their Fig. 17 shows that variation in wind energy from day to night is large within each of the three states. Combining all states reduces these swings considerably but they remain large, e.g., in general to half the range between 100% and 0% capacity, with highs twice as high as lows. (The highest value was six times the lowest.)

Figure 18 from Davy and Coppin represents a five day calm, again in winter, during which aggregate capacity across the 1,500 km region was about 15% of peak for two days in a row, falling to 5% at one point. In this period there was almost no output from one state for five days. In one instance capacity went from 10% to 80% over night.

Significant seasonal differences in wind availability are also evident in the analysis of the three states. For each state, and for all combined, autumn winds are in general two-thirds summer values. In other words aggregation of sources over a very large area still leaves a problem of significant variation in wind energy available as the seasons change. At Adelaide, autumn wind energy is 23% of the October figure (Davy and Coppin, 2003, p. 15). Data from the Australian Bureau of Meteorology (2005) aligns with Davy and Coppin. At Wagga, in Central-Southern NSW, there is calm 14% of the time in April, and 11% of the time in the most windy month, August.

Finally there is annual variation. In some years total wind energy is only about half as great as in others (Coppin, Ayotte and Steggle, 2003, p. 16, Coppin and Katzfey, 2003, p. 18).

Figure 3 from Davy and Coppin sums up the situation, showing that 30% of the time aggregated supply from a wind system spread across the 1,500 km would be generating at under 26% of capacity, and for 20% of the time it would be under 20% of capacity. (These are given as predictions we can be 95% certain about.) 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.

As has been explained, Denmark and other small European countries are able to export surpluses of wind energy to large neighbours, or make up deficits from them. Also the high proportion of hydroelectricity generating capacity in the Nordic region enables rapid accommodation to fluctuating wind supply. None of these conditions applies to South East Australia, meaning that integration problems would be encountered there at a quite low wind penetration. (Note again that these difficulties have arisen in Germany with only around 5% penetration.)

The detail on variability provided by Davy and Coppin reinforces the point regarding means and variances made above. Plots of mean wind speeds per month can be misleading. What matters is variation about means; how often speed falls how far below the means. The point is also evident in the overlapping plots for the wind distribution and mill output for a typical mill given by Coppin, Ayotte, and Steggle (2003, Fig. 23). The wind mean is 7 m/s but 13% of the time wind speeds are too low to generate any power. All the wind received below the site mean speed generates less than 10% of the mill's output. The energy generated at the site for half the time averages 5% of peak capacity. Thus if this mill provided electricity for a town, a backup source would have to function most of the time. (See below on "over-sizing" the supply system.) Combining many mills reduces this problem but note again that the capacity figures from the entire E.On Netz system for half the year were around 5%.

The significance of these figures applying to whole regions for the gap left to be plugged by coal, gas, nuclear or hydrogen generation is marked. These other sources would have to provide something like 90% of demand 10% of the time (not taking into account the difference that pumped or other storage might make).

Figure 3 from Davy and Coppin can be interpreted to mean that if we had a large area wind system in southeast Australia with an average capacity of 38%, then in the half the time that output was under this level, average output would be about 23% of system capacity. In other words for half the time backup generators would have to supply power equal to 40% of the amount that the wind system would supply on average (i.e., (38–23)/38%). So this backup amount would be about 20% of the amount the wind system would generate over the whole time. This would be well in excess of the gap that could be filled by coal-fired power without exceeding sensible greenhouse emission limits. (The per capita gap, 7 GJ(e), would require 21 GJ of fossil energy, which is about 10 times the limit discussed in Chapter 1, even allowing no use of fossil fuel for transport or other purposes.) It should be stressed that this south eastern Australian region is regarded by the CSIRO Wind Researchers as much more favourable for wind power than Europe.

Thus the evidence from this study by Davy and Coppin shows that the magnitude of the variability problem is considerable, indeed formidable. Even aggregating inputs from a very large wind energy system stretching some 1,500 km across these three Australian states would leave quite jagged supply curves. Dispatchers would often need to rely heavily or entirely on some other more flexible energy source for long periods. Even if over the year a wind system could generate much more electricity than was demanded, there would be many long periods in which it could only supply a small fraction of demand. This also means that maps showing national wind means, such as those above for the US from NREL, do not settle the issue of wind's probable contribution even though they might indicate that a very large wind resource exists. More important than the mean, indicating the sheer quantity available, is what gaps occur in the aggregate power supply from very large regions, from hour to hour throughout the year.

2.13. FORECASTING

These problems of integration would be reduced somewhat if winds could be forecasted accurately. Wind generating companies have to undertake to supply a particular amount of power in the hours ahead and if they can't they are penalised. E.On Netz has given a lot of attention to improving forecasting but significant errors are still routinely made. In their 5,800 MW system the average overestimate of wind supply in 2003 was 478 MW, and once the forecast was out by 2,900 MW. Sharman (2005b) says the errors in generation equal on average 21% of installed capacity, a large amount for backup generators to have to supply irregularly.

In his commentary (2005) on the E.On Netz report Constable says, "Wind forecasting is inaccurate and in spite of heavy expenditure on improvements, will remain so." "E.On Netz has invested heavily in wind forecasting. In spite of this, large errors are still common . . . and there are natural limits to the quality of the wind power forecast."

It is important to recognise that even perfect forecasting ability would not solve the variability and integration problems. When winds are low, output will be low and there would be no consolation in being able to forecast that this would happen.

2.14. CORRELATION OF WINDS AT DIFFERENT SITES

Some advocates of wind energy have claimed that linking farms over large areas will enable the variability problem to be eliminated, because of the low correlation between wind speeds at many dispersed mill sites. If all the mills in a supply system are located close together, then all will be idle when the wind ceases at that site. However if the mills in the system are at sites distant from each other it is likely that some will have good winds when others are idle. That is, it is likely that the correlation between wind strengths at distant sites will tend to be low, and if the sites are quite distant it might approach zero. This means that for a wind system spaced over a very large region (i.e., where all inputs from widely spread sites are "aggregated") some of the mills are always likely to be generating.

The first question here is just how low are the correlations? To complicate matters somewhat, the measure of wind speed used could be an average over five minutes, or over half a day, and this affects the correlations arrived at. For our purposes the important correlation values are for averages over longer periods. Dispatchers are not concerned with whether over the last five minutes winds were much the same at all sites, but they would have a problem if the average speed all experience this morning tended to be the same, e.g., if all were idle all morning. Correlations for averages taken over longer periods tend to be higher, but the wider the area over which the mills are located the lower they tend to be.[9]

The E.On Netz report from actual experience within a large system raises considerable doubt about the optimistic expectations regarding correlations that have come from some theoretical studies, such as by Czisch and Ernst (2003). Their windmills are spread over 880 km yet the aggregate production from their whole system still suffers large variations in output, meaning that winds from their many mill sites are relatively correlated (i.e., sometimes all tend to be generating a lot and sometimes all are not generating much).

The detail on variability given above by Davy and Coppin (2003) is also significant regarding correlations. It indicates that aggregation (connecting all wind farms into one system) across some 1,500 km of South Eastern Australia would reduce variability from 70% to 50% of capacity, i.e., not that much. This means there is considerable correlation between winds across that large area. Other evidence is given in Notes 6 to 9. These cases and studies indicate that even across very large areas aggregation would still leave considerable variability, including the problems of seasonal variation and especially the problem set by lengthy periods of little or no wind in the region.

Some have proceeded as if establishing the fact that correlations across a region are low guarantees of good generation all the time from a wind system, on the grounds that even though at a point in time some mills might be idle, others will be generating well. This is mistaken. Yes a low or zero correlation would mean that while some mills are not producing much if anything, others are, but this says nothing about the mean wind speed *over the whole area* at that time. If some mills are idle the system output will be down and in times of relative calm across the region few or none of the mills will be producing much. It would be no consolation to know that the (low) strengths of the winds at all the mill sites were in general quite uncorrelated.

Obviously, whatever the typical correlation values are, this does not alter the fact that in Europe in summer mean wind energy is far below winter mean wind energy. Similarly there are periods shorter than seasons when the whole of a continent can experience mild weather for days on end. Duguid, et al., (2004) say, "Most of Europe can lie under high-pressure with not a breath of wind for days. In winter these conditions bring frost and fog, so demand for heat and light soars." To repeat the quote from Hayden (2003, p. 123), "There are times when the wind is down *everywhere*." Similarly as noted previously Schurman,(2005a) reports almost no output from the Danish wind system on 54 days in 2002, and E.On Netz reports that for their large German system average mill capacity over several months of the year was a surprising 5%.

2.15. INTER-CONTINENTAL AGGREGATION

Czisch and Ernst (2003), discuss the possibility of linking the whole of Europe to regions such as Siberia, Morocco and Kazakhstan, several thousand kilometres away in order to overcome problems set by wind variability within smaller regions. Similarly Czisch (2004) puts forward very optimistic claims about wind's potential from large systems. "An entirely renewable and thus sustainable electricity supply is possible . . ." Czisch and Ernst argue that such a system would reduce the variability of supply to about 10% and enable the associated need for storage to be met by pumped storage using existing dams. Saharawind (2005) have put forward a similar proposal based in Morocco.

Czisch and Ernst say their proposed system could supply 30% of European base load demand, if it had a non-wind backup capacity equal to 26% of the rated power of the windmills. This is a surprisingly large backup requirement for a system that is claimed to be capable of reducing supply from coal or nuclear sources by only 30%. It would mean building backup capacity capable of delivering almost the same amount of electricity as the wind plant delivered.[10] These figures align with the evidence below that introducing large amounts of wind power into a system brings little "capacity credit."

The scheme has the merit of tapping a very large wind resource, but this is achieved by assuming Europe can harvest winds over an enormous area. Their Figure 1 actually shows this to be almost one-third of the planet's land mass, extending from Ireland to India, and from the Arctic circle almost to the equator. This would imply significant transmission losses, probably of the order of 25% according to Czisch's own assumptions (i.e., 4% per 1000 km, for the losses in the mains, not including losses in inversion and connections between the mills at a farm, see below), and embodied energy costs for the lines.

To deal with the integration problem satisfactorily we would need to have the kind of data Davy and Coppin (2003) detail for the region in question, i.e., a clearly established wind distribution aggregated from all sites, which represents means *and variances*. Their Fig. 3 shows what proportion of the time the output aggregated from mills across the whole region is likely to fall below various proportions of system peak capacity. To support the optimism of Czisch and Ernst these would have to show that a remarkably high, reliable and consistent supply all or most of the time throughout the year could be generated. (Their Fig. 5 presents a reassuringly smooth summary plot, but this is for means, with no indication of variability around them.) Secondly Czisch and Ernst assume that pumped storage can eliminate the remaining integration problem, but again this is difficult to understand. World hydroelectricity generating capacity is only about 10% of electricity demand so it could not meet a large fraction of demand when winds are low.

There is also the problem of seasonal variability outlined above. The figures Czisch and Ernst give indicate that for the intercontinental system they consider wind energy would still be far higher in winter than for the four summer months, and November output would be lower than the summer average. (See Czisch, 2004, Fig. 5, and Czisch and Ernst, 2003, Fig. 5.)

Again these problems are not solved by pointing out that there is always wind blowing somewhere within a system including one-third of the planet's land mass. To guarantee 100% supply of electricity at all times from somewhere within that area would in effect be to construct several wind systems each in a different region and each capable of meeting c.100% of demand. When the winds are down in Europe in summer, electricity might come from Morocco where they are strong in summer, but that would mean building as much wind generating capacity in Morocco as in Europe. And when the winds happen to be low in Morocco, is Europe going to draw the same amount from a plant located in Kazakhstan? Czisch actually proposes connecting five large and distant regions, which would mean building five distinct supply systems (to be further augmented by very large PV and solar thermal systems in North Africa for use in summer).

The above detailed evidence from Davy and Coppin does not support Czisch and Ernst's optimism regarding correlations and aggregation over very large areas. They found that large-scale aggregation (i.e., linking mills spread across 1,500 km) makes a difference to the fluctuations in the amount of electricity that would be available, but leaves quite variable aggregate supply patterns, and they make clear the severely disruptive effects of frequent, lasting extreme events, especially calms.

Another problem is that Kazakhstan and Siberia are a long way east of Europe, meaning that peak demand would be many hours distant from peak output, every day. How would this quantity of electricity be stored for the necessary time? It has also been pointed out that some of these regions, such as Morocco, have intense dust storms and the effects of grit on machinery could be significant.

The proposal would also involve political and moral difficulties. It would harvest for Europe the wind resource from an area some 5–6 times as large as Europe, in order to meet only 30% of (present) European demand. Surely the many people living between Mauritania and Kazakstan would also like access to energy harvested from their lands. In a just and sustainable world some energy exporting might be acceptable, but the figures Czisch and Ernst give do not show that tapping this large area would reliably provide European per capita electricity consumption for all the people who live within it. The quantity is not the main issue; it is not clear that the variability problem could be overcome.

The problem set by variability also seems to rule out schemes relying on the "over-sizing" of systems, e.g., from Cavallo (1995). Some argue that wind power will be so cheap that it will pay to build much more capacity than is usually needed, so that when winds are low there will still be enough energy being generated to meet demand, and when winds are high some mills can be idled.

Some over-sizing is probably a good idea but it is difficult to assess its limits. The first problem here is that wind energy is far from cheap. Its capital cost could be ten times that of coal when "capacity needed to deliver a kW", as distinct from peak capacity, is considered, and when the cost of grid extensions and backup capacity is taken into account (see below). Any country could in principle supply most of its electricity from wind, if it built the number of mills needed to do that when winds were at their lowest. The question is obviously the extent to which it would make economic sense to move how far in this direction? However, no amount of oversizing is going to overcome those periods when there is little or no wind anywhere across wide regions.

Figure 3 from Davy and Coppin (2003) makes it clear that oversizing can reduce the problem of gaps but cannot eliminate it. For a system in which peak output met demand, 20% of the time it would meet less than 20% of demand, so if this system was doubled in size, then for 20% of the time output would fall 10% short of demand.

Nevertheless it is likely that a significant proportion of European power could come from far afield, and this is one of the possibilities most capable of invalidating the general conclusions arrived at in this chapter. The potential would be clarified by plots of the kind Davy and Coppin offer, for various regions, especially Europe.

2.16. ‘BUT WE WOULD NEED LESS COAL-FIRED PLANT’: HOW MUCH CAPACITY CREDIT AND BACKUP IS NEEDED?

To the uninitiated the more windmills we built the less fossil fuel plant we would need, but this is largely mistaken, especially where the proportion of wind energy in an electricity supply system is relatively high. There are two factors here. “Capacity credit” refers to the amount of coal, gas or nuclear plant that no longer needs to be generating all the time. “Backup capacity” refers to the amount of plant that must be kept available for use if the winds fall.

If we think of this issue in terms of how much coal or nuclear capacity can be eliminated by adding another windmill to the system, at first the curve rises steeply but it levels out remarkably quickly. An estimate for Holland states the surprising conclusion that adding mills more or less ceases reducing the need for coal or nuclear capacity when wind contribution has risen to only 1.8% of national electricity generating capacity (*European Wind Energy Atlas*, 1991, p. 23).

The 2005 E.On Netz report quotes two independent studies concluding that capacity credit was 8% “ . . . in macro planning terms, effectively zero.” (Constable, 2005. See Fig. 7 in the Report). The report also stresses that as the contribution of wind to supply increases, capacity credit falls (Fig. 2). The UKERC report also makes this point.

The DENA Grid Study proposes increasing the German wind supply system to 36 GW and states that this would enable retiring 2 GW of fossil-fuel generating plant. (For critical comment on the study see Note 4.) Hayden (2003, p. 123) says, “There are times when the wind is down *everywhere* . . . the utilities must maintain full reserve to handle the situation when the wind does not blow. In other words wind turbines do not add meaningful capacity to a system.” In his revised edition he says, “Wind turbines . . . do not allow a utility to get rid of so much as one power plant.” (2004, p. 154). From the other evidence being reviewed here this would appear to be an over-statement of the situation, but not that far out.

Davy and Coppin (2003, p. 11) give remarkably low figures for the “reliably available capacity” that there would be in a wind system spread across South East Australia, i.e., wind capacity likely to be available with a 95% certainty. For NSW during the best half of the day 4.6% of installed peak capacity could be predicted to be available with 95% certainty. For the worst half of the day it is 0.5%, and 1.3% overall. For all three southeast states, extending across some 1,500 km, the combined figure is 9.5%. Coppin notes that in autumn the figures would be lower still.

Similarly the very large-scale proposal Czisch and Ernst put forward includes the estimate that to provide 30% of European demand would require also building about as much conventional backup plant. (They say it would have to be equal to 26% of the peak wind plant, but even assuming 33% capacity, the peak capacity of the backup plant would be about equal to the wind energy generated.)

Milborrow (2004) says that if wind provided 20% of power demand, backup capacity would “only” have to equal 10% of demand. That is not trivial. It means that for every two units of wind energy generated, sufficient coal-fired plant to provide one unit must also be built. Sharman’s report on Denmark (2005a) emphasises that for each windmill built, additional coal, gas or nuclear plant of almost the same capacity must be built to meet the demand when the windmills cannot contribute.

The 2004 E.On Netz report says (p. 3), " . . . traditional power station capacity must be maintained . . . at a total level of more than 80% of the installed wind capacity." This is a remarkable figure, meaning that if 1 MW of wind capacity is built it will deliver on average 0.16 MW, but another 0.8 MW of coal-fired plant must also be built to stand idle much of the time. The 2004 E.On Netz report on the German experience states that wind cannot reduce the need for conventional generating plant more than 20%. In fact they had to build euros 100 million worth of new coal-powered plant to be able to cope with the times when their new windmills were not operating (p. 9).

So in general the more windmills we build, the more coal-fired, gas or nuclear plant we must also build. This problem does not occur in a supply system in which wind is a negligible contributor. Wind supplies only about 1% of US electricity and therefore when winds are low there is no difficulty replacing wind's contribution from other sources. Danish mills only provide the quantity of electricity that about 68,000 people use, and the need for backup there is also reduced by the ability to store and to export to larger countries.

In other words, in general windmills are built *in addition to* conventional plant, not *instead* of it, and their virtue is in avoiding use of coal or gas fuel, not in avoiding building coal or gas plant. As Constable (2005) says, "Wind is not an *alternative*, it is a *supplement*."

In addition, because some coal-fired plant must be kept "spinning", i.e., warm but idling and ready to "ramp up" when the wind drops, carbon is being released and the small amount of power the plant is generating is at low efficiency.

Ferguson (2005a) argues that building windmills would actually result in more coal or gas plant being built and fossil fuel being used than would have been the case had they not been built. This is because the most efficient gas plants (combined cycle gas turbines) must be run at a constant output but the plants capable of varying their output to follow wind changes quickly are much less efficient. In addition frequent variation reduces the life of gas turbines (Sharman, 2005b, p. 168).

2.17. 'AT LEAST WE'D BURN LESS COAL'

This is true, and important. Every kW of wind power replaces coal or nuclear power. However Ferguson (2006) gives the following puzzling figures. Between 1990 and 2003 Denmark increased wind generation to equal 18% of electricity use and per capita carbon dioxide emissions fell 0.3%, to 10.9 tonnes. UK wind generation rose to 0.5% of use in the same period, far less than Denmark, but emissions per capita fell 8.5%, to 9.5 tonnes, lower than in Denmark. It would seem that the increased use of wind in the country with the world's highest commitment to it has not reduced carbon emissions.

Would wind power reduce the need for coal to below the quantities permitted if safe greenhouse emission levels are to be achieved? Unfortunately as has been noted the figures given in Chapter 1 show that the answer is definitely no. The IPCC carbon emission scenarios indicate that we should be cutting carbon emissions to no more than about 1 Gt/y and probably much less. Averaged across 9 billion people this means about 0.15 tonne of fossil fuel per person per year. Even if none was left to meet liquid fuel demand this quantity would generate about 330 kWh of electricity per year, i.e., it would supply one person at the rate of 33 W . . . which is about 3% of Australia's per capita electricity consumption. A wind system would require about eight times as much generation from backup sources to plug the gaps. Remember that Davy and Coppin found that in a large south eastern Australian system aggregate capacity would be under 26% of system peak capacity 30% of the time, and to plug the annual aggregate gap would require about eight times as much fossil fuel as the above carbon limit allows, even without leaving any for transport.

2.18. PLUG THE GAPS WITH HYDROGEN?

The problem of wind variability could in principle be overcome if the energy from high winds could be stored as hydrogen for use when the winds were down. Again the question is, with what quantity and cost implications?

Chapter 6 will discuss the problems involved in dealing with hydrogen. Bossel (2004) explains that the large energy losses involved determine that only about 25% of the energy initially in the electricity will end up coming from the hydrogen fuel cell. In other words to deliver one unit of electricity after storage as hydrogen, four must be generated. (Worse estimates will be noted.)

If we take the plot of output for October from the 104 MW Lake Benton wind farm, it can be seen that it could deliver a constant 18 MW if all of the electricity above this level of output was converted to hydrogen, stored and then used to generate electricity when the winds were down. In other words this is the output level at which the gaps would be filled by 25% of the energy represented by the peaks above it.

The mills in this farm would have had a capital cost of $(US)104 million, assuming the usual figure, $(US)1000/kW(peak). Note that this does not include the other factors contributing to the total system cost. (See below on costs.) But it would be delivering only 18 MW, so its capital cost per kW delivered would be $(US)5,780.

These figures are for a very good site. If we took the figures from the E.On Netz report for the German system, or those from Sharman for the Danish system, i.e., capacities less than half that of Lake Benton, the capital cost per delivered kW of hydrogen energy could be $(US)11,500. If we then took the capital cost recently reported for a number of South Australian wind farms, (farms and systems include much more than windmills) one close to $(A)2,500/kW (see below), and an Australian dollar equivalent to 0.7 US dollars, the Australian capital cost per kWh delivered, for the mills in a system that plugged the gaps with hydrogen, would be about 11 times that of a coal-fired power station plus fuel.

Let us think of it in terms of the common "hydrogen economy" assumption that there will be very large numbers of windmills and solar panels generating hydrogen all the time for storage and use as we wish. If a wind system that operates at 25% capacity delivers energy as electricity after storage via hydrogen, its effective capacity will be 6% and the cost of a windmill that could deliver 1kW constantly would therefore be around at least $(A)32,000, given current Australian mill costs (see below). If the coal plant plus fuel costs $(A)3,700 to deliver 0.8 of 1 kW then the plant to deliver 1kW by wind will cost more than eight times as much as the coal-fired plant plus fuel.

Although these are crude estimates, whatever the actual figure is, to it would have to be added the cost of the hydrogen generating plant, the hydrogen storage, compression and pumping equipment, and the (very expensive) fuel cells for regenerating 18 MW from hydrogen. All this seems to leave no doubt that it would not make sense to try to "plug the gaps with hydrogen."

Even if we were able and prepared to pay the cost, the problem we would then run into is the limit to the sheer quantity of energy derivable from the wind discussed at the beginning of the chapter. For Australia to derive let's say half its 4 EJ of energy from wind via a hydrogen system in which four units of electricity must be generated to provide one unit that can be used later would require 8 EJ of wind electricity. Taking the above area assumptions and a 40% exclusion factor we would need mills over a 620,000 square km area, which is something like 200 times the area we have in NSW plus Victoria at 8 m/s or better.

2.19. EVENTUALLY USE WEAKER WINDS?

The area over which winds average 6 m/s is much greater than that over which they average 8 m/s. In Victoria there is about five times as much area at 6.5 m/s as at 7 m/s. (This trend then suddenly reverses as there is only about one-fifth as much area of 6 m/s land as there is 6.5 m/s land.) It might seem therefore that the development of mills capable of operating on lower wind speeds promises a large increase in wind energy potential. Unfortunately the situation is complicated and clear answers probably can't be derived, given that at present evidence on mill performance comes only from the best possible sites. However there is reason to expect that a cut-off in viability will be suddenly encountered as we move to use of lower wind speeds.

Because the energy in wind varies with the cube of the speed, as the mean speed drops the energy available to be harvested drops rapidly. As noted above, winds of 7, 6 and 5 m/s have 67%, 43%, and 24%, respectively, of the energy in an 8 m/s wind. However harvestable energy falls off even more sharply than these figures would suggest. It seems that most of the energy delivered by a windmill is due to the relatively few high winds it gets.[11] This means that as the speed declines the viability of wind energy does not decline at a linear rate but at an accelerating rate.

Note 11 sketches reasons for thinking that a mill that would perform normally at an 8 m/s site might perform at 11% capacity at a 6 m/s site.[12] What then would the summer average capacity be (especially if the summer/winter wind energy ratio is 1/4.7 in Europe)? Surely it must be around 5% or less of the capacity of a normal mill at an 8 m/s site. And finally, what would be the distribution of wind and capacity around that summer mean, and therefore how often could capacity in effect be negligible?

At this point in time little effort has been put into designing mills that work well on low winds, but this does not seem to be so important because the above discussion focuses on the amount of energy available for harvest. Further, the discussion assumes mills as efficient as those in operation today. Mills designed for low winds would surely be less efficient. They would also probably have bigger blades and therefore be more prone to storm damage, and have a lower cut-out speed.

This has been a speculative and at best suggestive exercise and more confident conclusions would require much better evidence, which is not likely to be available, but it does caution against enthusiasm about a very large potential in lower winds.

2.20. DOES THE CORRELATION BETWEEN SUPPLY AND DEMAND HELP?

In some cases the peak in supply of a renewable energy resource coincides with the peak in demand. On hot summer afternoons when air conditioning demand is high, PV panels can be set west of north to maximise their output at that time. Unfortunately for wind the peak electricity demand is in summer and on hot still, i.e., windless, days. Winds tend to be stronger in winter, but there are often long calm periods of intense cold. The E.On Netz report (2004, p. 6) notes how both events are characterised by stable, high-pressure weather systems across large regions.

Coppin, Ayotte and Steggle (2003) conclude that there is little correlation between demand and wind strength in SE Australia. Demand is not correlated with wind strength at all in NSW, and not in winter in the other states

2.21. THE PROBLEM OF THE SPIKE IN PEAK DEMAND

As societies become richer, people demand more air conditioning and this is causing a major headache for electricity suppliers. On the very few days of the year when air conditioning demand goes through the roof, supply capacity might have to be some 20% greater than the level of demand most of the time. In Australia this capacity is needed only about 1% of the time. These are hot *still* days, so wind can't help much. In addition during hot conditions resistance and difficulties in electrical supply systems increase. Only 43% of Australian houses have air conditioning so there is plenty of scope for further increase (*Sydney Morning Herald*, 23.5.05).

NSW electricity demand is growing at 2.2% p.a., but peak demand is growing at 2.9% p.a. Australian electricity consumption, 22.4 GW on average in 2002, was actually only half the peak demand of 45.3 GW. (Carbon Sequestration Leadership Forum, 2005). The system's maximum generating capacity must be higher than peak demand to cope with the possibility of an unexpected record demand, and this figure (not the actual or average consumption) indicates the number of mills that renewable energy advocates must take as their target.

2.22. TRANSMISSION SYSTEM COSTS AND LOSSES

National and intercontinental wind energy systems would involve losses incurred in sending large quantities of electricity several thousand kilometres. Transmission lines would probably be limited to 5 GW each. Czisch and Ernst (2003) estimate that at present these losses would be 16% for 4,000 km but could fall to 10% given construction of high voltage DC (HVDC) lines. Ogden and Nitsch (1993) give much the same figure. Saharawind (2005) estimates future losses at 15% over 4,500km. (Other evidence on costs etc. is given in Note 13.)

Some have estimated the cost of 5 GW High Voltage DC lines at $(US)1000/kW, and predict that this would add 40% to the cost of coal-fired power. The cost of 4,000–5,000 km lines from wind farms in Morocco or solar thermal plants in the Eastern Sahara capable of supplying 1000 MW, would probably be as great as the cost of a 1000 MW coal-fired plant. If a 15% total energy loss is combined with a 40% increase in cost, the capital cost per kW delivered would be multiplied by 1.3.

Technical breakthroughs in the development of "super-conductivity" might make a significant difference here. At very low temperatures the resistance to the flow of electricity diminishes. Research into achieving the effect at higher temperatures is progressing, but it seems that as temperature increases the quantity that can be transmitted falls off.

Apart from the costs of the very long distance transmissions linking continents there is also the significant issue of the need to build more robust transmission capacity within local and national regions to cope with the variability problem. Germany has found that at times large amounts of power have to be moved from whatever region in which the winds are blowing strongly to the bulk of users somewhere else. The 2005 E.On Netz report points to this need and estimates high outlays will be required in Germany in coming years. An estimate for the UK puts required grid expansion to support increased wind capacity at a remarkable 250 pounds per kW (Dale, 2005). If this refers to peak mill capacity, and if UK average capacity is 22%, the system's grid capital cost per delivered kW would be about twice the cost of the windmills.

The cost of the feeder lines from the individual windmills to the HVDC line would also be substantial, given that a 5 GW line might have to be connected to some 10,000 mills in a network over 6,875 square km, (or 11,760 square km assuming a 40% exclusion factor). The connections between the mills would probably require around 8,000 km of buried wiring, plus conditioning equipment. Also significant and rarely taken into account is the energy loss due to all these connections. Hayden says the connections between just 10 mills in a farm can lose 6% of the energy generated by them.

2.23. RESOURCE COSTS OF WIND SYSTEMS

The resources used in mill construction and installation has to be taken into account, although the overall energy cost of individual mills would probably be relatively low.

A study by Guipe (1992) concluded that for windmill production energy payback is only a matter of months. Millborrow (1998) makes a similar claim.

However, as with PV systems (see below), these estimates tend to assume high capacity factors, e.g., 35% or more for wind, in arriving at energy output over the mill's lifetime. The E.On Netz report indicates that this commonly assumed figure is more than twice the figure achieved in their system. If wind is to meet a large proportion of demand, many less than ideal sites will have to be used.

If we assume a 750 kW mill operating within a system in which average capacity is 16%, it will generate 0.85 million kWh/y. If it takes 200 tonnes of materials to construct, at an energy cost of c. 10,000 kWh/t, then it would take four years to pay back this energy cost.

Off-shore mills will have high capacities but if built on a large scale in deeper waters (e.g., going from the present 18 metres to the 55 metre depths Czisch envisages) they are likely to involve much higher materials and energy inputs.

It is important to distinguish between mill costs and system costs. There are a number of significant factors that must be added to mill costs for a complete evaluation of the "energy return" for wind, including operations and management, connections between mills and to grids, reinforcement of grids to cope with variability, and construction of backup generating capacity. The 2004 E.ON Netz report notes that the development of wind power in Germany has required construction of 1,500 km of new high and extra high voltage lines. Use of winds 4,000 km away would involve use of much energy to build the HVDC lines, according to one estimate, 22,800 tonnes of aluminium per GW (Solarwind, 2005).

Existing grids have been designed to distribute power from big centralised generating plants out to scattered users through smaller and smaller capacity lines. The structure of a wind supply system would have to be quite different if from time to time large amounts of energy have to be sent from whatever regions had strong winds that day to users everywhere else, as E. On Nertz stresses, or to storage. If pumped storage is used, then at some point in time a lot of energy would need to be sent to it from wherever the winds were high. The cost of enlarging hydro generating capacity should also be added to system costs.

Also, detracting from the output factor in the numerator of energy return figures for whole systems will be the losses of power associated with integration problems.

The total energy cost of a completed new wind system would therefore be considerably more than the amount commonly claimed when only the cost of producing the mill is taken into account.

2.24. SUBSIDIES

The considerable penetration achieved by renewable energies has been due in part to large subsidies. While these are desirable in order to stimulate development of renewable energy, they can give a misleading impression regarding the economic viability of the technologies. Coal-fired power can be produced for under 4 c/kWh, yet in Australia, Pacific Power pays home owners 10 c/kWh for power fed into the grid from home rooftop PV systems. German subsidies are much higher. Evidence on other cases (see Note 14) makes it difficult to see how wind projects even at the best sites could be viable without a subsidy that enables 2–3 times the coal-fired generating cost to be charged for electricity generated. This is not an argument against subsidies but it adds to the evidence that in a renewable energy era, costs will be high.

2.25. THE 'COAL-FIRED EQUIVALENT' CAPITAL COST

The capital cost of PV, solar thermal, wind and other renewable technologies is usually stated in terms of "peak watts", i.e., the output the plant would achieve if running at its maximum rate. For wind the cost is now claimed to be around $(US)1000/kW(e)(peak) or under. Oakshott (2005) estimates the South Australian cost at c. $(A)1,500–$1,600 per peak kW. However significantly higher figures have been given for a number of recently announced projects. The four listed by Peacock (2006, p.7) average $(A)1,916/kW(p). Another mentioned by him on p. 15 will cost $(A)2,115/kW(p). The 95 MW AGL Hallett wind farm north of Adelaide, announced early in 2006, will cost $(A)236 million, which is $(A)2,485/kW(p). This is about the same as for the Babcock and Brown venture mentioned in Note 14. The distinction between mill cost, farm cost and system cost is important as the last of these includes all connection, grid extension, storage and backup provisions. None of the figures given above are system costs. (These additional factors must of course be included in estimates of coal system costs too.)

For coal-fired power stations the cost is around $(US)1,000/kW of peak capacity. Taking these raw figures for wind and coal could give the quite misleading impression that the capital cost of wind energy is about the same as that of coal-fired electricity generating plant. However coal-fired plant can operate at full output almost all the time, thus being capable of generating 7,008 GWh/y (at 0.8 capacity), so the capital cost per "delivered" kW is $(US)1,250. On the other hand, even at a very good site a windmill will only have a capacity factor of about 0.33, meaning that a farm of 1000 MW peak capacity will have an annual output of 330 MW. So at a good site such a farm will have a capital cost per delivered kW that is 2.4 times that of the coal-fired station.

The recently reported cost of $(A)2,485(p) per kW for an Australian farm, combined with a 16% capacity factor, yields a capital cost per delivered kW that is 13 times as much as for a coal plant, or 4.2 times as much as for a coal-fired plant plus fuel. Taking the European wind system average capacity factor of about 25% yields a multiple of 2.7.

Thus the raw cost figures typically quoted for wind are not very meaningful until probable capacities per delivered kW are taken into account and until whole systems as distinct from individual mills are considered. Of course a full accounting would improve wind's situation by taking in the ecological costs of coal use.

2.26. CONCLUSIONS ON WIND ENERGY?

In many regions such as Europe, Canada, New Zealand, Central US, and parts of Australia, wind can clearly make a considerable contribution to electricity supply. However, problems of variability, integration and availability of space seem likely to limit the contribution to a small fraction of present demand, perhaps 20% and possibly 10%. This is an average annual figure and there would often be much less wind power available, especially in summer and autumn.

It is important to keep in mind that whatever the fraction is, we can only get it if we have other generating plant to fall back on when there is no wind. But the focal question in this book is whether or not we can we function on renewables alone, and in that situation getting a significant proportion from wind would not be possible without some form of large-scale storage, or access to other renewables capable of providing the other 80% of demand (. . . and 100% when there is no wind). Chapters 6 and 7 argue that this is not foreseen.

Uncritical optimism about wind energy is common, but some have expressed serious doubts, notably Hayden, Ferguson, and also Tyner who concludes " . . . under the most optimistic assumptions, the analysis suggests that wind power is capable of furnishing only a small fraction of the net energy needed to power the US economy . . ." (Tyner, 2003b.).

The common suggestion that transport could also be run on electricity generated by windmills assumes that, as well as meeting electricity demand, the wind could *deliver* twice as much energy for transport as is now used as delivered electricity. As has been explained, to deliver one unit of energy via hydrogen might require generation of four units, and therefore to meet transport demand could mean generating 7–8 times as much energy as would be needed to meet electricity demand.

"Well then, why not do that – indeed why not have a very large number of mills generating enough hydrogen to overwhelm the losses and power everything?" The answer is, firstly the generating plant would cost 10 times as much as coal-fired plant capable of meeting demand (above), and secondly there isn't enough wind for that given the losses in dealing with hydrogen. As has been explained, to meet half of Australia's total energy demand, Australia would need more than 200 times the good wind area in NSW and Victoria.

If wind is to meet a high fraction of electricity demand, in the absence of very large storage technology, we would seem to be faced with the following choice. The first option would be to have the number of windmills needed to meet demand when generating at their lowest, so that system capacity credit is equal to the demand (plus safety margin). The problem then is that because such a capacity credit even in Demark can go down to 5% at times, peak capacity would have to be something like 20 times average demand. The number of windmills needed would be impossibly large.

The second option would be to have many windmills and plug the gaps that storage cannot remove with coal-fired power. The problem with this is that the fossil fuel use limits set, if we accept responsible greenhouse targets, are far too low to allow much gap plugging. Let's ignore the fossil fuel we would want to use on the transport problem and aim to use it all to supplement wind generation. To repeat the key numbers, the responsible budget explained in Chapter 1 is about 0.11 t/person/year, which would generate about 2.5% of the Australian per capita electricity consumption . . . which is growing rapidly.

Most wind energy enthusiasts would probably not be upset at these conclusions. They would be delighted to see wind providing 20% of electrical demand, as most have not claimed that it can provide most of the electrical energy needed. But the focal concern in this book is whether renewables can fully substitute for fossil fuels and there would seem to be a strong case that wind cannot meet more than a small fraction of the demand for electricity, let alone a high fraction of all energy.

CHAPTER 3

SOLAR THERMAL ELECTRICITY

One of the most promising solar electricity options involves focusing the sun's energy to produce steam to drive generators. Enthusiasts foresee solar thermal making a considerable contribution, in summer and in hot regions and the following discussion does not challenge this view. Its main concern is to form some idea of how useful solar systems might be in winter and at less than ideal sites, so we can become clearer about its potential to contribute to a wholly renewable world energy supply. The conclusion reached is that although solar thermal sources will have a central role in a world powered by renewable energy, that world cannot provide a consumer society to all.

The great merit of solar thermal technologies is the ability to store energy as heat, and thereby overcome to some extent the major problem that affects PV and wind technologies. However a significant problem could be that solar thermal concentrating systems can use only the direct fraction of solar energy that comes straight from the sun to the reflector. The diffuse radiation which comes from all directions and can be almost half of total radiation, even in Texas, cannot be focused. Another merit is that solar thermal systems are at their best when demand peaks, in very hot weather. This also enables their high costs to be offset by higher electricity peak demand prices.

3.1. THE THREE APPROACHES

There are conflicting claims over which is going to be the best of the three technologies, trough, dish or central receiver (tower). Because at this point in time trough technology is the most developed of the three, this chapter will deal mainly with troughs and assume that the general conclusions arrived at are loosely appropriate for the other options, pointing to some differences where appropriate. An understanding of the approximate potential and limits is sufficient for the purposes of this inquiry.

3.2. EFFICIENCY AND COSTS

The available evidence varies so it is difficult to arrive at clear and confident conclusions about efficiencies and costs for solar thermal generation. The efficiencies achieved by operating trough plants seem to have ranged between 7% and 11% (see Note 2). The cost estimates to be used here will be those given by Sargent and Lundy (2003, Tables 5–10, 4–39). Their estimate for the "near term future cost" of plant including heat storage capacity is $(US)4,859/kW(e)(peak), which is approximately $(A)6,941/KW(e). For coal-fired power it is about $(A)1,200/kW(e) (Garlic, 2000). They estimate that the longer term future cost, e.g., for 2020, will fall to $(US)3,220/kWh (4–12).

As with all claims and predictions about renewable energy it might not be wise to take these numbers too confidently, partly because of the characteristic "optimism" common in the renewable energy field and especially in view of the high probability that the cost of energy and materials used in construction will rise greatly from here on. Note 2 refers to a number of other efficiency (and cost) estimates and instances.

It should be stressed firstly that this figure refers to solar thermal plant located at ideal sites, where annual solar energy is around 7 kWh/m/d. Such sites involve long distance transmission of electricity to users, and thus additional costs and energy losses. In addition these are gross figures and the energy costs of building the plant and of running it have to be deducted from its gross output (below).

Some argue it is not likely that the costs for solar troughs will fall markedly, given that the technology involved is relatively simple, involving steel supports, elevated absorber pipes and tracking equipment for the reflectors. "There is little scope for future performance improvements or cost reductions for solar trough systems." (Commissioner of the European Communities, 1994, p. 25). Figures given by Sargent and Lundy (5.37) state that little cost reduction will occur in the period 2005–2030. They describe the technology for troughs as "mature" (although they think costs will fall in the long run, presumably from economies of scale in production). However Mills (below) claims significant reductions will be achieved via the linear Fresnel arrangement of reflectors.

3.3. THE 'COAL-FIRED EQUIVALENT' CAPITAL COST

When comparisons are being made between coal-fired, gas and nuclear plant on the one hand, and plant for intermittent sources, it is important to note the difference between capital costs per watt *delivered*, as distinct from per "peak" watt. For instance if a coal-fired plant costs $(A)1,200/kWe(peak) and a solar thermal plant costs $(A)6,941/kWe(peak) it might seem that the latter is only five times as expensive. But the coal-fired plant can operate at its peak rating just about all the time (output at 0.8 of peak capacity usually assumed), whereas the solar thermal plant will only approach it at the middle of a hot day and will probably average (annually) an output that is about 25% of its peak capacity. For the coal-fired plant the capital cost per kW(e) delivered would be \$(A)1,200/.8 = \$(A)1,500. For the solar thermal plant it would be \$(A)6,941/.25 = \$(A)27,765. (For Sargent and Lundy's long term cost estimate the corresponding delivered figure would be \$(A)18,400/kW(e). For related evidence and cases see Note 3.

Thus the ratio for capital costs per kW delivered is 18.5/1. However for a meaningful comparison we must include the fuel. Assuming coal at \$20/tonne, the lifetime fuel cost for a coal-fired power station would be about \$(A)2.5 billion, making the cost of plant plus fuel about \$(A)3.7 billion. The fuel for the solar thermal plant, sunlight, adds nothing to plant lifetime cost. Thus the cost of a solar thermal plant in a good location capable of delivering the same total amount of electricity would be 7.5 times as much as for a coal-fired plant plus fuel.

3.4. THE SOLAR HEAT AND POWER ANALYSES

A solar thermal system has been developed by the Solar Heat and Power group to pre-heat water for the Liddell power station in NSW, using linear Fresnel reflectors. In Fresnel arrangements reflectors are in long strips close to the ground and parallel to the absorber pipe, set at different angles, thus not in a trough shape. The costs associated with the arrangement are probably significantly lower than those for "U" shaped mirrors. Mills, Morrison and Le Lievre (2004) have developed proposals for 240 MW and 400 MW power plants to be located in NSW. The cost and performance figures stated are remarkably low, but do not seem to be detailed publicly. Consequently it is difficult to assess the analyses, to know what figures derive from modelling and what from actual experience in the field.

The stated overall cost of \$(A)1,784 per kWe(peak) is about 25% of that arrived at by Sargent and Lundy for the near future. From the figures given the capital cost per delivered kW would be \$(A)5,614. Another figure stated on the Solar Heat and Power website for a modelled 200 MW plant, \$(A)884 million, corresponds to \$(A)4,410kW(e). In a third paper the collector field cost is given as \$102/metre, which is again remarkably low, some 25–33% of commonly quoted figures. Sargent and Lundy (Table 4–4) state \$286/m as the long term goal.

Unfortunately these optimistic figures are not detailed or explained so their plausibility cannot easily be evaluated.[4] It is therefore not clear what this project might achieve at what cost. This is particularly unfortunate because the Solar Heat and Power website has been enthusiastic about the potential of solar thermal power in mid-latitudes such as south eastern Australia and it would have been valuable to have been able to assess their numerical grounds for this optimism.

For the purposes of this Chapter it has seemed best to use the cost estimates for the "near term" future given by Sargent and Lundy, keeping in mind their predicted 2020 costs.

3.5. NET ENERGY AND ENERGY RETURN ON INVESTMENT

A thorough assessment of solar thermal technology would have to deduct the energy cost of constructing and operating solar thermal plant from the gross energy produced. "Parasitic" energy losses, i.e., the energy needed to run the plant, are equal to about 8–10% of gross energy output, although they might be 17% on a cloudy day.[5] They are likely to be higher in winter, e.g., because of the need to circulate heat at night to maintain absorber temperature. Sargent and Lundy (Table 4–3) estimate that these losses will not be reduced much in future.

According to Lenzen (1999) the energy cost of building the plant could be equal to about 3% of its life-time output.[6] However it could be argued that the appropriate figure to take from these sources is 8–11%, which is not a trivial fraction. (See Note 6.) Adding these parasitic and energy losses indicates that less than 80% of the power generated by a solar thermal plant might be available for use. This would be a substantial "energy pay-back" cost figure but it has not been taken into account in the following discussion.

In addition the best solar thermal sites tend to a long way from population centres, such as in the south western corner of the US or in the Sahara desert. Transmission of power over thousands of kilometres would also involve significant power losses, perhaps 15% of power sent in future according to Saharawind. (See Chapter 2.) As was evident in the discussion of wind, the cost of a solar thermal *system* (i.e., including many plants) should include the cost of the grid extensions, backup sources, and the energy losses in getting the power over long distances to users, and in integrating it into the grid.

3.6. HEAT STORAGE

A major advantage of solar thermal systems is to do with their capacity for energy storage. Heat collected during the day time can be stored in oil, molten salt or crushed rock and used to run the generator later.[7] The loss of energy for storage will probably be quite low in future. Sandia (2005) claim losses are already close to 1%.[8]

At this point in time systems for storing heat in salt have been developed to provide for several hours supply, up to twelve hours in some cases. Storage for 24 hour supply is likely to be standard practice in future. To provide for longer cloudy periods would involve large additional storage plant. To store sufficient energy to meet demand on a 1000 MW power station over three cloudy days in a row would require capacity to store enough heat to generate 3 × 24,000 MWh(e), i.e., 72,000 MWh(e), or more than seven times the equivalent of the 12 hour nigh time demand now built into some solar thermal systems. To generate 1kW of electricity requires about 3 kW of heat energy so the system would have to be capable of storing 216,00 MWh(th), or more if generating efficiency is lower.

Some years ago Mills and Keepin (1993) estimated the cost of heat storage at $(US)39.29/kWh(th). More recently Sargent and Lundy (2003, 4.3.5). gave much the same figure, $36(US)/kWh(e), or $(US)10.7/kWh(th). Sandia

(Personal communication) confirms the general figure. At this rate, to store the nigh time demand from a 1000 MW power station, 660 MW × 16 hrs = 10,560 MWh(e) or 31,680 MWh(th), would cost \$(US)339 million, or \$(A)484 million. To cope with three cloudy days by storing 216,000 MWh(th) would cost \$(US) 2.3 billion or \$(A)3 billion, 2.5 times the cost of building a coal-fired plant.

Sometimes it is cloudy for much longer than three days in a row, and much of the time in winter there would probably not be enough sunlight to meet daily demand while also recharging the three-day heat store. Therefore an electricity supply system in which solar thermal plant played a large role would be likely to need considerable coal-fired or other backup capacity and at times this would be drawn on heavily.

3.7. THE PROBLEM OF WINTER: ESPECIALLY DIFFICULT FOR SOLAR THERMAL?

The foregoing discussion has only dealt with annual average and peak capacities, and ideal conditions. Solar thermal technology is clearly very promising in the hottest regions, but as with all solar technologies the crucial questions are what contribution can be made all through the year, and especially in winter, and under what conditions and at what locations would such systems cease to be viable? These questions are very important for thinking about how useful solar thermal systems could be in a renewable energy world.

An examination of plots published for modelled and actual output over different seasons shows large summer-winter differences in performance for solar thermal plants.[9] This means that the annual figures often quoted are largely achieved in summer, and winter performance is far lower than one might expect. The ratio of summer to winter solar energy received is about 2 to 1, yet for troughs the ratio of output drops to around 5 to 1.

The figures in Note 9 indicate that, even for solar thermal plants located at the best sites, winter performance is around one-fifth or less of summer performance, although solar radiation entering a trough is about half as much. That is, performance deteriorates rapidly as insolation decreases. There is also evidence that the ratio deteriorates further as latitude increases, as would be expected. Conclusions from modelling by Mills and Morrison (n.d., Fig. 5) show ratios of 1/5+ for 33 degrees south and 1/7 for about 40 degrees south, for east – west and north– south troughs. (On polar axis troughs see below.)

If we relate this to the previous cost and capacity figures it is evident that the area and therefore the cost for a solar thermal plant capable of delivering 1000 MW in winter, even at an ideal site, would be about five times as great as one capable of this output in mid-summer, and greater as latitude increases.

Following is an attempt to throw some light on the main factors underlying this marked summer–winter performance difference. The purpose is to find clues to the limits of solar thermal technologies. Are there forces at work which mean they cannot contribute that much outside ideal locations, or would it be possible to design them to do so at a reasonable cost?

3.8. EXPLORING THE CAUSAL FACTORS

Of course a solar thermal plant could be designed to generate well on the very low intensity insolation available in mid-winter, simply by increasing the area and concentration ratio, i.e., the area of mirror reflecting on each metre of absorption pipe. Obviously the question this poses is the rate at which this strategy would increase costs, heat losses, and the amount of energy dumping in summer. Because solar thermal systems are being developed only in the very highest intensity sites, it is not surprising that there is little information available on which to base conclusions about how quickly difficulties would increase as we attempt to use these systems in areas of lower insolation, and at what longitudes the attempt would become uneconomical. Again thinking about the factors responsible for the low winter performance might throw light on the limits for solar thermal technologies, and how useful they might be in less than ideal conditions. The four factors identified here will be discussed in increasing order of importance.

3.8.1 Cold

In winter regions or those with relatively low solar intensity, solar thermal equipment will be quite cold at night and will take more energy to warm up in the morning. In practice, a plant is kept warm overnight by slow circulation of stored heat at 150 degrees, meaning that this parasitic loss is greater in winter. In addition air temperatures through the winter day will be lower, meaning greater loss of heat from the absorber. On the other hand the lower ambient temperature tends to increase the efficiency of the generator (SANDIA, 2005). This coldness factor is not likely to be a major drawback in mid-latitudes.

3.8.2 Adding Reflectors at Increasing Angles

If the problem is to heat the absorber tube to what it would be under 800 W/m conditions, but at a site where insolation is 400 W/m, this will require more than twice as much reflecting area per metre of absorber. This is because mirrors added to the outside of an existing set will be at increasingly slanted angles to the sun. Buie, Dey and Mills (2002) show that if the width of the linear Fresnel reflector with a 12.5 m high absorber is doubled from 10 to 20 m, the mirrors at the outside will be reflecting about 3% less energy than those at the centre of the system. This might not seem to be very significant, but if the amount of energy received from a 10 m wide set of reflectors focused on a 10 m high absorber is to be doubled, reflector area and therefore width must be multiplied by 2.3, and the tilt of the outer mirrors would then be significantly higher. According to SANDIA (2005) in some operating plants absorbers are 50 m apart and 12 m high, meaning that outlying reflectors would already be at a considerable angle. Thus the angle of outer mirrors added would be significantly less than normal to the sun, and there would be diminishing returns in trying to overcome intensity and threshold problems this way.

3.8.3 The Sun's Low Angle to the Horizon: The Cosine Effect

Solar thermal troughs are usually set out on a north – south axis. As they rotate to follow the sun through a summer day the sun's rays are always as close as the latitude allows to normal to the plane of the collector's aperture, so it will be collecting maximum energy all day. But in winter the sun is low in the sky so its rays will be slanting into the trough at a sharp angle over one end and less solar energy will be entering the trough. The amount of energy entering the trough is proportional to the cosine of the angle that the sun has departed from normal to the trough.

If the goal is the best winter performance, then in higher latitudes it is better to set the troughs out on an east – west axis. The same cosine problem occurs, but not all day, only in the morning and the afternoon, because at these times the sun is again hitting at a steep angle to the plane of the trough's apperture.[10]

The east – west trough layout improves winter performance because the sun is on an angle to the plane of the aperture in the morning and afternoon but not at midday, whereas with the north – south layout it is at a steep angle to the plane all day. In summer the north – south layout enables the troughs to be pointing almost straight at the intense sun all day, so its performance in summer far outranks its performance in winter, and it outranks the performance of the east – west layout at any time of the year. But in summer the east – west layout also suffers the cosine effect in mornings and afternoons, so its annual output is reduced. If the goal is to maximise annual output from a high solar energy region, then the troughs have to be on a north – south axis, but as has been explained performance will be down to about 20% in winter months.

So in higher latitudes, and therefore less than ideal locations, the dilemma is, either maximise annual output (with a north – south layout), accepting very poor winter output, or raise winter output (with an east – west layout) at the cost of lower summer and annual output.

The problem can be reduced by raising one end of north–south aligned troughs through an angle equal to the latitude of the site. This is called a "polar axis" arrangement. Obviously it would be much more expensive. At Sydney's 34 degree latitude the raised ends of 10 metre long troughs would be about 5 metres high, with absorber pipes and structures much higher still if it is a linear Fresnel system, generating greater construction cost, materials cost and maintenance problems. Mills says one of the merits of the Fresnel design is that reflectors are close to the ground, minimising the considerable cost of frequent washing. Mills also notes that the raised trough ends would also encounter greater wind force and thus require greater structural strength.

Another problem with the polar orientation concerns the "end loss effect." When the sun slants into a trough over its near end, the rays incident on the far end reflect out and miss the absorber.[11] Sargent and Lundy (2003, Table 4–21) expect that by 2020 this loss will still be a surprising 8.2% of gross energy entering the troughs. Note that this will be a reference to good sites which are close to the equator, meaning that the raised ends of the troughs would not be that high and the troughs could therefore be relatively long. But as noted above, if located at Sydney's 34 degree south latitude, polar axis troughs would not be likely to be longer than 10 metres, meaning that there would be many short troughs with many ends.

Mills (n.d. a, n.d. b) reports on modelled (not observed) performance of a polar array at Longreach, central/northern Australia, and at Wagga in the southeast. Although Wagga is some 35 degrees south it lies within an unusual region of relatively high insolation (5 kWh/m/y annual average) given its distance from the equator. (This region extends a long way to the south within the Australian mainland. It actually has the same level of solar energy as Brisbane, some 1000 km to the northeast (See Mills n.d. c, Fig. 5). In other words estimated performance at Wagga is not likely to be typical of locations so far from the equator.)

At Longreach, modelled winter performance for a polar axis array is 3.64 kWh/m/d, about 63% of summer performance and at Wagga it is 38%. These are marked improvements on the performance of the Luz system which was also modelled, (although that system was not designed to maximise winter performance). However at Wagga only 2 kWh/m/d would be collected, indicating generation of perhaps 0.4 kWh(e)/m/d, which would surely be much too low for economic viability, earning less than 2c a day from the sale of the electricity from each square metre.

We should note again that these modelling studies were concerned with the effect of different trough orientations on heat reaching the absorber and did not take into account end loss effects, coldness, or start up intensity (below). Obviously the further from the equator the plant is located the bigger the cosine effect will be.

It therefore seems that the cosine effect in winter and in mid-latitude regions is rather intractable for trough and Fresnel systems. The same problem affects central receiver systems but not dish systems as these can always point directly at the sun (discussed below).

3.8.4 The Intensity of Solar Radiation: The Start-up Threshold Problem

The most important factor determining the winter/summer difference in trough performance would seem to involve the "threshold intensity" needed for system start-up. As soon as a PV panel begins to receive weak sunlight it will generate some electricity. But until the energy delivered by the solar thermal plant's reflectors reaches a specific level the turbines will not start to drive the generator. According to Jones, et al. (2001) steam pressure must reach 16.2 bar for this.

Grasse and Geyer (2000) provide a valuable plot (Fig. 22) from SEG VI for the solar incidence, collector efficiency and generating rate, for a cloudless mid-summer day in 1997 in which incidence reached 1000 W/m. The sun rose at 6.45 a.m. but there was no electrical output until 7.30 a.m. when solar incidence had risen to approximately 700 W/m. At about 8 a.m. when solar incidence was 800 W/m, electricity output had reached around 75% of maximum. Peak generating output was only reached at 9 a.m. when incidence was 1000 W/m. Solar incidence fell to zero at 8 p.m. but generation did not fall from its peak until 6.30 p.m. Thus for this design intensity had to reach a quite high level before significant generation began. The effect is evident in a number of other sources.[12]

In Longreach, central Australia, which has a high winter (global, horizontal plane) insolation, the winter to summer ratio of kWh/m/d is 0.54, far better than in Europe. In May, June, July and August the intensity of radiation on a horizontal plane is over 400 W/m for six hours a day, but it is over 700 W/m for only 2, 0, 0, and 2 hours respectively for each of these four months. For Alice Springs the hours over 400 W/m are 6, 6, 6, and 7, and over 700 W/m for 0, 0, 1 and three hours for these months. For Albuquerque in the southwest US, solar energy entering a north – south trough in winter is 0.62 of the summer figure, i.e., a somewhat better ratio than for global radiation (Renewable Resource Data Centre, n.d.) Again it is noteworthy that despite this rather high ratio the winter/summer performance ratio is much lower. (In addition these figures do not indicate what proportion of the daily total radiation is over say 700 W/m.)

If the intensity of insolation has to be above 450 W/m for any electricity to be generated, then at Longreach in winter the amount of energy capable of generating electricity would be less than 20% of that in summer (derived from Morrison and Litwak's tables, 1988). In other words, although energy received from the sun per square metre over a winter day is more than half as much as in summer, the amount of electricity generated would probably only be about one fifth as much, because only one-fifth as much solar energy received is at an intensity over 450 W/m. (This aligns with the above observations from operating installations that winter output is c.1/5 summer output.) If intensity must be over 700 W/m, then the amount of solar energy received capable of generating electricity in winter in Longreach would seem to be negligible. This is somewhat surprising given the common assumption that central Australia would be one of the world's best locations for solar thermal systems.

With this in mind it is sobering to examine plots for the intensity of irradiation throughout the day at some other quite sunny locations in the world. One often encounters plots from US sites where intensity can exceed 1.1 kW/m at particular times of the year. However these are mid-summer levels (June and July in the US) and when the intensities at these ideal US sites at other times of the year are examined a quite different picture can emerge. For example the number of hours a day in January (winter) when irradiation is over 700 W/m in Arizona, Colorado, Nevada, New Mexico, Texas and Utah is 3, O, 2, 2, 3 and 0 hours respectively.[13]

It is commonly stated that for solar thermal systems to be viable, solar irradiation must be over 7 kWh/m/d. Even in good sites such a level is only achieved in summer. The annual mean solar energy received on a horizontal plane per day in Utah, Phoenix, Albuquerque, California (Deggett), and Arizona are 5.7, 5.7, 6.4, 5.1, 5.8 kWh/m respectively. In other words the summer figures for these regions are high but they are balanced by low winter figures, making annual means rather low. In Utah, Texas and Florida the winter figures are only 3, 3–4, 3–4 kWh/m/d respectively. A location receiving 3 kWh/m/d is likely to average only 450 W/m through the 5–6 middle hours of the day. Thus the low winter output figures reported above for very good sites are not surprising.

The Australian Bureau of Meteorology (2005) provides the following winter average hours of sunshine for some mid-latitude east Australian sites; Orange 4.5, Griffith 5, Adelaide 4, Melbourne 3. For Cobar in Central Australia it is 6.5. Wagga where the possibility of locating solar thermal plant has been contemplated, has 126 completely cloudy days a year. In the four winter months it is cloudy about half the time. In May and June there are an average of only 6.2 completely sunny days a month in that area.

Thus the threshold problem seems to be rather intractable for trough systems. The foregoing evidence seems to indicate that for the designs in use for trough systems an intensity of at least 700 W/m is needed for satisfactory output in summer. However the more recent development of direct steam generation (not using oil in absorbers to transport heat to the steam producer) reduces the threshold problem somewhat.

3.9. WOULD DISHES BE BETTER IN HIGHER LATITUDES?

It is likely that in less than ideal latitudes and seasons dishes would perform better than troughs, primarily because they can be pointed directly at the sun at any time of the day and therefore can avoid the cosine problem and reach start-up temperature more quickly. It has not been possible to form a clear understanding of this issue, partly because there has been much more experience and commercial application of troughs, but also because various agencies which have the data do not want to reveal it (despite requests). Following is an attempt to derive indications from the information that it has been possible to glean.

The most relevant device for assessing dish performance in mid-latitudes is the Australian National University's 400 square metre "big dish" because it is located at 36 degrees south. Unfortunately it is for research purposes and not for continuous power generation so its operators say data on monthly performance throughout a year is not available (Personal communication).

A McDonell-Douglas's dish is reported to have achieved 28.4% efficiency on a particular test run. The big dish website says it operates at about 16–18% (although this is not given as an annual figure). The data for a whole year for the US Mod 1 and Mod 2 devices represent 17.8% and 16.7% efficiency (Mancini et al., 2003), and the other three systems reported on by Mancini, et al. range to just over 20%. Heller (2006) says the annual figure for European devices is 16–17%. Efficiencies in winter are lower than in summer (ANU Personal communication). It is claimed that in future efficiencies up to 30% will be achieved. Thus dish efficiencies do seem to be considerably higher than those for troughs.

Probable future costs for dishes are difficult to be at all confident about because they are not in large-scale production. The estimates in Note 1 vary and US agencies approached have not been willing to give information. However the European estimate for large-scale future production is Euro 4,500/kW(p), or approximately \$(A)6,428/kW(p) (Heller, 2006). Note that this does not include heat storage capacity which is included in the figures used earlier for troughs.

The crucial question is how the winter performance of dishes compares with the summer performance, and would it be much better than the performance of troughs. Somewhat surprisingly the solar energy entering a dish which points straight at the sun all the time, is not that much greater than the amount entering a north – south trough. (See Renewable Resource Data Centre, n.d.) For example for Albuquerque, US, in summer it is 9% more (June average) and in winter 6% more (January average).

In the best US sites in summer about 8.5 kWh/m/d (beam) of solar energy enters the dish. At 18% efficiency this would generate 1.53kWh/m/d. If winter output is 38% of summer output it would be 0.58kh/m/d. The equivalent of a 1000 MW power station would therefore have to have 41 million square metres of dish area. Taking a long term predicted cost of \$(A)6,500/kW(e) (see Note 1) for an approximately 50 square metre 10kW(e) (peak) dish (i.e., \$(A)1,300/m), the total cost for a power plant capable of delivering 1000 MW in winter would be \$(A)54 billion. This is an uncertain derivation but it results in a multiple of around 15 times the cost of a coal-fired plant plus fuel. To this would have to be added emergy costs (energy used in constructing the plant), parasitic energy losses, energy costs of backup plant required, storage and transmission losses and costs. (The lower figure arrived at in Section 3.3 above for troughs was based on assumed annual performance, not winter performance.)

This crude estimate applies to good sites. What might be speculated about higher latitudes in winter? Unfortunately beam solar radiation falls off rapidly as higher latitudes are considered. A plot by Kaneff (1992, p.33) shows that at 34 degrees south the winter/summer ratio is around 0.6 but at about 40 degrees south it is around 0.3, and beam insolation in winter there is under 2 kWh/m/d. The rapid fall-off is evident in the tables given by the Renewable Resource Data Centre (n.d.).

Thus it does not seem that dishes would perform a lot more effectively than troughs, in winter or at higher latitudes. Like troughs dishes would have to be located in hot regions, thus a long way from most users of electricity.

It should be kept in mind that the above figures for dishes do not include provision for energy storage, which is included in the basic trough cost figure taken from Sargent and Lundy. This is a very important difference, not just for cost reasons. The focal point of dishes moves as they track the sun, making it difficult to take heat from many dishes through flexible couplings to a single central generator. This can be done but it would be awkward and costly and is not under development (Heller, 2006). The systems being used have a Stirling (hot air) engine at the focal point of each dish, generating electricity. Such systems therefore do not have the great merit of trough (and tower) systems of being able to store energy as heat. In other words the dish systems under development would suffer the same considerable handicap afflicting wind and PV systems, being unable to contribute to meeting demand when there is not good sunlight or wind.

The emergy situation for dishes is also a concern. The figures given for the big dish indicate 70 tonnes of material for a 50 kW(peak) device, i.e., 1.4 t/kW(peak). This corresponds to 5.8 tonnes per kW delivered, and this appears to be around 17 times the comparable figure for a large windmill. Hagen and Kaneff's materials figures for the big dish indicate that it would take three years for the energy generated to pay the energy cost of construction materials (i.e., not including energy used in the construction process).

This somewhat unsatisfactory evidence indicates that dishes might be better than troughs in mid-latitudes and in winter, but not remarkably so. Their efficiency is likely to be higher, but their costs are too. Above all, units under development do not store energy. The winter contribution from both looks like inevitably being rather limited, and requiring them to be located in hot regions, imposing significant transmission losses.

3.10. A VARIABILITY PROBLEM FOR SOLAR THERMAL, TOO

Another factor which can be overlooked is the variability of solar thermal energy. The capacity to store energy as heat to use for electricity generation at a later time greatly advantages this technology over PV or wind, but variability can still be a significant problem. It is conceivable that in the future, three-day storage might be routine. However, cloudy periods often last much longer than this. The year-long output plot for the US Mod 2 shows one period of 22 almost continuous days of no output at all, except for two days when output averaged 12% of capacity. Australian Bureau of Meteorology data (2005) for mid-latitudes shows that there is cloud cover about 25% of the time in winter. Even at Longreach, possibly the best location in the country, the figure is 20% (and surprisingly about the same in summer). Longreach gets a lot of solar energy, but apparently it is punctuated by a lot of cloud, again setting a variability problem.

As with wind energy where it is easy to be impressed by mean wind speeds and to overlook variation about the means, attention should be given to how often, and how far, solar energy falls below monthly means. The NREL insolation figures show that minimum monthly values are in general about half the average values. So in Nevada for instance, where the monthly average beam radiation has reached 10.6 kWh/m/d, it has been down to 2.1 kWh/m/d (Renewable Resource Data Centre, n.d.)

Therefore solar thermal systems involve the same kind of variability, integration and need for backup problems as wind systems pose, although they are not as great because of the capacity to store heat. Yet there will be times when heat storage is stretched or exhausted, irregular clouds thwart regeneration of storage, and considerable backup by coal will be needed. The discussion in Chapter 2 documented the fact that weather events such as clouds can affect continental-sized regions for several days at a time. Fortunately a shortfall from solar thermal sources is most likely in winter when wind sources are at their best. Wind systems somehow have losses that can bring system capacity down to half that of a mill at a good site, probably due mostly to integration difficulties. The possibility of a similar significant gap for solar thermal systems should be kept in mind.

3.11. CONCLUSIONS REGARDING WINTER AND LOW LATITUDES?

From these rather approximate and uncertain considerations it is not possible to derive confident conclusions regarding the regions where solar thermal generation is likely to be marginally effective, or not at all viable, but the prospects do not seem to be very promising either for winter or mid-latitudes.

For trough and Fresnel systems this conclusion seems to be inevitable given the above understanding of the alignment geometry for the troughs, and the threshold problem. Again in plants designed to maximise annual output in ideal regions, troughs cannot deliver very well in winter and plant output is typically around 20% of summer output. If the troughs are set up to maximise winter output, using the polar axis alignment, then in addition to a higher cost for elevated trough ends, end loss effects would seem to be quite problematic if not prohibitive. This loss factor makes it difficult to imagine that it would ever make sense to build polar axis arrangements in the mid-latitudes where troughs would have to be angled steeply. Either way it seems that the capital cost of a plant designed to deliver 1000 MW all through a winter day and night would be around five times that capable of doing so in summer. The general solar thermal cost per delivered kW was estimated to be more than seven times that of a coal-fired plant plus fuel. The combined multiple for average winter performance would therefore be quite high. Again these speculative numbers refer to good sites and would rise as higher latitudes are considered, and a thorough accounting would add the parasitic and emergy costs which it was seen above might come to 20% of output, transmission losses and costs, and the cost of whatever backup capacity the system required.

The main problems discussed do not affect dish systems so much, but it is not obvious that they would perform markedly better than troughs in winter. Lack of storage disadvantages dishes. Neither seems capable of satisfactory winter performance of solar thermal systems in mid-latitudes. Even at ideal locations whether winter performance would be adequate is not clear. It would involve using insolation of 5–6 kWh/m/d and relatively low intensities and therefore a threshold effect, and in most cases very long transmission distances (although maybe not so long in Australia).

The fact that solar thermal systems are already being built close to Sydney to pre-heat water going into coal-fired power stations does not necessarily clash with these conclusions. For that purpose any heat collected is helpful even though all of it might be well below the threshold temperature that would be needed to start generating electricity, and even though the output in winter might be low. But this does not mean that such systems can be part of a viable wholly renewable energy winter supply.

3.12. FOR EUROPEAN SUPPLY, LOCATE IN NORTH AFRICA?

Some European solar thermal advocates argue that the best sites for European supply are in North Africa where the summer–winter difference is less than in Europe. Unfortunately sites far South of the Mediterranean would have to be used for this to be the case.[14] The situation improves deep in the Sahara, especially in a region towards the southeast. (Mamoudou, n.d.) [15] However the amount of solar energy received in the eastern Sahara in January is not very high, c. 5+ kWh/m/d, so the above cost estimates would be relevant.

If these sites were used the electricity generated would have to be transmitted some 4,500 km to northern and western Europe, involving a crossing of the Mediterranean Sea. This would add costs in dollars and lost energy, including for the construction of the High Voltage DC lines. (See Chapter 2 on transmission costs and losses.) In addition, being a long way east of Europe, supply would not correspond well with demand. Daylight in the collecting regions would end three or more hours before it ended in western Europe, requiring storage, although this should not be a major problem.

If we assume 5 kWh/m/d for annual average North African insolation, dish efficiency of 15% (i.e., much more than for troughs in winter), parasitic and emergy loss totalling 15%, and transmission loss of 15%, then each square metre of a collector field will deliver 0.54 kWh/d. To deliver a day's output from a 1000 MW plant, 24 million kWh, would require 44 million square metres. At the $(A)1,300/m cost indicated by Heller and Mancini, et al., the cost of a plant to deliver 1000 MW in winter would be $(A)58 billion.

This estimate is likely to be far too low because it does not include heat storage, and the absence of this would seriously undermine the contribution that could be made from a source that would not be available on winter evenings. If troughs were therefore preferred for their storage capacity, their winter contribution would be very low, because at the best US sites, comparable to the best north African sites, it is only about 20% of summer performance.

Supply to Europe would be more difficult and costly than to US or Australian populated areas, because of the longer distance from the best North African winter sites, and the need to cross the Mediterranean sea. Some have also pointed to the security implications of dependence on long transmission lines across what might be politically unstable territory.

It is therefore not obvious that North African solar thermal plant could make a major year round contribution to European electricity demand at an acceptable cost.

3.13. SINGLE PLANT VS WHOLE SYSTEM CAPACITY

In the discussion of wind energy it was seen that there can be a big difference between the performance of a mill at a good site and the performance of a whole system spread over a large area. For Denmark and Germany the latter figure, system capacity, has been around 16% in some recent years, whereas a single mill at a good site could have a capacity factor of over 40%. Thus the performance of a typical solar thermal plant might not be a good guide to the performance of a whole system. However the capacity to store energy is likely to reduce the losses due to integration difficulties.

3.14. CONCLUSIONS

There is no doubt that solar thermal systems can make a significant contribution, in summer in the hottest regions, although this will mostly involve very long transmission lines, such as from the far southwest US, or to Europe from deep in the Sahara. They are also likely to be quite effective in summer located in mid-latitudes. The major advantage of solar thermal plant is that energy storage can be fairly easily provided, at least for a day. However the near future capital cost of solar thermal electricity plant per delivered kW even in good sites seems to be more than seven times that of coal-fired plant plus fuel, and the technology seems not to be very effective in winter even in the best latitudes. In the middle latitudes, e.g., as close as 34 degrees to the equator, solar thermal technologies seem quite capable of making a significant summer contribution, but not a significant winter contribution. From the somewhat limited information reviewed it is difficult to see how they could perform a major role in a wholly renewable energy world except in summer. A winter contribution in the regions where most people in developed countries live would seem to depend on the more expensive dishes, and therefore would involve a storage problem and long transmission distances. (Most people live in tropical regions but clouds make solar technologies less than ideal there in late summer; Kaneff, 1992, p. 33.) Again it is important to note that these conclusions have not taken fully into account parasitic losses, emergy costs, transmission losses and the cost of backup systems.

If correct these conclusions probably would not worry most solar thermal enthusiasts because they see this technology as making a valuable partial contribution to future electricity supply, from favourable regions and mostly in summer. But our concern is whether they could be important contributors to a wholly renewable world electricity supply sustaining consumer-capitalist society, and this does not seem to be the case.

CHAPTER 4

PHOTOVOLTAIC SOLAR ELECTRICITY

Chapters 2 to 5 on the four main renewable energy sources take for granted that large quantities of energy can be derived from them, and Chapter 11 discusses their capacity to enable a satisfactory society. The purpose of these inquiries however is to form some idea of their limits and their capacity to sustain a consumer–capitalist society. This chapter will argue that PV sources could be part of an energy supply system that enables that goal only if some other renewable source met demand when there is little or no sunshine, or a way of storing very large quantities of electricity could be found. Other chapters argue that neither condition seems likely to be met.

It is necessary to begin with a brief look at some basic cost and efficiency figures.

4.1. THE BASIC PV FORMULA

The output and the capital cost of a PV generating plant is determined by a) the solar incidence at the site, measured in kilowatt-hours per square metre (KWh/m), b) the efficiency of the PV module, i.e., what percentage of the incident solar energy is converted to electrical energy, c) the cost per watt or per square metre of the module, d) the dollar cost of the "balance of the system" (BOS), such as the supporting structures, wiring, control equipment, installation etc., e) the lifetime assumed for the system, f) the energy losses imposed by the BOS, and g) the proportion of the energy generated that it takes to produce the plant.

4.2. EFFICIENCIES

The efficiency of a solar cell refers to the proportion of the energy falling on it that is converted to electricity. Although efficiencies above 25% are being achieved in the laboratory, the efficiency of PV cells in use seems to be around 13%. (Kelly (1993, and see Note 9 which includes evidence of performance in the field lower than this.) PV panel performance can be lowered by imperfect alignment, dust and water vapour in the atmosphere, dust on panels, ageing of the cells, losses in wiring and inverters, loss due to protective covering glass (Kelly, 1993, p. 300) and the heating effect of sunlight on the cells. The nominal ratings usually quoted derive from tests in ideal laboratory conditions which do not include these factors. Heating reduces output 0.4–0.5% per degree C above the 25 degrees used for laboratory testing (Corkish, 2004.) For Australian roofs in summer this indicates a significant loss, perhaps 40% of lab efficiency. Knapp and Jester (2001, p. 45) say that "system losses" due to wiring resistance, inverters etc., typically reduce output by 20%.

The figures reported above and referred to in Note 9 indicate that the actual efficiency of systems in the field is somewhere between 6% and 11%, on average under half the figure usually assumed in energy pay-back claims, i.e., claims about the time it takes to generate the energy used in the production of the panels. (This aligns with the performance of my own home PV system; see below on pay- back periods.)

At 13% efficiency each square metre of PV collection area would produce 0.7 kWh per day in winter in central Australia, where annual average solar energy can be around 5.5 kWh/m/day. At the Australian wholesale price for electricity this would sell for about 2c, or $7.30 p.a.

4.3. PV MODULE COST

The cost of PV modules has fallen considerably in the last two decades, but the curve seems to have flattened out recently. One report indicates that costs have actually risen in recent years, from $(US)4.98/W to $5.10/W (Solarbuzz, 2005). Some believe this is due to insufficient production of suitable silica. Some evidence on recent costs is given in Note 1. It will be assumed below that the cost is $(A)10 per watt retail and $(A)5 per watt wholesale, i.e., the price power plant builders would have to pay.[1]

4.4. THE 'BALANCE OF SYSTEM' COST

The "balance of system" cost, i.e., the cost of mounting panels, connecting wires, control devices etc. has generally been assumed to yield a total system cost that is approximately double the cost of the modules. This is at first sight a surprisingly large amount, but it is consistently evident in the reported system costs for the cases outlined in Note 2.

If we assume 75 Watt panels, i.e., 150 peak watts per square metre, at $5(A) per watt, the cost per square metre would be $750 for the panels, and if BOS costs are equal to panel costs, then the cost for a whole system would be $(A)1,500 per square metre. Note that this usually refers to systems installed at homesteads or on building roofs, not to the costs of large-scale PV power stations which would add land costs and site works such as levelling, roads and water supply (for panel washing; see on Odum below).

4.5. THE COST OF COAL-FIRED VS PV PLANT?

Garlic (2000) states coal-fired capital costs per kW of \$(A)1,000–1,440.[3] Coal for 25 years will be assumed to cost \$2.5 billion (Garlic, 2000). Therefore the total cost of a 1000 MW coal-fired power station, plus fuel for 25 years, will be assumed to be approximately \$(A)3.7 billion.

Over a 25 year lifetime such a power station, operating at 0.8 of its full capacity as is usually estimated, would generate (1000 MW) × (0.8) × (8,760) × (25) = 175.2 billion kWh, and thus the capital cost per kWh for plant plus fuel would be 2.1 c/kWh.

If we take the above capital cost and efficiency figures for PV panels, along with Sydney's 34 degrees south annual average solar incidence of 4.6 kWh/m/d, what would be the cost of electricity supplied at a rate equal to a 1000 MW coal-fired plant operating at 0.8 capacity? To generate this amount of electricity at 13% efficiency, 6.154 million kWh of solar energy would have to be collected per day, and if solar incidence is 4.6 kWh/m/d this would require 32.1 million square metres of panels. At \$1,500 per metre the cost would be \$(A)48.2 billion, some 13 times the cost of the coal-fired plant plus coal.

This is not a very meaningful comparison, firstly because there are many additional cost factors below to add to the PV account, and secondly because the environmental costs of coal use should be taken into account. More importantly, when it comes to thinking about very large-scale electricity supply from renewable sources there is not that much value in having a lot of plant that will perform well for only 6 to 8 hours on a cloudless summer day. We need a fairly constant supply all through a 24 hour day. Solar thermal systems can do this because they can store energy as heat, but the most likely way PV systems would have to do it is via hydrogen production. The implications of solving this problem with a PV plant that uses hydrogen to store to meet nighttime demand are discussed later.

4.6. EUROPE AND THE USA

The foregoing discussion has been based mostly on the Australian situation and has assumed plant located 25 degrees from the equator, and about 4.25 kWh/m/d (horizontal plane) winter insolation. Even at the most southerly sites in the US, which are more than 35 degrees from the equator, the figure is well below this. For instance for Arizona, San Francisco, Las Vegas, New Mexico, Austin Texas, and Salt Lake City, the winter daily insolation figures are 2.9, 2.4, 2.9, 2.9, 2.8, and 2.0 kWh/m/d respectively (Marion and Wilcox, 1994).

At middle and northern European sites the situation is far worse. Most of these receive very little solar energy in winter. Mid-winter daily insolation can be 1/10 the mid-summer values.

4.7. DOLLAR PAY-BACK PERIODS

Although not central to the present discussion it is of interest to note the long times required for costly PV systems to meet their dollar purchase and installation costs. A 450 W household system offered by Pacific Power for \$(A)8,500 (that is, \$6,000 after the \$2,500 subsidy from the Federal government) would probably produce about 2 kWh a day in Sydney (annual average). Coal-fired electricity can be sold from the generator at 4 c per kWh in Australia. Thus if electricity generated by the three modules sold at the usual wholesale electricity price, annual earnings would be \$29, and it would take 294 years to earn the purchase price. From this should be deducted the electricity that no longer has to be purchased, although this would only be about 7% of the approximately 30 kWh/d household use.

The Victoria Market system referred to in Note 5 yields comparable figures. The \$1.75 million system is expected to produce 290 MWh per year, which would sell for about \$11,600 at the price of coal-fired electricity. At this rate the system would take 150 years to pay its capital cost, i.e., not including operations and management costs. These systems do not include any provision or cost for storage, as they are grid-connected.

These long dollar pay-back periods indicate the magnitude of the increases in electricity price that would have to be accepted in an economy based solely on renewables.[4]

In their commendable efforts to stimulate the development of renewables governments have given very generous subsidies (said to be 55Euro cents/kW for German PV electricity, some 30+ times the Australian cost of coal-fired electricity) but this can obscure the real economics of renewables.

4.8. PV ROOF CLADDING SYSTEMS

Integration of PV cells into roofing material reduces balance of system costs, e.g., for support structures (and roofing replaced). It also avoids transmission losses and costs which make up one-third of the retail cost of US electricity, but only if systems are elaborate enough to be completely independent of the grid. Such systems would have to include the excess generating and storage capacity needed to cope with long cloudy periods. They would increase some costs, especially for storage in many small units, each with its own batteries and power conditioning equipment such as inverters and regulators and petrol-driven backup generators.

The first question might be whether the solar incidence where the house is located is adequate. For instance in Sydney, 34 degrees south, in winter the solar incidence is 2.78 kWh per horizontal square metre per day, 2/3 of the 4.25 kWh per square metre per day in central Australia where large-scale centralised PV systems would be ideally located.

Rooftop collection surfaces are fixed in orientation and on average rooftops differ considerably from ideal orientation, and are subject to shading by other structures. It is likely that no more than 40% of the surface of a house roof would have an orientation enabling effective use as a solar collector in winter, assuming a house aligned close to an east – west axis. In mid-winter in Sydney the mid-day sun is 56 degrees from vertically overhead, so a typical roof surface facing north with a 12 degree slope will be 44 degrees from ideal inclination. However because it is angled somewhat towards the sun the roof might intercept around 3.12 kWh/m/d. This is 0.73 of the 4.25 kW/m/d falling on a horizontal surface in central Australia at the Tropic of Capricorn at that time of the year.

However, houses are not all aligned close to an east–west axis. In fact only about one third would have their longer roof line aligned close enough to that. Mills (2002) refers to an analysis which concludes that combining the above limitations would mean that on average about 35 square metres of roof space would be useable per house. The following discussion assumes 40 square meters.

At 13% efficiency, 40 square metres of PV panels receiving 3.12 kWh/m/d would generate 16 kWh/d, probably about half of household demand, if storage issues are ignored. At the $(A)2004 price for BP modules, $1,292/m, the modules would cost $51,680. Over a 25 year lifetime they might generate 148,000 kWh at Sydney, so module cost per kWh generated would be 35c. BOS costs are not included, and access to the grid for storage is assumed.[5]

To also fuel an electric car via rooftop PV panels would be to more or less treble the magnitude of the task, given that Australian transport energy is almost twice electrical energy used. This is only a statement about the gross amount of energy needed and does not take into account factors such as the loss via battery inefficiency.

Monitoring of the rooftop PV Solarsense House in South Australia found that 1,157 kWh were generated p.a., equal to 38% of household use, and an average of 1.4 kWh per day was sold to the grid (Oliphant, 2004). If the wholesale price of 4 c/kWh had been paid for this, annual earnings from the sale would have been $(A)20.44. (The householder was probably paid 3.5 times this amount.) The system also produced 646 kWh of electricity used by the house, so in effect its annual "earnings" were $65. At the rate of total annual income, $85, it would take 114 years to pay off the modules alone.

An 11 square metre system from PV Solar Energy would produce about 7.15 kWh/d in Sydney. If the electricity produced was priced at the current subsidised figure of 10c/kWh, or if sold at the wholesale cost of coal-fired power, 4ckWh, the annual incomes would be $259 or $104 respectively. It would take 77 or 189 years to pay the $20,000 installation cost.

The main problem with the rooftop option is that it is available only for that proportion of houses that can be integrated into a grid running mostly on some other energy source. On average much less than half a house's electricity demand could be met while the sun is shining, even ignoring cloudy days, and a rooftop PV house without its own storage would have to draw from the grid for 16 hours a day. The existence of the grid also enables the house to sell the surplus energy it produces.

4.9. CONCENTRATOR PV TECHNOLOGY

Large reductions in PV costs are promised by the development of cells that receive sunlight focused from reflectors, enabling the area of PV material to be much smaller than the area over which solar energy is collected. Cells capable of concentration factors of 1000 to 2000, and over 25% efficiency, are being developed. The ANU cells are 22% efficient (Smeltink, 2003). However such figures can be misleading as field conditions for concentrating systems can differ considerably from lab conditions, especially with respect to the proportion of solar energy that is direct or "beam", and therefore capable of being focused.

Because these systems reduce the area of PV material in relation to the area of the collector, even if the PV component cost was very low the cost of the collection apparatus which must track the sun is likely to remain high. It is likely to be higher than for concentrating solar thermal systems because the target on which the solar energy is to be focused is so small, and therefore the accuracy of the focus and the tracking will have to be greater.

Swanson (2000) discusses the fact that although this approach has been under development since the early 1980s it has not been taken up enthusiastically. One reason is that it is not as suitable for the many small and stand-alone tasks that flat plate technology is being used for. Concentrating systems are more complex and thus are best suited for large-scale power supply, and here their high cost has been the main impediment.

An experimental 20 kWe peak system operating at Rockingham in Western Australia is in the early stages of operation, although performance has been reported as disappointing so far (Personal communication). The best daily output recorded, 75 kWh/d, represents an efficiency of about 5.5% (i.e., electrical energy produced as a percentage of solar energy falling on the collector). I have been unable to get cost figures (especially balance of system costs) from the developers, although these would not be a clear guide to costs for eventual large-scale production.

An experimental system at Australian National University (Corkish, n.d.) involves a concentration factor of around 40, i.e., the area of PV cells required is only 1/40 of that over which sunlight is collected.

Sala, et al., (2000), describe the experimental 480 kW Euclides system. Efficiency is reported at 8%, over a year. Total plant cost was Euro 2.13 million, or Euro 4.4 per Wp. The future achievable PV receiving module cost is estimated at 81(US)cents/W.[6] However the balance of system cost is estimated at 82% of total cost.

The project announced for Mildura, Australia late in 2006 has a surprisingly low predicted cost of $3/W(p). Cell cost is estimated at around $1(A) per watt but tracking system cost is claimed to be at about the same as for solar thermal systems, making the above total system cost estimate somewhat puzzling. (Solar Systems, personal communications.) The final figure therefore might be taken with caution at this stage but this could turn out to be the lowest cost form of PV electricity generation.

The overall cost of concentrator systems will be determined primarily by the cost of the relatively elaborate balance of system. As has been noted, for systems which do not track the sun this is usually assumed to be about equal to the cost for normal flat plate PV modules per metre. However concentrator systems must track the sun accurately, so structures will have to be fairly elaborate, involving supports for collecting surfaces, accurate machinery and control systems, moveable in at least one dimension and capable of withstanding strong winds. An additional cost not involved in other tracking systems comes from the need to take out the considerable amount of heat accumulating at the cells. (If this could be sold this would lower net cost.) Costs for these items are not likely to fall greatly due to technical breakthroughs as they already involve technically relatively mature structures. Note 7 reports some of the relevant evidence.

From this diverse and rather unsatisfactory evidence on trough systems and that in Chapter 3 on solar thermal systems, it would seem that the structures for supporting the concentrating cells might cost in the region of $(A)500 per square metre but little confidence can be placed in this figure. Nevertheless it suggests that even if PV concentrator cell technology becomes very cheap, the balance of system cost for very large collection areas is likely to remain relatively high. Perhaps the most meaningful reference here is to the balance of field for flat plate systems, which Chapter 4 indicates appear to be around $750/m. Systems which must track the sun accurately could be expected to be much more expensive than fixed flat plate arrangements. Unfortunately these BOS cost indicators are not consistent.

Another important consideration, noted above, is that any system which concentrates solar energy uses only the direct and not the diffuse component of solar radiation. At some times and locations most of the light reaching a site has come from all angles rather than straight from the sun. Only the latter can be reflected onto a target. Flat PV modules can use all the energy reaching them, regardless of angle, but concentrators can only use the direct or beam proportion. They would therefore have to be located in regions with high average beam incidence.

Again the evidence is uncertain but it would seem that concentrating systems might more or less halve flat plate PV system costs.

4.10. POWERING A NORMAL HOUSE

Let’s briefly explore the cost of running a normal house with a stand-alone PV system. It is not likely that anyone would want to do this, but the numbers further illustrate the limits and difficulties involved in PV electricity.

If we assume a house which uses 25–30 kWh a day, located in Sydney, where 2.6 kWh of solar energy are received per metre per day in winter, using 13% efficient PV modules, then the two panels in a 1 square metre area would collect 0.33 kWh per day. However because of the inefficiency of battery storage only about 70% of this can be drawn from the battery. Other system losses, e.g., in inverters, which would be significant will be ignored here.

To meet the total power demand of the household in winter about 100 square metres of modules would be needed. At the retail price of $(A)600 (which I paid in 2004), the modules would cost $120,000. To this would have to be added a balance of system cost. This might double module cost, but not if a roof cladding system is used. BOS will be ignored here.

This system would be capable of meeting demand in winter but in summer more than half the electricity generated from the higher level of solar radiation could not be used.

If 10 kWh/d had to be stored for night time use, enough 12 volt batteries would be needed to deliver 833 amp-hours at 12 volts. A 220 amp-hour lead battery costs $(A)320. Easily overlooked here is the fact that a battery must not be discharged more than about 20% of capacity at any one time or its life will be shortened too quickly. This means that useable storage is only 44 ah per battery and it is costing $7.25 to store one amp-hour. Thus the total storage capacity we need, 19 batteries, (for one night) will cost $6,060.

The next question is how long will the batteries last. The makers will tell you perhaps eight years, but in the real world there's a good chance that it's three or less. Why? Because something goes wrong, that's why! Having written off a number of sets of batteries I know. Sometimes it's a possum that somehow shorts the wires . . . on Christmas Eve so you can't find a garage to charge them quickly. To guard against this add $2,000 for an emergency generator (which would have to be run perhaps 10 hours on a cloudy day . . . with what lifetime energy cost?) But let's assume an eight year battery lifetime, so we will need three sets of batteries over the 25 years.

That battery capacity provides for one day's storage. What about the times when it is cloudy for a week? Let's us go for three day's storage, i.e., capacity to store 75 kWh, or the capacity to deliver 6,250 ah at 12 volts. Thus we would have to pay $45,300 for batteries. We would still not be sure of always having sufficient energy in storage to cope with three days of cloud, because when those days arrive the batteries might not yet be recharged after the last cloudy period. This is a constant worry with stand alone systems in winter, and as has been noted it affects solar thermal storage systems too.

Our system, without the balance of system costs for mounting the panels, the power conditioning equipment, a number of inverters over 25 years, the backup generator and its fuel, would cost about $165,000. At Sydney with an annual average solar incidence of 4.6 KWh/m/d, the 100 m area would collect 545,675 kWh of electricity over the 25 years, and the panel plus battery cost per kWh would be 30c. It would take around 190 years to pay this off if the power sold for 4c/kWh. Adding a BOS cost might raise the final total to 50c/kWh. The panel plus battery cost of producing our power would be about 72c/kWh. If the electricity generated was sold at the same price as coal-fired electricity it would take 452 years to pay these costs.

4.11. A 1000 MW PV PLANT TO MEET 24 HOUR DEMAND OVER A WINTER DAY?

PV systems are at their best in decentralised use, on house roofs connected to the grid, or powering isolated households. However if PV electricity is going to be a major contributor to solving the main task set by the prospect of a renewable energy world, then it is important for us to explore what might be involved in having a 1000 MW PV plant meeting 24 hour demand. This is the crucial "base load" task for a wholly renewable energy world. One way of doing this is by storing energy in the form of hydrogen for night time regeneration of electricity. It is not being implied that any electricity supplier would contemplate the following scheme, but it is being outlined here in order to make clear the huge and costly problem set by the inevitable need to store PV electricity for use when the sun is not shining. If this cannot be done, then a renewable energy world cannot be created. (The possibility of getting round the problem by other storage options or by having a multitude of renewable options to move between is considered in later chapters.)

Let us assume a site at the tropic of Capricorn where the average daily solar incidence on a horizontal plane in winter is approximately 4.25 kWh per square metre (University of Lowell Photovoltaic Program, 1991). This means that the sun would be approximately 35–40 degrees from vertically overhead throughout most of winter. Thus the incidence of solar energy on panels set at optimum inclination would be about 5.18 kWh/d in winter, and collectors set at this angle will be assumed for the following discussion. (Note that this maximises the achievement for winter performance but to maximise annual performance the tilt would be at half this angle.)

It will be assumed that for eight hours a day electricity from solar PV plants will be supplied directly, and for the other 16 hours it will have to be stored before being supplied to consumers. Night time electricity demand is about one-third lower than daytime demand (Mills and Keepin, 1993) so in the following discussion supply from a power plant will be assumed to be at the rate of 1000 MW for eight daylight hours and 670 MW for the other 16 hours, i.e., a total of 18,720 MWh/d.

A 15% loss of this output in DC transmission from the northern inland generating site to the widely scattered southern coastal consuming areas will be assumed. (The figure could be lower in the long run, but this is uncertain; see Chapter 2 on transmission losses.) Losses could be reduced if generating plant was located close to users, but for Sydney, winter solar incidence would then be about half the Central Australian level. A loss of 6% in converting from DC to AC current for use will also be assumed.

From these figures the overall efficiency of delivering electricity directly to consumers in the daytime would be 10.3%. In other words to deliver 1 kWh, solar energy equivalent to 9.7 kWh would have to fall on the collecting surface. Therefore to deliver 8 hours × 1000 MW directly, 77,600 MWh of solar energy would have to fall on the collector each day.

Now we come to the main problem, storing the energy for use at night. Storing in the form of hydrogen gas will be assumed here. (Other storage options will be considered in Chapter 7.) The significant problems deriving from the occurrence of a series of continuously cloudy days will be ignored, although obviously much greater storage capacity would be required to deal with them.

The energy efficiency of producing hydrogen gas from electricity will be assumed to be approximately 70%. (Commercial supply in the US is currently via methane reforming at 65% efficiency.) Again a 15% loss in transmission and a 6% loss in inversion will be assumed. Generation of electricity by burning the hydrogen gas or by use of fuel cells will be assumed to be 40% energy efficient. (Generation of electricity by hydrogen fuelled gas turbines is likely to be more efficient. Possible future fuel cell efficiencies are discussed in Chapter 6.) The combined effect of these efficiencies would mean that for each kWh of solar energy falling on the panel surface only 0.03 kWh would be delivered in the form of electricity after storage; i.e., the process would only be about 3% energy efficient. Thus the need to store a unit of energy increases the collection area required by a factor of about 3.6.

To meet the 670 MW demand for the 16 hours of the day when the sun is not shining, i.e., 10,720 MWh, via a 3% efficient process, 357,300 MWh of solar energy would have to fall on the collection surface each day. Adding the direct and the night time figures indicates a need for a total of 451,400 MWh to fall on the collecting surface each day. At 5.18 kWh per square metre the collection area would have to be 84 million square metres.

At $1,500/m the capital cost of a generating plant 84 million square metres in area would be $126 billion. (This assumes a BOS cost the same as for household systems, and this is debatable. One might think it could be much lower, but Odum (1996) concluded that the emergy cost of a PV power station would be quite high.) Many additional cost factors not included in this derivation are noted below.

Thus the PV solar option would cost approximately 34 times the cost of the coal option. Different assumptions and future costs might lead to a rather different figure, but this multiple is so large it would seem to rule out any possibility of very large-scale 24 hour electricity supply from PV sources via hydrogen. As is detailed below, PV systems can be large as long as they are still small compared with the other sources feeding into the grid that they are serving, and capable of meeting demand when the renewables cannot.

4.12. OTHER COST FACTORS NOT YET INCLUDED

The discussion to this point has dealt only with the cost of constructing the collection area, and there are many other factors that would multiply the final lifetime cost for the total system considerably. The cost of construction accounts for only about 20% of the present price of electricity generated by coal-fired plants. Following are several additional factors which would significantly increase the cost of the solar PV plant. (There is some overlap between these.)

a) *Operations and management costs*, especially the cost of regular cleaning of the large collection area. For wind systems operations and management costs over plant lifetime add approximately 0.7 times construction cost.

b) *No provision has been made in the above estimate for the extra capacity needed to cope with extended cloudy periods*.[8]

c) *The inverters* required to convert the 12 volt power coming from the panels to 240 AC will only last about 10 years, so they will have to be replaced about 2.5 times in the assumed lifetime of the system (Sadler, Diesendorf and Denniss, 2003, 9.4).

d) *The energy cost of constructing the plant* must be subtracted from its lifetime output before we can discuss the amount of energy it would actually deliver.

PV cell manufacturers usually claim pay-back period for modules of about 3 years (Corkish, n.d., Knapp and Jester, 2000, Alsema, 2000). In his recent review of 10 studies Gale (2006) concludes that the payback period is about four years.

The main problem with such figures is that the value for power generated is usually derived from module performance under ideal laboratory conditions and many factors reduce panel performance in the field to well below these levels. This means that real pay-back time in the field will in general be considerably longer than might be expected from the manufacturers' statements. If we focus on a homesteader dependent on battery storage the situation is much worse, because he only gets 0.7 of energy generated after it goes into the battery.[5]

Also relevant is the assumed insolation level. Gale (2006) indicates 4.6 kWh/m/d, and most users more than about 35 degrees from the equator will get less than this.

As Gale notes the pay-back discussion usually focuses on the domestic situation where there is little need for elaborate balance of system structures, but the situation is quite different if we are talking about large-scale PV power stations. These would require a lot of concrete, steel, energy and earthworks etc. to construct, which household systems do not involve. Odum's pay-back calculations (1996, discussed by Gale) are usually dismissed as being exaggerated but they are unusual in being for a large power plant and include these factors.

In addition, as the discussion of wind made clear, there can be large differences between performance figures for individual generating units at ideal sites and those for whole systems. The latter include losses from all factors that intervene after the mill or PV module, including those due to integration problems.

e) *The cost of building and operating the hydrogen production, pumping and storage systems would be large*. The equipment to produce hydrogen from electricity at present costs about $1000/kW, as much as a coal-fired power station (although some claim this figure will fall significantly). To store the hydrogen to meet night time demand would involve a huge storage volume given the low energy density of hydrogen. To retrieve the 10,560 MWh from hydrogen via a process that is 70%(in) × 40%(out) efficient would require storage of 37,700 MWh of hydrogen a day. At 3 kWh per cubic metre, the volume of hydrogen would be approximately 12 million cubic metres, or a mine shaft some 1,300 km long. Compressing the gas would reduce the volume but it would also increase plant costs, and take perhaps 20% of the energy in the hydrogen (see Chapter 6).

f) *The cost of the plant to convert the stored hydrogen to electricity* would have to be added. This would be comparable to the cost of a coal or gas-fired power station assuming the hydrogen is used as fuel to generate steam. The fuel cells of the future will probably be more efficient but at present are very expensive. Use of the hydrogen in gas turbines would probably be considerably more efficient and cheaper.

g) *Most of the silicon for production of cells has been coming from scrap left over from the computer industry*, and might cost more if produced specially for the solar industry.

h.) *The cost of the capital that would have to be borrowed to build the plant, i.e., the interest to be paid, might double the total construction cost* figure from all the above factors combined.

i.) *The cost of company profits and tax* have not been taken into account here. If a very large amount of capital must be invested, then adding a 10% return p.a. on this, and a perhaps 40% rate of tax on income, would add a large amount to the above cost figures.

j.) *Most importantly, the future cost of energy should be used in estimates of this kind.* A decision to build large-scale solar generating plants with the sort of costs under discussion here would obviously not be made until the cost of energy from other sources ceases to be cheaper than the energy generated by these solar plants. We must assume therefore that in the distant future the cost of the energy required to build all components of the solar plant including PV cells, balance of system and all contributing factories, deliveries, trucks, tools etc., will be approximately the same as the price of the energy it will generate, which it has been indicated would be very high. Remember that energy-intensive materials make up much of the construction cost. These higher costs of inputs will in turn have a multiplying effect further raising the cost of the energy produced. Thus decades from now the cost of PV plant could well be far higher than that assumed in the above derivations, which assume present energy costs for construction and materials.

Combining these factors would indicate that the initial $126 billion cost estimate might be far below a realistic total cost figure.

4.13. A RARE ELEMENTS LIMIT?

The most common PV cells are made from silica, which is abundant. However thin film technologies require small quantities of rare elements such as Gallium, Indium and Tellurium. The potentially recoverable resources of some of these elements are not sufficient to enable these kinds of cells to contribute a large fraction of world electricity consumption (Hayden, 2004, p. 141, Ehrenreich, 1979 Anderson, 2000).

Thin film technologies are associated with lower costs, but also with lower life expectancies and efficiencies, and in some cases with toxic materials

4.14. WHAT DIFFERENCE MIGHT TECHNICAL ADVANCES MAKE?

The assumptions made within the above analysis are apparent and enable derivation of the conclusions that would follow if different assumptions about efficiencies and costs were made. If we assume a) cells with 20% actual operating efficiency in the field (as distinct from nominal peak watt rating), compared with the 13% taken above, b) a cost of $2 per watt for PV cells, i.e., a 60% reduction, c) fuel cells producing electricity from stored hydrogen at 60% efficiency, then the cost of the plant to collect enough solar energy to deliver 1000 MW would fall to around 1/6 of the cost estimate arrived at earlier, i.e., to the region of five times that of a coal-fired plant plus fuel, not including any of the other 10 factors listed above.

If the cost per square metre of PV technology fell to zero, the cost of the large collection area required would still be high. If the PV material was sprayed at no cost onto 6 mm toughened glass at the wholesale price of approximately $60 per square metre, the cost of the glass alone for the above 84 million square metre collection area would be $5,040 million. Littlewood (2003) estimates the cost of PV glass in 2003 at $50/m, and at $70–80/m for curved glass for concentrating systems.

In other words the “balance of system” cost sets a difficult limit when the collection area must be very large, and one that is not likely to be greatly affected by technical advances as structures are simple and major breakthroughs in their design are not likely. As has been noted, the BOS cost per metre for actual installed systems seems to have been about the same as the cost of the panels, i.e., at present c. $750/m.

Almost all of the materials cost of modules is due to aluminium, glass and silicon. For silicon cells it is 85% and for thin film technology it is 97% (Knapp and Jester, 2000). Thus there would seem to be little scope for cost reduction from advances in the solar technology as distinct from the materials required for supports etc., although increased scale of production would make a significant difference to overall production costs. Again it should be noted that BOS cost could be the most uncertain element in this analysis of PV systems, and the one most likely to lower the above estimates.

4.15. PV CONCLUSIONS

It does not need to be said that PV electricity is currently making a significant and valuable contribution, and it could be a very important part of a sustainable society. However it could be part of a renewable energy system which meets all (or almost all) the demand only if some other sources met demand at night and in cloudy times, or if a way was found to store very large quantities of electricity. The fact that PV is best in decentralised situations and that the large plant using hydrogen storage considered above is not what PV advocates suggest, does not affect this situation.

The foregoing discussion has focussed on probably the world's most favourable regions for solar energy, central Australia, but the figures seem to show that in winter at such a site there would be great difficulties and costs involved in large-scale electricity supply systems based largely or wholly on PV. In mid to northern regions of Europe in winter the incidence of solar energy is somewhere between very low and negligible. The three winter month average solar energy received in Belgium, Montreal, Paris, Dresden and Finland is 0.66, 1.16, 0.86, 0.66 and 0.25 kWh/m/d respectively, i.e., around 13% of the central Australian figure. Large-scale PV supply to Europe would probably have to come from deep within Africa, involving 3,000 to 5,000 km transmission, across the Mediterranean sea, and a very large-scale storage problem. However in that region solar thermal systems are more promising because the energy can be stored as heat for generation and high voltage DC transmission when the electricity is needed.

It is often argued that PV would be supplemented with other renewable sources, so that when it is not contributing much the wind or the tides etc. could be taking most of the load. This is true to some extent but it would involve building a number of distinct, large and costly systems, each to meet demand at a different time, and each to be idle much of the time, and it would not eliminate the need for coal or nuclear backup when there is little sun or wind.

On the other hand, PV can play a part in the fully renewable energy economy of The Simpler Way detailed in Chapter 11, primarily because the energy demands could be so very much lower than they are in consumer–capitalist society. Many of the storage technologies noted in Chapter 7 could make their small but sufficient contribution in such a situation. But if the goal is to sustain a very high energy consumer–capitalist society almost entirely on renewables, PV electricity could make a significant contribution only if some way was found to get around the problems set by night time, clouds and low winter insolation.

CHAPTER 5

LIQUID AND GASEOUS FUELS DERIVED FROM BIOMASS

The most clear-cut and severe limits to a renewable energy future have to do with the supply of liquid and gaseous fuels. Despite the uncertainties, the conclusion arrived at below is that, even if the most optimistic estimates and assumptions are taken, biomass is not capable of supplying more than a small fraction of the present global demand for liquid fuels, let alone the future demand that would be generated by growth in population, global equity and economic output. Chapter 6 explains why it is also not likely that hydrogen will solve this crucial liquid fuel problem.

Assessing the potential and limits of biomass energy involves a consideration of the amount of biomass we might harvest and the amount of fuel we might derive from each tonne of biomass. Unfortunately both issues oblige us to wade through much uncertain and sometimes conflicting evidence. The limits to liquid fuel production have not primarily to do with the energy return ratio for producing fuels from biomass. They have to do with quantity, i.e., the areas of land available and the associated yields.

5.1. BIOMASS YIELDS AND QUANTITIES

Non-plantation sources such as crop and timber wastes are not likely to make a large contribution in relation to the vast quantities of biomass needed for renewables to replace fossil fuels.[1] As will be emphasised below, the same is true of biomass from cropland, such as via corn or wheat inputs to ethanol production, because the areas required would be far too great. Thus the major source must be cellulosic (woody) material, mostly from trees, shrubs and grasses.

5.2. PLANTATIONS: POSSIBLE AREAS AND YIELDS

The plantation question should be seen in terms of what areas are likely to achieve what yields per year, via procedures that are sustainable over very large areas in the long term. High yields from biomass plantations are often reported or predicted, but these typically refer to experimental or unusual sites using good land. Experimental sites tend to involve the most favourable conditions, and very large-scale biomass plantations would have to use mostly land that is well below ideal. In fact proposals often envisage use of degraded land.

Some predicted yields seem to be quite unrealistic for very large areas. For example Lynd (1996), the European Environmental Agency (2006) and Foran and Mardon, (1999) assume dry weight yields can be 20–21 t/ha/y, and these can be maintained year after year. Discussions often make reference to instances where high yields have been achieved in specific locations or experimental conditions. Sugar cane yields can be over 80 t/ha/y, although most of this weight is water. Hall, et al., (1993) assume 15 t/ha/y can be averaged over 890 million ha of Third World land. They give little evidence for the claim, admitting it is optimistic, but it would seem to be far beyond the realm of possibility. Note 2 refers to other estimates.

5.2.1 USA

The Oak Ridge National Laboratory (Walsh et al., 2000) estimates that 510 million tonnes, 10.2 EJ gross, could be harvested in the US, if all sources are combined (making the quite high 15 t/ha yield assumption). Fulton says 50% of the 35 million ha that Walsh assumes would come from cropland. Sheehan's conclusion is considerably lower, 332 million tonnes (Fulton, 2005, p. 134). Both estimates are for the highest biomass price considered, $(US)50/t. Fulton says this would displace about 30% of US gasoline demand (i.e., not including diesel demand). A study by the Batelle Memorial Institute (Smith, et al., 2004) states the same figure for the near term potential from plantations on US crop land, forest waste, and agricultural waste. If used to produce ethanol this would provide less than 10% of present US transport fuel.[3] Perlack, et al. (2004), from the Oak Ridge National Laboratory, have argued that the US could produce 1 billion tonnes of biomass for energy purposes.

Fulton says 32 million ha, 24% of all cropland, are presently used to grow plants capable of producing ethanol or biodiesel, and that if it was all used to do so 253 million tonnes could be produced. This would convert to 2.3 EJ of ethanol gross (assuming 397 l/t).

There is considerable interest in the US in the use of Switchgrass, a highly productive native suited to large areas of the Great Plains. Graham, Elison and Beck (1997) claim that US Switchgrass and Short Rotation Woody Crop potentials are (205 million acres) × (4–5 t/a) and (266 million acres) × (5 t/a) respectively. These overlap, meaning that both would not be possible at the same time, and no indication is given of the proportion of this land currently in use for other purposes. Either indicates a yield of c. 200 million tonnes, with an energy content around 14% of US transport fuel (indicating the potential to produce liquid fuel equal to 4% of transport fuel; see below). Lynd (1996) estimates that 281 million tonnes could be harvested in future, at 16 t/ha.

5.2.2 Europe

The European Environmental Agency (2006) concludes that biomass production in Europe can be equivalent to 295 million barrels of oil, by 2030, i.e., 12 EJ, or about 40 GJ per person of primary energy. However the net ethanol yield is not given and the biomass yield assumption is very high, equivalent to 20 t/ha/y from agricultural land (derived from p. 7). It is also assumed that more than 25% of this land area will have been moved out of food production as bio-energy prices rise and food demand is met by more imports. However this simply shifts the location of the total footprint; that area will still be producing food for Europe but it will be located somewhere else. In other words it could be argued that the available area for biomass production should be taken as 14 million ha, not 19 million.

5.2.3 Possible World Yield

Estimates of world biomass potential are rather unsatisfactory. Often they vary greatly, some are quite implausible, and assumptions are not clear. Especially important is the fact that most crop, pasture and forest are already heavily used or overused and the proportion of annual biomass growth that could be taken for non-energy purposes is not deducted. Fulton (2005) lists 11 estimates from six studies, ranging around 400 EJ (with one at 1,301 EJ).

Berndes, Hoogwijk and van den Broek (2003) review 17 studies of global total biomass yield potential. Unfortunately these differ greatly in assumptions and conclusions, and some seem to involve quite implausible growth rate assumptions (e.g., 46–99 t/ha which they say are not supported). However inspection of the core plot of estimates indicates that potential world aggregate yield would be approximately equivalent to a total yield of 10,500 million tonnes, which is 210 EJ of primary energy. If this was all converted to ethanol the gross yield would be 85 EJ (see below). FAO (n.d.) gives the current world primary energy consumption as 410 EJ.

Obviously the amount of this annual biomass growth available for energy production would be far below 210 EJ, firstly because much of it is already going into crop, pasture, timber and fuel use. Secondly it would not be economic to harvest for commercial biomass the low yield areas represented by the right-hand tail of the graph, which might cut off one third of the total area. Much of this harvest is by Third World people to whom it is "economic" to collect from areas producing at yields well below those that would meet the costs of industrialised biomass production systems. As population goes from 6+ to 9+ billion, demand for food producing land will significantly reduce the area available for biomass production. As Ravilious (2005) says, " . . . the earth is rapidly running out of fertile land."

The 210 EJ figure is about the same as that arrived at if one assumes 3.5 billion ha of world forest growing at an average of 3 t/ha. Adding grassland growth might increase the total by 20%. Obviously conversion to liquid fuels, gas or electricity would greatly reduce delivered quantities of energy.

It would seem therefore that if we simply take the total global biomass growth available for energy production we can see that it would not enable production of anywhere near present global liquid plus gas use (discussed further below). The proportion of this growth that could be harvested for energy production would be small, and from this the energy costs of fuel production would have to be deducted. In other words, from these general global figures it seems clear that there is no possibility of world biomass production meeting more than a quite small proportion of present world liquid plus gas fuel demand.

A major and quite unsettled question regarding large-scale biomass plantations concerns the sustainability of continual cropping. In timber production only a small proportion of the nutrients are removed, as most remain in bark, branches and leaves. However it is generally assumed that for energy production all above-ground material would be taken, posing problems of both erosion and soil nutrient depletion. Fertilizers might offset the problem significantly, although these cause other problems in the long run, and impose energy costs. Pimentel and Pimentel (1997, pp. 238, 241) stress the high erosion rates associated with significant removal of biomass.

5.2.4 Australia

World average forest growth is around 2 t/ha/y (FAO, n.d.) and the Australian average forest growth rate is probably well below the world average rate. However Mason (1992) reports pine growth in Australian plantations at around 4 t/ha/y on average and Bartle (2000) reports mallee harvest at 7.5 dry t/ha/y. Some Australian plantations achieve 10–12 t/ha/y growth (McLelan, 2004), but these are in select regions where conditions are unusually favourable. Giampietro, Ulgiati and Pimentel (1997) say woody biomass can be harvested at 8.5 dry tonnes/ha/y, although this also assumes relatively favourable growing conditions, and application of fertilisers with a significant energy cost.[4]

The exclusion factor applying to forest use can be quite significant. Nilson, et al., (1999) conclude that in general possibly 40% of existing forest areas might not be accessible to biomass harvesting. Much forest is on steep slopes, near creeks, on private land or on protected catchment.

In addition if Australia were to be self-sufficient in forest products, local production would have to be increased considerably. At present imports cost $3.8 billion p.a., while exports earn only $1.6 billion p.a. This should be redressed as much of the imported timber comes from Third World countries where forests are being rapidly destroyed.

Also, approximately 6 million tonnes of wood are presently being harvested p.a. for domestic heating in Australia. (The ABARE estimate is one-third higher but disputed). Given the rate of forest loss, current Australian and world timber and fuel wood demand are probably well beyond maximum sustainable quantities.

Currently there are only about 1.4 million ha under plantations in Australia and its relatively poor soils would probably place severe limits on the extent to which this area could be increased and continuously cropped at an acceptable yield. Mercer says Australia might increase timber plantations to 10 million ha (1991, p. 81). As will be shown below far more than that would be needed for biomass energy production.

Consider the following yields for Australian agriculture; wheat, 1.9 t/ha/y (i.e., grain; total plant biomass might be 3 t/ha/y), fodder, 3.5 t/ha/y, overall agricultural production excluding sugar cane, 2 t/ha/y. In other words biomass yield from Australian cropland, which is obviously the best growing land available, is under 4 t/ha/y (. . . after the application of 3.5 million tonnes of fertiliser and considerable pesticide and irrigation inputs. Australian Bureau of Statistics, 1997–8).

Foran and Mardon (1999) argue that biomass energy for Australia could come from the areas that need to be replanted to remedy Australia's dryland salinity problem. However degraded dryland could be expected to have biomass yields that are a small fraction of those for average Australian cropland. Nevertheless Bartle (2000) reports coppicing of Eucalyptus mallees yields 5–7.5 dry tonnes of feedstock per ha per year.

Bugg, et al., (2002b) claim to have carried out the first thorough study of biomass land potential in the Australian state of NSW.[5] It is somewhat difficult to draw confident conclusions from these estimates for potential biomass energy harvest. The first issue concerns the point where the economic yield might cut off. The total yield, around 190 million t/y, includes 134 million tonnes in the last three categories which Bugg, et al. say would not be economic to harvest for timber. Even the third last category in which growth is given as 8.6 t/ha/y is described as "not usually considered for conventional plantations". Timber production is likely to earn much more per tonne than the production of biomass for energy.

Use of the second to last category would seem to be ruled out. If its energy content is sold at the same price as coal the 4.7 t/ha/y of biomass gross income would be $94/ha, compared with perhaps $(A)500 per ha for hay production. The following three possibilities seem to straddle the probable potential.

- If we take the figures for the first three categories, a total of 65 million tonnes, and assume that 50% of these areas suffers from some kind of exclusion factor, the total biomass production resulting might be taken as a lower limit of around 32.5 million tonnes.
- If we take a lower exclusion factor and assume some use of the 8.6 t/ha/y category we might conclude that output could be 55 million t/y, or around 7+ tonnes per person living within NSW.
- If we take the first four categories without any exclusion factor, which are unrealistic assumptions, the total yield is 107 million tonnes, or 15.3 tonnes per person.

In view of these numbers a realistic figure could be in the range of 50–70 million tonnes, or 7–10 tonnes per person. As will be explained below Australia would probably need well over 300 million tonnes to meet the equivalent of present oil plus gas demand via ethanol, i.e., over 18 tonnes per person (and given present rates of increase in energy use, perhaps three times as much by 2050).

These figures suggest that the NSW potential per capita yield would be under half the required amount. However compared with most of the rest of Australia NSW has a considerably higher than average potential biomass yield so the national yield per capita might be one quarter to one third of the required amount if all potentially useable land was harvested. An uncertain estimate of the national total extrapolated from Bugg, et al might be 200 million tonnes, but it might be less.

The considerable uncertainty in this kind of exercise is illustrated by comparing the above figures with those from Bartle (2000). Their analysis of the Australian wheat belt, the large area most suitable for biomass production, concluded that in their most optimistic case, 38 million tonnes of mallee biomass might be harvested each year for energy.

Few if any other rich countries are close to Australia with respect to the potential per capita area of biomass producing land. In any case it is inappropriate to consider the situation of individual countries. What will matter in a highly integrated global economy will be the situation of the rich countries as a whole, and thus their average quantity of land available per capita, or their access to land beyond their borders.

5.3. THE YIELD ASSUMED

Although plantation yields for cellulosic biomass inputs of 20 t/ha/y are likely to be achieved in future, especially assuming the development of new genetic lines, this is not likely to be the global norm for very large-scale biomass energy production. It is achievable now in some specially favourable locations and conditions, especially within Europe, but it is argued below that in a renewable energy world biomass will have to be almost the sole source of liquid and gaseous fuel, meaning use will have to be made of very large land areas, and it is not plausible that the average yield from these will be anything like 20 t/ha/y. For the purposes of the following discussion the yield assumption will be 7 t/ha/y. It will be shown that even if this is doubled the general conclusion arrived at in the chapter is not affected significantly.

5.4. BIODIESEL

The most productive biomass energy path would seem to be biodiesel from vegetable oils. Yields of oils can be over 4 tonnes of oil per ha, and energy returns over 3.3 have been reported (Sheehan, et al., 1998). However Foran and Mardon say present Australian canola oil production would be about 0.75 t/ha/y. The main limit is the need for good cropland for most of these plants. Oil producing crops already take 200 million ha of good land globally.

Oil palm has a high energy yield per ha but is confined to the tropical band, and requires cheap labour to harvest. Present output is causing serious concern regarding the take-over of Third World land and rainforest destruction (Pearce, 2005). It has been claimed to be responsible for almost 90% of Malaysian forest destruction.

Candlenut has a high yield but suitable growing conditions would be a major limit for very large-scale production.

Fulton says 30 million ha of US cropland are growing crops suitable for biodiesel production. This is 25% of US cropland and could produce 530 l/ha, or a gross national total of 0.46 EJ.

Another limit to the very large use of biodiesel is the fact that for each 4 to 10 units of vegetable oil energy produced, one unit of alcohol energy must be used, making biodiesel dependent on the ethanol and methanol situation (which is problematic; see below).

For these reasons, especially the dependence of oil crops on use of agricultural land and on favourable growing conditions, biodiesel will not be given much attention in the following discussion. As has been said above, very large-scale liquid fuel production will have to come mostly from cellulosic inputs from less than ideal land.

5.5. ALGAE AS A BIOMASS SOURCE

In ideal conditions some species of algae grow at very high rates, up to 30 times the rate for land plants. Of special interest for energy production is the possibility of using sea water in large shallow desert ponds. Sheehan et al. of NREL (1998) claim the rate can reach 50 g/m/d, dry weight, which equates to 180 t/ha/y although they do not say this growth rate can be kept up for a year. They point out that average growth rates are more like 10 g/m/d in field conditions, as distinct from in the lab. This is equivalent to 36.5 t/ha/y dry weight. Sheehan et al. refer to a proposed scheme intended to harvest 67 t/ha/y, more or less equivalent to sugar cane, and says that the oil content can be 40% of dry weight. (NREL recently terminated its algae research program.)

The water content of algae is very high, 90–95% according to Pimentel. He estimates the average oil content at 8% of dry weight, whereas for soybeans it is 18%. It is not clear whether the high oil content species are easily processed; some are more difficult to process (below). Briggs (2004) assumes 25% oil content for the project described below, but believes species with 50% oil can be developed.[6]

There are a number of difficulties with the use of algae. A major problem is that constant high temperatures facilitate high yields, but large-scale energy production would involve large open ponds in deserts, where temperatures fall at night. Siting ponds close to power plants would enable use of warm cooling water. Using power station CO2 would not affect the impact of that carbon on the atmosphere, because it would end up in the atmosphere after the biodiesel was burnt. This factor alone, the need for artificial carbon inputs, would seem to disqualify large-scale use of algae for the production of liquid fuels.

Another difficulty is that the conditions which increase growth rates reduce oil content. Starving the algae of nutrients raises their oil content. Another is that the sunlight conversion rate and therefore efficiency of the process is highest in low light levels, e.g., 10% of full sun. However Mardon (2004) points out that water depth must be no more than about 30 cm to ensure that enough light reaches the algae, so pond areas must be large. This rules out sealed ponds for large-scale production, and thus increases seepage losses, contamination and weed problems. Mardon says algae grow best in the tropics, but heavy rains can wash out shallow pond contents. Ponds also require aeration and mixing to distribute nutrients evenly, difficult where very large areas are involved.

A major consideration is where inputs would come from for very large-scale production. Some advocates refer to use of nutrient-rich waste water from agriculture, but far greater quantities of nutrients would be needed to make a significant contribution to replacing fossil fuel dependence. Around 40% of the input material must be carbon dioxide. In addition inputs of NKP would be required in large volume. This poses the problem of transporting very large volumes of these inputs to the best growing sites, and the associated energy costs. World petroleum production is around 2.7 billion tonnes per year, so if algae is expected to replace a significant proportion of this mass, very large quantities of the inputs would have to come from somewhere.

Mardon (2004), who has worked for the Australian CSIRO on various biomass input sources including algae, says they found that the energy cost of the process is so high that the energy return is negative. " . . . the energy required to grow (and more particularly to harvest and process) the algae is considerably greater than what you can get out of it." Winter growth rates were found to be slow. " . . . filters are not an effective way of harvesting them, so a lot of energy is required for centrifugation. Even then, the cell mass is very wet, and some form of de-watering may be required . . . " " . . . our field work showed that it was not practical as a way of harnessing solar energy." Mardon also notes that ponds are prone to contamination, and require aeration.

Briggs (2004) gives a remarkably optimistic assessment of the potential of algae, based on Sheehan's estimate. He believes that the ER could be 10 and even 20. He has made little information available on the technology envisaged or the energy budget, because of patent applications. Figures given indicate 13 GJ gross of energy output per tonne, when the 20% of the algae that is carbohydrate is added to the oil. This is about 1.5 times the gross ethanol energy yield likely from cellulosic inputs per tonne (below).

Briggs' process will involve use of 2.5 m triangular polycarbonate tubes through which the algae are circulated in sunlight, indicating that very large-scale open pond production is not envisaged. Thus capital costs are likely to be high. Briggs says the energy costs are low because there is no planting or harvesting cost. This does not deal with the energy cost of processing, which Briggs appears to think is manageable, (but which Mardon thinks is prohibitive), although he does not provide quantitative information. The process is intended to use agricultural waste water inputs and power station flue gases.

Others expect far lower yields than Sheehan suggests. The highest yield Pimentel (2005) has encountered is 9 t/ha/y. Mardon (2004) estimates 11 tonnes of dry algae per ha per year. If the oil content of this is 30% (Mardon does not think 50% is likely) the gross energy yield would be 145 GJ/ha/y, or much the same as wood harvested at 7 t/ha/y.

If a dry weight of 36.5 t/ha/y of algae can be produced, and 15–40% of the weight is oil as Briggs expects, then the gross oil yield would be 248–660 GJ/ha/y. This is very high but a long way below Sheehan et al.'s 5,000 GJ/ha/y figure.

It seems clear that the energy produced per ha by algae is quite high, but at this point in time we do not have clear and confident estimates for the energy cost of producing biodiesel from the algae, nor therefore for the net energy yield. Consequently we do not have good grounds for expecting this path to make a major contribution to replacing the huge volumes of oil and gas consumed.

5.6. SUGAR CANE

Maciel (2005) reports Brazilian cane growing at 80 t/ha/y, although most of the weight is water content. The non-sugar biomass makes up 28% of the weight. Therefore gross ethanol per tonne is low, at about 3.5 GJ. Fulton (2005, p. 60) states 68.7 t/ha harvest, yielding gross ethanol at 2 GJ/t, 90 l/t, and 6,210 l/ha) resulting in a quite high gross ethanol production of 138 GJ/ha. Walsh (2004) reports a somewhat lower figure, 5,170 l/ha and gives a high energy return ratio of 6.9/1. Maciel's figures for Brazil represent 5,370 l/ha, or 123 GJ/ha of ethanol gross. These figures are about 2.5 times the net ethanol yield likely to be achieved from wood (below).

Fulton says the energy return can be 8/1, but points out that this includes a co-product energy credit for bagasse of about 10% (p. 60). This is not a large figure but it can obscure the energy return for liquid fuel output, when, as Maciel indicates, electricity produced from bagasse is exported from the process. (See below on energy return accounting.)

Pimentel and Patzak (2004a) conclude that the energy return for ethanol from cane is negative. Unfortunately at this point in time it has not been possible to identify and resolve the differences between their analysis and that of Maciel.

The global limit to ethanol from cane is set by the availability of suitable land, rainfall and other cane growing conditions. Cane requires a lot of water. If all growth from Australia's 450,000 ha of cane fields was put into ethanol production, at the above rates, gross output would be around 2% of national oil plus gas demand. Although Maciel believes Brazil's potential is great, given its unusually large area of suitable land, he says sugar cane cannot solve the global liquid fuel problem. Only 2.7 million ha produce ethanol fuel in Brazil and the 14.5 billion litres produced per year equate to less than 5% of US gasoline consumption.

Elephant Grass (Miscanthus) has been reported growing at 60 t/ha/y, and on average at 30 t/ha/y in Europe. However like sugar cane it requires a lot of water and thus could not be expected to achieve such high yields on very large areas of less than ideal land.

It is being assumed here that very large-scale ethanol production would require far more land than is available with conditions suitable for sugar cane production.

5.7. ENERGY RETURN ON INVESTMENT (EROI)

Crucial in assessing the potential of biomass energy forms is the difference between the amount of energy produced in the required form and the amount of energy that has to be used to produce it. Two issues need to be distinguished here. The first is the proportion of the energy in the input biomass that ends up in the liquid fuel, which could be defined as the gross output. The second is the amount of energy it takes to produce this gross output. The gross output divided by the energy it takes to produce it is the energy return ratio, ER, or EROI.

5.8. WHAT PROPORTION OF ENERGY IN THE BIOMASS ENDS UP IN THE LIQUID FUEL?

Commercial ethanol production at present results in about one-third of the energy content of the input biomass ending up in the ethanol (Lynd, 1996, Australian Bio-fuels Association, 2003, Wyman, 2004, Lovins, et al., 2005). Lynd (personal communication, and Lynd, et al., 2003) predicts that it will become possible to convert up to 56% of the energy in the biomass feedstock to ethanol, corresponding to a gross yield of 380 litres per tonne of feedstock (. . . assumed as having an energy content of 20 GJ/t, although Switchgrass is more like 16–18 GJ/t). Fulton's review points to much the same figure for future production, 400 l/t, a gross yield of 9.2 GJ/t.

5.9. HOW MUCH ENERGY IS NEEDED TO PRODUCE LIQUID FUEL?

The production of liquids from biomass takes a considerable amount of energy and some claim it takes more energy than is produced. First it is important to consider how the accounting should be carried out. For example should useful waste energy from the fuel producing process be subtracted from the input energy before a net energy cost is determined? This would be appropriate if that waste energy could be used in the process. Where cellulosic materials produce methanol the lignin waste can be used to produce the electricity needed. However some accounts include as energy produced the energy content of the "co-products", (for example the energy in, or the energy it would have taken to produce, oil seed cake animal food that comes from some ethanol production processes). This will not be done in the following discussion because our concern is solely with the net quantity of liquid fuel that can be obtained. The fact that in producing liquid fuel we also get other things that it would have taken energy to produce does not help us meet the crucial liquid fuel demand. What we are concerned with here is how much liquid fuel we can get from biomass after paying from biomass sources the energy it takes. The possibility that we can pay the electricity cost and have some left over does not affect our capacity to meet liquid fuel demand, the Achilles heel of consumer society.

Secondly, should we be concerned only about the input energy that must be in the form of liquid fuel, and subtract only this from output in order to arrive at a net energy return figure for liquid fuel production; i.e., should we ignore non-liquid fuel inputs such as electricity? This might be acceptable if the non-liquid energy inputs needed are easily derived from other cheap, abundant or renewable sources. However in a sustainable world stretched for energy the large volumes of non-liquid energy inputs would also probably have to come mostly from biomass, so it seems appropriate to subtract all input energy costs from gross output energy when deriving an ER figure for liquid fuel. Theoretically the electricity could come from non-biomass sources independent of the ethanol plant but Chapters 2 to 4 above have argued that, in a renewable energy world, electricity supply will be problematic. It will therefore not be assumed here that surplus electricity will be available from external sources for liquid fuel production. The focal concern will be how much liquid fuel can be produced when all input energy costs in whatever form are deducted from the biomass inputs.

Fortunately the issue does not depend much on how ER is defined. Again what matters most is the amount of ethanol we can take away from the process for use after the energy costs of producing it have been paid in biomass.

5.10. ETHANOL FROM CORN

Ethanol today is mostly produced from corn or wheat. There have been intense debates about its energy yield. Pimentel and his coworkers (e.g., Pimentel and Patzak, 2004a, 2004b) have produced several reports finding that the ER for ethanol from corn is markedly negative. " . . . about 29% more energy is used to produce a gallon of ethanol than the energy contained in a gallon of ethanol." A number of others report positive but quite low ERs.

Shapouri, et al., (2002) set out conclusions on energy return from ten studies of the production of ethanol from corn, ranging widely, from –33,500 BTU/gal to +30,600 BTU/gal, but then go on to conclude that the energy return is 1.34. This conclusion is widely quoted. Walsh (2004) gives much the same figure: see www.usda.gov/oce/oepnu/net%20energy%20balance.doe. (See also Fulton, 2005, p. 56. Other estimates are given in Note 7.)

However Shapouri et al.'s figure is derived by subtracting from input energy the energy that would have been required to produce useful output co-products, such as corn meal. If the energy content of the non-liquid fuel co-product is disregarded Shapouri, et al say the ER falls to 1.08.[8] This is the relevant figure for our purposes, i.e., assessing the viability of ethanol as the major or sole source of the most crucial energy form, liquid fuel. This figure is quite unimpressive when our concern is finding the liquid fuel to run transport etc. It means that to produce liquid fuel from corn takes almost as much energy as ends up in the fuel. It is no consolation to know that at the same time we end up with some energy-intensive animal feed.

Farrell et al. (2006) report a study which examined six recent ethanol energy budget papers, looking in detail at assumptions, mistakes, etc. They more or less endorse Shapouri, et al., concluding that the energy return for ethanol from corn is about 1.2 when energy credits for co-products are included

Although he does not throw light on the co-product issue, Fulton (2005, p. 131) concludes that to provide 10% of US gasoline and 10% of diesel fuel consumption via corn would take 45% of US cropland. This reflects the relatively low ER for ethanol from corn.

Despite the differences and the controversy it would seem from these studies that ethanol from corn is not likely to be the main source of the vast quantities of liquid fuel that would be needed to run consumer-capitalist society.

5.11. ETHANOL FROM CELLULOSIC MATERIAL

Very large-scale production of liquid fuels from biomass would have to be based on cellulosic or woody input material, given that there would be far too little land of the necessary quality to grow sufficient corn (or wheat, or biodiesel inputs). There are no commercial ventures underway at present producing ethanol from cellulosic inputs, so theoretical estimates cannot benefit from real experience (Fulton 2005, pp. 37, 125), and Natural Resource Defence Council and Climate Solutions, 2006, p. 2). Net energy output estimates vary remarkably, although the higher figures are for predicted longer-term production. Note 9 refers to a number of these but the following estimates summarise what seem to be the essentials.

The IEA (Fulton, 2005) gives a range for near term future gross output from 6.6 GJ/t to 7.5 GJ/t. Mabee, et al., (2006), also of IEA, state 2 GJ/t to 7.5 GJ/t for near term, and believe that 10.9 GJ/t could be achieved in the long term future, assuming breeding of new plant varieties etc. NRDC and CS, (2006, p. 13) review five studies and conclude 7.2 GJ/t (after rejecting the figures from Pimentel and Patzak, 2004a). Lynd's review (1996) also gives this approximate figure for future production. Fulton (2005, p. 135) says it is thought that in future production could be 400 l/t gross, i.e., 9.2 GJ. This figure aligns roughly with the 9.7 GJ/t figure anticipated by the US NREL (Walsh, et al., 2000, Wolley, et al., 1999).

Table 18.1 in Lovins, et al, (2005) *Technical Annex*, indicates that for corn 14% of the energy in the input material ends up as net ethanol, but for woody inputs it can be 37%, i.e., a gross 7.4 GJ/t (Lovins, et al., quote Wyman, 2004).

It is important to note firstly that most of these cases are stated as gross output figures and net figures are not given. Secondly and also very important is that, as Mabee points out (personal communication), these figures do not refer to ethanol yields separate from energy credits for the co-products possible from the processing of cellulosic inputs. (Remember that for corn crediting co-products raises ER markedly, from 1.08 to 1.34 according to Shapouri et al. and Fulton.)

Some evidence regarding co-products for wood is available. The Berkeley EBAMM group (2006) lists 4.1 MJ/l for Switchgrass, and also for general cellulosic inputs. This is a rather high figure. It is unfortunate that it cannot be confirmed from other studies, but as little if any ethanol is being commercially produced from woody inputs it is not surprising that there is little evidence on the energy content of co-products. Energy budgets accessed do not give information on possible co-product credits.

These points suggest that it would be generous and probably misleading to assume a net ethanol yield of 7 GJ/t for ethanol produced from cellulosic inputs. Yet this is the general figure that will be assumed in the following discussion.

Mardon (2004) arrives at a much lower figure. His recent analysis is valuable in making energy cost assumptions clear. He regards ethanol from wood as problematic and sees methanol as a better option. Gross output could be 3.45 GJ/t, and ER 1.7, giving a net output of 1.4 GJ per tonne of input material. Mardon points out that all claims can only be theoretical estimates as no wood hydrolysis plants have been built since the German Heinau plant in 1960. He also points out that the wet lignin output is problematic as there is at present no practical way of drying it for efficient use as a contributor to electricity input. (Fulton does not say whether the theoretical estimates he refers to, which usually assume use of lignin for electricity generation, deal satisfactorily with this issue.)

By far the most optimistic claim is made by Lovins, et al., (2005) who say 680 litres of ethanol could be produced per tonne of cellulosic input material. This is a remarkable claim, an output of c.15 GJ/t, and this from Switchgrass which has an energy content of only 16–18 GJ/t. It is not clear whether the figure is meant to be a net or gross output, and no reference is made to whether or not energy co-products are credited. Unfortunately no support for this figure is given in *Winning the Oil End Game* or the *Technical Annex*, apart from a reference to Pearson Technologies, Colorado, who have been uncontactable, and to an inaccessible paper by Schlesser (n.d.) There seems to be no academic literature on the topic. (Mabee agrees, personal communication.)

Lovins, et al say this technology could yield 9.2 quads of ethanol in the US, around half present gasoline plus diesel consumption. (This aligns with the 9.5 quads stated by Battelle as being possible, although their ethanol yield assumptions are quite different from those of Lovins, et al.) In other words even though Lovins et al's production claim is extremely high, it would not enable the US liquid fuel problem to be solved by woody biomass. (See further below.)

Again it is unfortunate that the estimates differ greatly and do not permit precise or confident conclusions, especially because of lack of information on net vs gross outputs and on co-product credit. In the following discussion a net yield of 7 GJ of ethanol per tonne of cellulosic input material will be taken fairly confidently as the basic working assumption in view of the pronouncements of the US NREL the IEA via Fulton and Mabee et al. Mardon's 1.4 GJ/t estimate and Lovins et al.'s 15 GJ/t figure will be kept in mind.

5.12. METHANOL

According to some estimates methanol produced from cellulosic material could be a more promising option than ethanol. Unfortunately again estimates vary so much that clear and confident conclusions are elusive, partly because no commercial plants producing methanol from woody input material have yet begun operating. Note 10 summarises some of the analyses that have been offered.

Foran and Mardon (1999) and Mardon (2005) conclude that the methanol from wood option is better than ethanol from wood. Mardon believes the yield will be double that for ethanol, and the fuel will be much cheaper. (However Lovins et al. are much more enthusiastic about ethanol from wood.)[11] The overall situation according to Foran and Mardon is that 2.6 tonnes of wood yield 13 GJ of methanol, net, so the net yield per tonne of wood used as feedstock plus fuel is 5 GJ.

Berndes, et al., (2003) present an optimistic estimate, again a prediction of what future technology could achieve. They believe that 9 GJ of methanol net could be produced from each tonne of input biomass, which is equivalent to 380 litres or 72 gallons of petrol. This is 2.5 times the amount Giampietro, et al. state, and 1.8 times the amount Foran and Mardon arrive at. It is somewhat difficult to evaluate their account from the information provided.[12]

Stucley and Schuck (2004) refer to another optimistic but puzzling estimate from the Swedish BAL proposal (Ecotraffic, 1997), briefly stating that 57% of the energy in the feedstock will end up in the methanol. That is, gross yield would be 11.4 GJ/t. It is claimed that if biomass is used to provide processing energy, the figure is 49%, implying that the processing energy is equal to only 8% of the energy in the biomass, i.e., 1.6 GJ/t.[13]

The differences between these several estimates are again large and unsatisfactory but perhaps understandable given that there appears to be little or no evidence from operating plants. What is clear however is that in general they do not imply that methanol will be a much better option than ethanol from wood.

5.13. TECHNICAL ADVANCE?

In view of the optimistic expectation expressed by Berndes, et al., above it is noteworthy that the Swedish Ecotraffic study concluded that little or no technical advance in the production of methanol from wood is likely as the processes involved are well established (Stucley and Schuck, 2004, p. 160). This is not the case with ethanol.

5.14. TOXICITY?

Unfortunately there seem to be significant problems regarding the toxicity of methanol, especially with respect to exposure of mechanics during motor repair. This factor has been reported to have led BMW to abandon research on methanol technology.

5.15. THE DEMAND FOR LIQUID FUEL AND GAS

US petroleum consumption will be taken as around 41.3 EJ, and the oil plus gas total 57.8 EJ, which corresponds to 203 GJ per person (This is the 2002 *UN Statistical Abstract* figure; unfortunately different sources give somewhat different figures; see Note 14.)

In 1998–9 Australia used 1681 PJ of petroleum and 881 PJ of gas, a total of 2562 PJ or 128 GJ/person (Australian Bureau of Statistics, 2000). Combined petroleum and gas consumption is the equivalent of 20.5 billion gallons or 77.5 billion litres of petroleum.

We can now consider whether the quantity of biomass required given the yields of ethanol and methanol above, is likely to be produced.

5.16. CAN THE DEMAND BE MET?

If we assume 7 GJ of ethanol net can be produced per tonne of biomass, then to meet the present Australian oil plus gas demand of 2,562 PJ would require an input of 366 million tonnes of biomass p.a., or 18 tonnes per person. If we assume an average yield of 7 t/ha, 52 million ha would have to be harvested, which is almost 2.5 times all Australian cropland, 1.5 times good forest area and about 35 times present plantation area.

These areas would be in addition to the increase of perhaps 8.5 million ha anticipated for timber plantations. Further, if Australia were to become self-sufficient in timber more of the potential area and yield would have been accounted for, leaving less for biomass production.

Above it was loosely estimated from Bugg, et al. (2002b) that in NSW the total annual growth yield might be 50 million tonnes, or around 7 tonnes per person, and that the national harvest per capita would be lower. Bartle, et al.'s conclusion for biomass production potential from the wheat belt, Australia's main potential source of biomass energy, is under 2 tonnes per capita, which he regarded as optimistic.

To meet the US oil plus gas demand more than 8,274 million tonnes of biomass would have to be harvested p.a., and at an average yield of 7 t/ha this would require 1,162 million ha. This is about nine times all US cropland in use and eight times all presently forested land. These figures generally align with those arrived at by others.[14]

Earlier in this chapter the European Environmental Agency's conclusions were stated, i.e., that by 2030,12 EJ of primary energy gross could be produced in Europe from biomass. Ignoring the reasons given for challenging the figure, this would be, as the report states, 17% of present primary energy demand. If it was all put into electricity generation, leaving none for transport fuel, it would deliver about 0.4kW per person (assuming 0.33 generation efficiency, when 0.22 might be more appropriate for a biomass system as distinct from a single plant, see Hohenstein and Wright, 1994), a little over one-third of the Australian per capita consumption.

These huge areas would have to be found and put into biomass energy plantations more or less in addition to all the areas now devoted to agricultural and forest production. It should be stressed that most regions of the world have much less capacity than Australia or the US to meet liquid fuel demand from biomass. The Australian total cropland, pasture and good forest area, 4.9 ha per capita, is much more abundant than for most regions of the world. The figure for Europe is 1.6 ha, the UK

0.35 ha, Africa 3.3, USA 2.8, Asia 0.55, and for the world 1.43. FAO figures (n.d.) point to similar conclusions. Brown's somewhat different definitions (2003, p. 329) yield even greater multiples; Australian cropland per person is 3.5 times the US figure and nine times the European figure. If world population reaches 9 billion, total cropland, pasture and forest area per capita will be 0.8 ha, about one-sixth of the present Australian figure.

Consider the UK, with a total crop, forest and pasture land area of 0.35 ha per person. If half of this could be put into biomass production the resulting per capita liquid fuel plus gas output would be about 8 GJ per person, 6% of present Australian consumption.

Most if not all of the present forest, pasture and cropland areas are already fully committed, indeed most of them are overworked, so are not capable of a major contribution to the very large quantities of biomass that would be required.

The impossibility is clearly evident in the simple arithmetic involved in providing 9 billion people with present Australian per capita oil and gas consumption. If 9 billion are to be provided with 128 GJ per capita, from land producing 7 tonnes per ha per year and each tonne yields 7 GJ net of ethanol, then the plantation area needed would be *23.5 billion ha* . . . on a planet with only 13 billion ha of land and less than 4 billion ha of forest.

Even if all the ethanol produced went to the 1.5 billion people living in rich countries they would have to get by on about 15% of their present consumption. These kinds of figures rule out the possibility of densely populated rich-world countries with little land such as the UK importing their liquid fuels from the Third World.

If we assume that 500 million ha could be found globally and harvested at 7 t/ha/y, then the world average per capita amount of liquid fuel this area would provide 9 billion people (assuming ethanol at 7 GJ/t) would be under 3 GJ per year, a mere 2% of Australia's present oil plus gas consumption.

In "Footprint" terms it would take about 2.61 ha of productive land to provide each Australian with 128 GJ/y of liquid and gaseous fuel from biomass via ethanol. Of course to this must be added the productive land providing food, water, settlement area and energy that is not liquid or gas. However the average per capita amount of productive land available for a world of 9 billion people will be no more than 0.8 ha.

Another way of making the magnitude evident is to take the average world forest growth rate of about 3 t/ha, and the approximately 4 billion ha of forest on the planet, meaning that total growth p.a. is about 12 billion tonnes. The gross energy content of this would be about 240 EJ which is about 60% of world energy use today.

These figures also make it clear that technical advances cannot solve the problem. Even if the figure Lovins, et al. give in their *Technical Annex* for future production is achieved, c. 15 GJ/t, and even if technical advance doubled the biomass yield from the 7 t/ha assumed here, there would still be no possibility of providing all 9+ billion people expected with anywhere near the present rich-world per capita consumption of liquid and gas fuel. More than 5 billion ha would have to be found for plantations.

The foregoing numbers would seem to give overwhelming support for the conclusion that there is no possibility of providing present per capita liquid fuel consumption from biomass, let alone coping with growing demand, or enabling all the world's present population to rise to rich-world rates of consumption. The situation is much more clear-cut than for electricity. (Note 15 refers to relevant comments from other sources.) The significance of this conclusion for thinking about the global predicament and social change could not be exaggerated. Some of the implications will be discussed in Chapters 10 and 11.

5.17. HOW ECONOMICAL IS BIOMASS PRODUCTION FOR LIQUID FUEL?

The Australian Biofuels Association acknowledges that farmers could not make a living producing inputs to ethanol production. At present ethanol is produced in Australia largely from "free" inputs supplied by the wheat and sugar industries. A report by the Australian government's Department of Industry, Tourism and Resources (2005), found that biofuel costs would be greater than benefits. The cost of fuel before tax would be about double that of petrol.

In the early 2000s power stations were paying c. $(A)20/t for coal, i.e., 80 cents/GJ. If wood biomass sold for 80 cents/GJ, a tonne would cost $16. At 7 t/ha yield, gross income would be $102/ha/y, whereas fodder producers in Australia gross around $550/ha/y.[16]

For biofuels to be economically viable against 2005 petrol prices, yields and/or dollar costs would have to be considerably higher than are likely to be achieved by very large-scale biomass production, which would have to use much more than the high yield lands available. At 7 t/ha/y, the price paid for biomass inputs to processing would have to be $(A)79 per tonne, or $3.85 per GJ, about five times as much as for coal per GJ before biomass production became as profitable as hay production.

This has important implications for the amount of biomass that is accessible, because it means that land must be reasonably productive before it becomes economic for energy production. Areas with potential yields under 7 t/ha would not seem to be economically viable today. If so this would significantly reduce the areas and yields that Bugg et al.'s analysis indicates. If their fourth category (4.2 million ha at 8.6 t/ha) is not economical, then NSW production would be 65 million tonnes. If we apply a 40% exclusion factor, the yield assumed earlier in this chapter might be cut from the assumed 50 million tonnes to 39 million tonnes.

In future much higher energy prices will be accepted, but how these will affect the situation is not clear. They will increase income and thus tend to make marginal land economical, but they will also increase the costs of production.

5.18. NEGATIVE FEEDBACK EFFECTS

There are several reasons why the prospects for biomass production are likely to become more difficult in future. Firstly within developed countries there is the constant pressure to increase land devoted to agricultural purposes and the ceaseless quest to increase export earnings. Expansion of cropland mostly comes through forest clearing. The above discussion of Switchgrass potential in the US noted that the land would mostly have to come from the present agricultural area.

Especially important will be several negative feedback effects of the increasing scarcity of petroleum. For instance if there is less fuel available and at higher cost, then irrigation, transport, fertilizers and pesticides will become more scarce and costly, making biomass production more costly and difficult. Agriculture will therefore tend to become more labour and land intensive, and agricultural produce of all forms will tend to become more costly. Change from the high “quality” of energy that oil is (e.g., easily “mined”, moved, stored, used, processed) to more difficult forms such as coal will mean increased energy consumption, because more energy will have to go into producing, mining, moving etc.

There will also tend to be a shift from energy-intensive building materials such as kiln-fired brick, aluminium, steel and plastics to timber, again increasing pressure on biomass fuel sources. Resource scarcity pressure will stimulate development of bioreactors to produce a wide range of plastics, chemicals and materials. Looming water shortages and the impact of the greenhouse problem will significantly reduce biomass production (although more carbon in the atmosphere will tend to increase it). Drought is expected to increase in many regions. The water resources of the Australian Murray-Darling river system could be cut by 25%.

As world population rises by 50% there will be a large increase in demand for land within the Third World to produce food. Forest will be cleared as poor people seek more land for subsistence, already a major destructive force in the Amazon and southern Asia. The last of the accessible Third World rainforest timber will soon have been shipped to rich-world hardware stores, increasing the pressure to put more land into timber plantations.

Conventional neo-liberal economic “development” is stripping people from subsistence ways and accelerating the rate at which they are moving to cities, where per capita energy and resource consumption is much higher. However the proportion of meat in Western diets could be reduced considerably, freeing much land for the production of biomass. Against this, as people become more affluent they demand more meat, and conventional development is rapidly increasing the purchasing power of Third World middle classes.

Global pressures, especially from the fast growth of China and India, are now causing rising energy and materials prices, and this will invalidate all the assumptions made in this and previous chapters to arrive at cost estimates.

There are therefore several reasons why the global prospects for very large-scale biomass production are waning. Available areas are likely to shrink, growing conditions are likely to deteriorate and other demands on land will increase.

5.19. CONCLUSIONS ON LIQUID FUELS

The conclusions this discussion points to are much more confident than those regarding renewable electricity. Although a large volume of liquid and gaseous fuel could be produced from biomass, this source could replace no more than a very small fraction of present global liquid fuel use. The magnitude of the current overshoot is driven home by the following re-statements of the situation.

- If 9+ billion people were to have the current Australian 128 GJ/y oil plus gas consumption from ethanol (assuming 7 GJ/t), the area of land that would have to yield 7 t/ha/y would be around 23 billion ha. However world crop land totals only 1.4 billion ha, world forest and pasture 4 billion and 3.5 billion ha, and the total world land area is about 13 billion ha.
- If we forget about the Third World and focus on delivering 128 GJ per person to the 1.5 billion in rich countries, we would need 4 billion ha, meaning we would have to use a lot of Third World land without them getting any of the energy it produced.
- If we take the extremely optimistic project sketched by Hall, et al., i.e., 890 million ha of biomass plantations yielding 15 t/ha/y for conversion to ethanol at 7 GJ/t, then for a world of 9 billion this would yield 10.4 GJ per capita, equivalent to 8% of the present Australian per capita oil plus gas consumption.
- If technical advance raised the efficiency of fuel production to 100%, (i.e., to 20 GJ/t), and raised biomass yield to 15 t/ha, we would need to harvest 5 billion ha to give Australia's present per capita oil plus gas consumption to 9 billion people.[17]

It would seem therefore that there is no possibility that more than a quite small fraction of liquid fuel and gas demand could be met by biomass sources. A few regions might derive a relatively high proportion of their present consumption, but the rich countries as a whole could only produce a very small fraction. No plausible assumptions about energy conservation or more efficient cars can solve the problem. Chapters 2, 3 and 4 argued that renewable electricity cannot provide much if any transport energy. Chapter 6 concludes that hydrogen can't either. Chapter 8 adds the fact that the demand for energy is increasing all the time; for instance Fulton (2005, p. 127) expects a 32% increase in US fuel demand between 2000 and 2020. Reflect on the demand that 9 billion living as Americans expect to live in 2070 would generate. If the above conclusions are more or less sound, then extremely radical implications for the future of consumer-capitalist society seem to be inescapable.

CHAPTER 6

THE "HYDROGEN ECONOMY"

It is widely assumed that the ultimate solution to the energy problem will be via "the hydrogen economy" in which there is large-scale use of renewable energy sources to generate vast quantities of hydrogen to fuel most things. There are persuasive reasons for concluding that this assumption is mistaken. Wilson (2002) says that bulk hydrogen will be useful in industry but " . . . numerous economic, technical and safety considerations make it non-viable as a replacement motor fuel for public use." Following their detailed review Bossel, Eliason and Taylor (2003), make an even wider claim; " . . . the elemental hydrogen economy can never become a reality."

It is not commonly understood that hydrogen is not an energy source. It is only a carrier, i.e., a form into which energy can be converted. The problem then is, from what source we are going to produce the huge quantities of hydrogen we would need, and in a renewable energy world the only sources of very large quantities are solar, biomass or wind. As previous chapters have shown it is not likely that these sources can meet electrical demand, let alone that plus liquid fuel demand.

6.1. THE DIFFICULTIES CAUSED BY THE NATURE OF HYDROGEN

Even if there was no doubt that the required quantity of hydrogen could be produced, a hydrogen economy would probably be prohibited by the physical nature of hydrogen. Because it is a very light and small atom, a large volume is needed to carry much energy, and it easily leaks through joints, valves and seals. Consequently converting energy to hydrogen, storing and transporting it involve formidable difficulties, energy losses, infrastructure requirements, and costs. These multiply the number of windmills etc. that a system would need to cover the losses. For example to convert wind-generated electricity to hydrogen, compress it for storage, pump it a long way, then convert it back to electricity would mean that about four times as many windmills would be needed to supply an amount of energy via storage compared with supplying it direct. Bossel (2003) points out that there are several easily overlooked steps in going from electricity via hydrogen to electricity again, or motor vehicle power, such as AC/DC inversion, and he argues that when all losses are included the electricity-to-wheels efficiency of hydrogen powered vehicles would be only 22%, and less via a liquid hydrogen path.

This factor 4 reduction seems to be the most common conclusion for the use of hydrogen for storage and transport of energy. Barber (2004) concurs with it but Wilson (2002) arrives at a 90% loss after taking into account further elements, such as DC to AC conversion and a 0.35 fuel cell efficiency claim.[1]

According to Bossel, Elliason and Taylor, to supply the petrol station with hydrogen will require 15 times as many tankers as would be needed to deliver the same quantity of energy in the form of petrol. (In another source, Bossel, n.d., the multiple is given as 22.) They say that to replace today's demand for petrol for motor transport with hydrogen would mean that one seventh of the trucks on the road would be carrying hydrogen, and thus perhaps one seventh of all truck accidents would involve large quantities of hydrogen under pressure.

They estimate the energy loss in road delivery over 200 km as equal to 13% of the energy delivered, and over 500 km, 32%. North (2005), a gas tanker designer, arrives at similar if not worse conclusions.

Use of hydrogen as a gas will usually involve compression for storage, given its low energy density. According to Bossel, Elliason and Taylor, compression to 20 MPa involves an 8% energy loss, and for compression to the 70 MPa appropriate for transport involves 20% energy loss. (Doty, 2004a says 15%.) Doty (2004b) says that even when compressed to 5,000 psi hydrogen has only 10% of the energy density of diesel. He points out that the mechanical energy in such a tank exploding would be equal to that of a 50 calibre artillery shell, not including the energy in the hydrogen. Impact safety for light weight tanks is not high; safer tanks would be heavy. Doty rates the danger as 100 times that for petrol fuelled cars. At 5c/kWh to compress hydrogen, the cost would be $3(US)/kg. Lovins (2003) points to the possibility of retrieving some of the energy needed for compression using valves that regenerate power as the gas is released into fuel cells. In a hydrogen economy this would seem to involve a significant cost for an enormous number of devices at the multitude of locations where hydrogen would be used. (See Note 2 for critical comment on Lovins' claims.)

Bossel, Elliason and Taylor point to the difficulties and losses in transferring hydrogen from tankers to filling stations and then cars. Because the 40 tonne tanker delivers only 288 kg of hydrogen, it will weigh almost as much on its return trip, meaning it uses as much fuel then as on the outward delivery trip. A returning petrol tanker weighs only about one third its loaded weight. Secondly, gas will flow from the tanker to the filling station tanks until the pressures in each are equal (and that would take time, due to temperature and density effects) meaning that it will not fully empty and the tanker will return to base carrying some hydrogen; 20% according to these authors. The tanker would take two hours to empty and would return with up to 25% of the hydrogen brought to the site. The same problem occurs when cars fill up at the fuel station. This problem can be overcome by pumping, which adds to energy and infrastructure costs and the embodied energy costs of the machinery.

Liquefying the hydrogen reduces the volume to be transported but at a much higher energy cost. Firstly to transform electricity into liquefied hydrogen requires energy equivalent to about half the energy in the electrical energy being stored. Liquid hydrogen is still not very energy-dense, requiring four times the volume for the same amount of energy as petroleum. Furthermore energy must be used to keep the hydrogen at −253 degrees C. The hydrogen tends to "boil off" at 0.3% per day, although this can be used, unless the device, e.g., car, is idle for long periods at a time. To store hydrogen for the six months from summer to winter would use up energy equivalent to more than half the stored energy. This seems to rule out storing energy from strong winds in winter for use in summer. Further losses would occur at filling points and through valves and joints.

Large-scale inter-continental transport of liquid hydrogen by sea tanker also seems to be highly problematic. Wootton (2003) points out that a modern LNG tanker delivers about 3 billion cf of gas. It would make about 12.6 trips p.a. from Nigeria to the US. US gas consumption is about 23 tcf/y, so one tanker working full time could deliver 0.17% of demand. The 38 bcf delivered p.a. is a gross figure; if the energy needed to produce, compress and transport the gas (and produce the tanker), and the losses, were taken into account, it would seem clear that only a very small proportion of a nation's energy could be shipped long distance in the form of LNG. Because the energy density of hydrogen is much lower than that of LNG, the problems would be increased accordingly. So it is not likely that large volumes of hydrogen will be produced in some regions of the world where there is abundant wind or sunlight and shipped long distances as oil is.

Transporting hydrogen via pipelines poses additional problems. The "hydrogen economy" vision usually assumes solar plants in the Sahara pumping hydrogen through pipes to Europe. This is a very unlikely proposition given the energy required to pump hydrogen long distances, again due to its low energy density. Pumping takes 3.85 times the energy needed to pump the same amount of energy in natural gas. Bossel, Elliason and Taylor conclude that to pump hydrogen gas 3,000 or 5,000 km would take energy equivalent to 34% or 65% of the energy in the hydrogen pumped. (Bossel, n.d., gives higher estimates.) Ogden and Nitch (1993, p. 935) state a lower figure; 34% for 5,700 km. These are formidable losses, and would seem to prohibit inter-continental transportation of hydrogen. (Long distance transmission of electricity via HVDC lines involves less loss, but does not help with the storage problem.)

It is not likely that hydrogen can be pumped through existing gas pipe lines. Firstly hydrogen makes metals brittle. Secondly pipelines lose gas through joints and valves. This is why engineers try to keep the pressures as low as possible. Hydrogen's small atomic size enables it to leak out more easily, yet because of its low density the temptation is to pump it at high pressure. Lovins says existing pipelines can be used if fitted with plastic liners and the loss rate can be kept very low, although he points out that in any case the existing gas lines will be needed for gas. Unfortunately for this proposal existing gas mains are too narrow for efficient pumping of hydrogen. Simbeck and Chang (2002) put the cost of appropriate new pipes at $0.5–1.5 million per mile. Crea (2004) also states this figure and says the US has 300,000 miles of gas mains. The astronomical cost of duplicating this would have to be added to the cost of any proposed wind-hydrogen system.

Bossel, Eliason and Taylor conclude that the overall energy efficiency of delivering hydrogen by generating it from electricity at the filling station would be about the same as generating it centrally and pumping it to the filling station. Bossel (n.d.) estimates overall losses at around 60%.

These figures indicate that, as Bossel, Eliason and Taylor say, long distance transport of large volumes of hydrogen seems to be ruled out. They also note that technical advances cannot make much difference to this situation, because the problems are set by the physics of hydrogen. (However some believe the energy loss in the production of hydrogen might eventually be cut from 35% to 20% or less.)

The basic figures given by Eliason, Bossel and Taylor have been criticised (Weindorf, Bunger and Schindler, 2003), but their more optimistic values do not seem to make a large difference to the prospects for a hydrogen economy. Losses for compression to 80 bar are claimed to be a little less than those from Eliasson, Bossel and Taylor. Losses involved in generating hydrogen from electricity at filling stations are about the same. Losses in piping hydrogen 2,500 km are claimed to be c. 19% rather than 30–40%, meaning that pumping hydrogen from the Sahara to northern Europe would still involve about a 40% loss.

Lovins says that the recent claim that losses from a hydrogen economy might be so large as to damage the ozone layer are mistaken. Wilson (2002) does not agree.

6.2. STORAGE IN METAL HYDRIDES

This could be the most promising energy storage possibility, but at this stage the difficulties are considerable and firm conclusions about potential and limits cannot be drawn. It is not clear that costs etc. are likely to be markedly better than for compressing hydrogen. The technology will be discussed in Chapter 7 on energy storage.

6.3. ADVANTAGES OF HYDROGEN

Some significant efficiency gains are associated with the end uses of hydrogen. Lovins claims that when the whole energy supply chain from oil well to wheels via petrol is compared with that from natural gas to wheels via hydrogen, the latter is two to three times as energy efficient as petrol. Thus he claims that very light and efficient hyper-cars could travel five times the distance on a unit of hydrogen energy as cars today travel on a unit of petrol energy. However Crea (2004) argues that when all losses are included the two have much the same energy efficiency.

The advantages of very light cars will tend to be negated by the heavy hydrogen containers needed, for hydrides or for compressed or liquid hydrogen.

6.4. DELIVER ELECTRICITY VIA HYDROGEN OVER VERY LONG DISTANCES?

Following is an indication of the energy losses that would be involved in the kind of proposal sometimes encountered, i.e., supplying electricity via hydrogen generated by windmills or solar thermal plants in good wind regions several thousand kilometres from users.

- Electricity converted to hydrogen gas at 30% loss.
- Hydrogen compressed for pumping at a 20% energy loss.
- Hydrogen pumped long distance at 30% loss (. . . or 65% loss to Europe from the Sahara?)
- Loss at filling stations, assume 5%(?).
- Loss in fuel cell, 50%, possibly 40%. (60% at present.)
- Fuel cell output transformed into AC, 5–10% loss.

Combining these losses means that only 13–18% (. . . perhaps 7% in the case of transmission from the Sahara) of the energy the windmill generates would end up as useful electricity, or vehicle motor power. North (2005) estimates about a 95% loss, even assuming 50% efficient fuel cells. If wind could supply 20% of electricity demand directly without storage, then for the other 80% we would need six times as many windmills as could generate the quantity of energy in question.

Long distance bulk energy transfer via HV DC lines would be much more energy efficient, but this could not contribute to the electricity storage problem, for instance the problem of meeting night time demand from solar power.

6.5. USE HYDROGEN FOR STORING ENERGY FROM WINTER TO SUMMER?

The general magnitude of this kind of task has been discussed in Chapter 2 but the following brief consideration of attempting to smooth out seasonal differences using stored liquid hydrogen throws further light on the situation.

A 1000 MW power station at 0.8 capacity generates 19,200 MWh a day. That is 69 million MJ and at 8 MJ/l it would equal 8,640 cubic metres of liquid hydrogen. To store three months output would require 795,000 cubic metres, under pressure at −273 degrees. That's bad enough but the subsequent losses would be substantial. Perhaps 20% of the energy going into the storing process would be retrievable, because half would be lost in liquefying, and the "boil off" rate is 0.3% per day. This could be used but that doesn't help with the storage problem. Then there would be the loss when electricity was regenerated from the stored hydrogen. Even if we assume 60% efficiency for this step via future fuel cells or gas turbines, we would get back around 9% of the original energy. So to retrieve at the rate a power station would generate in mid-winter we would need 11 power stations generating, and the storage volume would have to be around 8.8 million cubic metres, or a mine shaft 1,870 km long, kept under pressure at −253 degrees C. In addition we would have to pay for the hydrogen generating equipment and the fuel cells to regenerate electricity. Clearly anything like this would be far beyond economic viability.

6.6. REPLACE OIL PLUS GAS BY HYDROGEN FROM WIND?

The hydrogen economy vision often assumes such vast quantities of hydrogen will be derived from sun and wind that it will be possible to replace oil and gas, as well as meeting electricity demand. The impossibility of this vision is fairly easily demonstrated.

Australian electricity consumption is about 700 PJ and liquid fuel for transport consumption is about 1200 PJ/y. If use of hydrogen for transport loses 75% (or 50%) of the electricity generated, we would need to produce about 4800 PJ (or 2400 PJ) in the form of hydrogen. To fuel transport we would need enough windmills to meet 7 (or 3.5) times our electricity demand, i.e., in addition to meeting electricity demand. Chapters 2 to 4 showed that renewable sources are not likely to meet present electricity demand, let alone several times it.

“Well then, forget about hydrogen; let’s just run transport on electric vehicles.” Again, how are you going to store the electricity? “How about using all the heat energy storage capacity we will have in our solar thermal plants? After all they will not be doing much in winter when the winds are blowing.” But if we store electrical energy as heat, then use this to regenerate electricity, we will only get back about one-third of the electrical energy we stored. And most of the windmills will not be where the solar thermal plants and their heat storage tanks are.

6.7. FUEL CELL DIFFICULTIES

The hydrogen economy vision usually takes for granted the use of fuel cells, which generate electricity when hydrogen is fed in. At present these can achieve 40–45% efficiencies, but it is often assumed that 60% will become possible.

However Bossel points out that their use will involve various steps and losses that must lower system efficiency and are easily overlooked when figures from the laboratory test are used, such as compression of hydrogen and changes from AC to DC. As has been explained, he says that in practical situations their efficiency will not rise above 40%. He sets out a chain of losses showing that for use in vehicles an overall electricity-to-wheels efficiency of 22% can be expected (compared with 66% for electric vehicles.) Wald (2004) believes 37% will be the limit for fuel cell efficiency. Patzak (2005) also takes 38% as the maximum possible efficiency for “tank-to-wheels” via fuel cells.

A significant problem with large-scale fuel cell use might be availability of scarce materials for catalysts, notably platinum, although technical advances might avoid its use in time. The hydrogen must also be very pure or cells will deteriorate. Another rarely recognised but serious problem is that at present the life expectancy for fuel cells is reported to be remarkably short; only 200 hours. (Moore, 2004.)

This is a most important factor in any vision involving regeneration of power from stored hydrogen. How many times in the life time of the wind-hydrogen system will the fuel cell components have to be replaced?

Fuel cells are at present very expensive, so if their life expectancy is also short the need to replace them frequently would pose significant cost problems, compared with a coal-fired power station that could last 30 years once installed (National Academy of Engineers, 2004, p. 98). At present fuel cells could be four to six times as costly per kW of capacity as conventional energy generating plant. The US Department of Energy gives a multiple of 10 for car engines. Manger (2003) says the cost is 40 times that for advanced diesel car engines.

It might also be noted that a reason for moving to a hydrogen economy is to reduce the greenhouse problem, but the main exhaust product of hydrogen use is a powerful greenhouse gas, viz., water vapour.

6.8. DERIVE HYDROGEN FROM COAL?

Coal could be processed to yield hydrogen at large central plants enabling the carbon to be sequestered underground or in the sea. Sequestration involves harvesting the carbon, transporting it to the site where it is to be located, and burying it. (Reasons for rejecting the proposition are given in Chapter 7.)

If this process made coal into the major fuel, world estimated coal resources would not last long. Let us assume that, a) the present amount of energy used will come from coal, meaning that the present approximately 3 b t/y coal production would be multiplied by 3, b) all 6+ billion people will live as rich-world people do now so coal use will be multiplied by 5, c) population grows to 9+ billion so another multiple of 1.5 must be applied, d) energy use continues to grow as at present in Australia, meaning that by 2050 use per capita will be about three times as great as it is now, and e) 40% of the coal energy is lost in conversion to liquid or gas fuel for transport and carbon sequestration. Combining these multiples means that annual world coal output would have to be some 170 times the present rate, so even if the potentially recoverable resource is 2,000 to 4,000 billion tonnes this would be exhausted in about four to eight years. The commonly estimated 1,000 billion tonne recoverable reserve would last two years.

6.9. HYDROGEN FROM NUCLEAR REACTORS?

Hydrogen can be produced by thermo-chemical processes at about 950 degrees C and nuclear reactors could be used for this purpose. The relatively high efficiency achievable could yield twice as much hydrogen energy per unit of heat generated by the reactor, compared with electricity output (Schultz et al., 2004, p. 1). The process is very corrosive so high costs are likely.

If four units of hydrogen energy must be produced for one unit to drive wheels, and Australian transport energy use is twice electrical energy use, then to run

Australia's motor transport on hydrogen via fuel cells would require eight times as many reactors as would be needed to provide electricity. Chapter 7 will argue that there is far from enough Uranium accessible to meet electricity demand, let alone transport demand as well. It would be half as energy costly to use electrical vehicles, but that would add the problem of finding sufficient battery material.

6.10. HYDROGEN CONCLUSIONS

It therefore seems quite unlikely that we will ever have a large-scale "hydrogen economy". To the extent that it does eventuate it will probably involve high losses, costs and inefficiencies. As Bossel (2004, p. 58) says, " . . . it appears that hydrogen will not play an important role in a sustainable energy economy . . . " "The conversion of electrical energy into hydrogen is not wise at this time, nor will it ever be."

CHAPTER 7

STORING ELECTRICITY

Some of the most difficult problems with renewable energy are posed by the fact that they are intermittent, so very large quantities of energy have to be stored if these sources are to be major contributors. Electricity is difficult to store in large volume. In other words if solutions to the storage problem could be found, the prospects for renewable electricity would be considerably improved. For instance we would not have to worry much about the variability of the winds because we could store electricity when they are blowing well and use it when they are down.

Following are brief comments on the main storage options being explored. Some of these are quite promising for various applications but it seems that none point to satisfactory solutions for the very large-scale tasks, such as storing 10,000 MWh from a solar power station each day to meet night time demand.

7.1. PUMPED STORAGE

The simple and complete solution to the problem of intermittancy is sometimes claimed to be using some of the energy when it exceeds demand to pump water up into dams, and then generate hydroelectricity when it is needed. Hydroelectric generators are the most flexible, being capable of commencing full operation in a few minutes.

Overall "in and out" efficiencies for pumped storage systems have been reported from around 60%, although some claim 80%.[1] Ferguson has pointed out that the variability of wind energy for storage would probably lower the overall efficiency of pumping (or raise the capital cost), because the pumps probably have a rate at which their efficiency is maximised. The E.On Netz report showed that wind energy can rise or fall by a factor of 6 over a six hour period, meaning that a pumping system capable of storing the full wind surplus would mostly be idle a little later. Again intermittent sources set the problem of large amounts of expensive machinery being used for a small proportion of the time.

A major problem is the need for both high and low dams with sufficient storage capacity. Very large volumes of water would have to be pumped up and these must come from similarly large sources at the low level, within a reasonable distance.

There are few if any dams of any significant elevation anywhere near the best solar collection sites in the flat centre of Australia, or the US. The biggest problem would seem to be the lack of low dams. Most dams do not have below them large lakes with a lot of water that can be pumped up into the dam. In some cases there will be chains of dams along a river enabling pumping from one to the other.

An ideal low "dam" is the sea close to high coasts, but this poses the problem of long distance transmission to and from such sites, seepage of salt into surrounding soil, and the construction of large capacity special dams. Sadler, Diesendorf and Denniss (2003, p. 101) believe environmental considerations rule out construction of any more large dams in Australia.

Perhaps the biggest problem concerns the sheer amount of hydroelectric generation that is possible. Globally hydroelectricity contributes only about 7% of electricity consumed. This means that when there are no solar or wind energy sources contributing, dams could not meet more than about 7% of demand. To increase this would again be to build more backup generating plant, to alternate with wind, and in view of the efficiency of pumped storage for each unit of wind, energy we chose to store and regenerate this way we would have to build hydro-generating capacity capable of generating 1.4 units of energy.

In general the amount of electricity that dams could provide via surplus wind would be less than 7% because it would depend on what storage capacity was available when the wind surplus occurred. Dam levels tend to be lowest in late summer to autumn, when winds are also at their lowest and unlikely to be providing surplus energy to store. The main unknown is how much storage capacity would there be in mid-winter when the winds are strongest but when there is also likely to be more rain and therefore less space in dams?

How much more hydro-generating capacity would we need to build to meet demand when there is no wind at all? If hydroelectricity contributes about 7% of electricity now, and pumped storage has an in and out efficiency of 70% it would seem that the answer must be some 20 times as much. So in addition to a windmill system capable of meeting all demand it would seem that we would also have to build a hydro-system capable of supplying 20 times as much electricity as hydro-sources provide now.

The dam size required to store the night time output from a 1000 MW power station, via pumped storage at 70% efficiency, would be about 20 square km, if stored water is 5 m deep.[2] This is not a big challenge regarding the high dam volume, but it is for the low dams, especially when supply for SE Australia in a calm period would involve output from some 20–30 power stations.

The cost of the pumps, pipes and additional generating capacity would have to be added to the cost of windmills etc. to arrive at total system costs. Also important would be the distance electricity would have to be transmitted to the dams and the associated losses.

Some thought should also be given to the implications of the greenhouse problem for pumped storage. In many regions reduced rainfall is expected. In January 2005, not a summer period, Spanish hydro-power output was down to less than half its capacity, due to drought (Ferguson, 2005a). The coming Greenhouse effect on the Murray-Darling river system could reduce stream flow 50% according to some modelling studies.

The ultimate long-term problem for pumped storage is that dams silt up. At best their lifetimes are probably under 200 years.

7.2. COMPRESSED AIR STORAGE

Storage of energy in the form of compressed air is claimed to be much more energy efficient than storage as hydrogen.[3] Figures between 40% and 70% are quoted. Therefore to retrieve the 670 MW × 16 hrs needed when the sun is not shining, 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 we would have to build another capable of generating 660 MW at night from the compressed air.

A major drawback with CAES has to do with the very large storage volumes that 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 4,708 million cubic metre storage area, i.e., a mine shaft around 470 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 at the regeneration stage. In a wholly renewable energy world this will not be possible. Without burning gas the efficiency is 0.4 to 0.5. It could be that solar heat could be used, but this would mean 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. Heat availability would be at its lowest when wind energy for storage was at its highest, in winter.

For smaller applications, such as vehicles, Doty (2004b) estimates that a 120 gallon tank could store 0.576 kW at 15 atmospheres, for $(US)730, which is 85 times the cost of a diesel tank containing the same amount of energy, 40 times as heavy and 200 times as voluminous.

7.3. THE VANADIUM BATTERY

The vanadium battery promises a higher storage efficiency, initially 87%, but this will deteriorate with recharge cycles. Its attractiveness is that the electrolyte can be poured into a tank on a vehicle, meaning there is no loss of time in recharging. (Skylass-Kazacos: n.d.)

An 800 kWh storage facility has been built on King Island, Bass Straight, Australia, to store energy from windmills. Although the facility occupies a large shed and appears to have cost around $1 million, from the published information it stores the equivalent of only 83 litres of petrol. About 5 kg of Vanadium Pentoxide are required to store 1 kWh, so the energy in a 50 litre car petrol tank would require liquid weighing 2.3 tonnes, some 56 times the weight of petrol.

Similarly, volume is a concern. Sadler, Diesendorf and Denniss (2003, p. 101) say the storage volume is 90–144 MJ per cubic metre. This is 0.004 of the energy density of petrol. A car petrol tank full would fuel the vehicle for about 2 km. For a car to travel a normal distance before refuelling the tank would have to be about 14 cubic metres in volume.

To store the night time demand from a 1000 MW power station, 10,560 MWh, would require about 447,000 tonnes of Vanadium when storage efficiency is taken into account. To equip all US power stations with this capacity would require around 268 million tonnes.

7.4. FLYWHEELS

Flywheels spinning in a vacuum suspended by magnetic fields are used in relatively small-scale systems, such as providing emergency backup when power for vital systems fails and alternatives take some seconds to cut in. (Regenerative Powder and Motion, 2006.) Storage or delivery periods tend to be quite short, mostly a matter of seconds (Sadler, Diesendorf and Denniss, 2003, p. 101). The cost per kWh stored given by Active Power (personal communication) is $1,750–$2,000. This indicates how very far from applicable to very large-scale storage such systems would be at present. At this rate the night time storage capacity for a 1000 MW power station would cost $20 billion, although this would not be a good guide to costs for systems specially designed for the larger task.

Sadler, Diesendorf and Denniss (2003, p. 7) say that flywheels store 200 KJ/kg and 100 MJ per cubic metre. The storage task would therefore involve 380,000 cubic metres and 1,190,000 tonnes of flywheels, rotating in vacuums suspended by magnetic systems.

Here is a way to get some idea of the astronomical task involved. Imagine a powerful car, say 220 HP, accelerating at full throttle, but with no frictional loses. Now imagine 4,620 of them side by side, accelerating like that . . . for 16 hours. How fast would they be going then? Their combined momentum would be equal to the energy in 660 MW × 16 hours, the amount a power station would need to store for a night's delivery, so it is rather unlikely that a feasible flywheel system could store such an amount of energy.

7.5. HYDRIDES

Hydrogen can be stored in the form of metal hydrides with negligible loss over time, but the tanks must be heavy and expensive, the storage material is expensive, it can become contaminated, controls are required for heating, cooling and altering pressure, and there is difficulty extracting all the hydrogen stored. Unless the hydrogen is pure the hydrides will have reduced life expectancy. According to Bossel, Elliason and Taylor the weight of the storage vessel is 115 times that of the hydrogen stored. To store the equivalent of a car's 50 litre petrol tank would require a container of more than 1.2 tonnes. Sadler, Diesendorf and Denniss (2003) report the storage rate at 2–9 MJ per kg, meaning petrol is 4.5–21 times as energy dense as hydrogen within a hydride. Heavy "tanks" would reduce the potential for ultra-light vehicles and their attendant energy efficiencies.

Doty (2004a) says hydride storage costs $(US)16,000/kg of hydrogen stored, and takes 20 times the volume for the same amount of energy in petrol. Sorenson (2003) says the storage volume is only about the same as for liquid hydrogen. The energy efficiency of the process is also a problem, also being somewhere around that for liquid hydrogen.

Even if higher storage ratios of hydrogen to metal can be achieved it is not obvious that this would be a markedly better storage option than dealing with hydrogen gas, in terms of overall combined volume, weight, cost and efficiency. For instance it would not seem to be a viable means for transporting hydrogen, given that most of the weight moved would be in the metal containing the hydrogen. It might therefore be more viable as a large-scale store at stationary sites, such as power stations, but the huge quantities of the storage medium required would be extremely costly. As always with hydrogen the losses in creating and using it seem to fix the efficiency of the system using it below 30% regardless of how conveniently or cheaply it could be stored, and whether as gas, liquid or hydride.

7.6. SOLAR PONDS

Large shallow ponds are used in very hot regions to trap heat in the salt-laden bottom layers, which is drawn off to run generators. The major limitations have to do with the water consumed in evaporation. "Solar ponds however are unlikely to generate large amounts of electricity because they are limited by their significant water consumption." (de Laquil, et al., 1993, p. 289). In addition pond liners of some kind are usually necessary to prevent the salty water seeping into the ground. There is also a tendency for the salt to rise, requiring use of more fresh water to restore the surface layer.

7.7. OTHER STORAGE OPTIONS

Energy storage via thermo-chemical processes would seem to be about as efficient as hydrogen gas storage, and possibly somewhat less. Kaneff (1992, p. 43) reports efficiency as 60% but notes that for the whole path from original energy source input to electricity output, efficiency is likely to be 26%–33%. An important advantage is that the stored energy would last for a long time without loss, although as ever for large-scale electricity supply there would be a significant problem of storage volume. Storage of energy via methane reforming or ammonia recombination is more energy efficient than storage via hydrogen, yet these processes would require one cubic metre of gas storage per 1.54 kWh, at normal pressure. Thus to store the energy from a power station for the 16 hours when the system was not generating would require a mine shaft approximately 1,500 km long, assuming 60% energy storage efficiency. Obviously gases would be compressed to reduce space requirements but this incurs energy and infrastructure costs.

Hot rock storage, phase change materials, thermo-chemical processes, and molten salt are all more or less confined to storing heat, making them suitable for solar thermal systems but not capable of assisting with storing electricity from PV or wind sources. For very large storage from these there seems little choice but to use hydrogen and suffer the considerable losses and costs.

What about storing surplus wind energy in the heat storage tanks of solar thermal plant which will not be used that much in winter? As has been noted this would be worse than storing in hydrogen because in addition to losing 2/3 of the heat as it is reconverted to electricity, most of the regenerated electricity would then be lost if it was used to fuel electric or hydrogen vehicles (see Chapter 6).

Other interesting possibilities are under study, such as capacitors and advanced batteries, but at this point in time they do not rival pumped storage or compressed air for very large-scale use.

7.8. JUGGLING ADJUSTABLE LOADS?

A useful strategy that would reduce the storage task would be for various electricity users to switch their processes on when the supply is high, and cease operations when it is down. This is possible for example with ammonia or ice production, or boosting freezers. One difficulty is that this means expensive production plant, larger than if designed for constant operation, would be idle much of the time, thus raising costs. However most demand, for instance from households and for air-conditioning, comes at times that permit little adjustment.

7.9. CONCLUSIONS

Many of these technologies will be viable in The Simpler Way because the amounts of electrical energy used and to be stored will be quite small. However despite a great deal of research over many years on this extremely important problem we do not seem to have good reason to expect that ways will be found for storing very large quantities of electricity consumer societies use at an acceptable cost.

CHAPTER 8

CONCLUSIONS ON THE POTENTIAL AND THE LIMITS

8.1. NOTES ON OTHER RENEWABLE TECHNOLOGIES

Before attempting to sum up, brief comments will be offered on a number of renewable and conventional energy technologies not examined so far. This has not been an exhaustive study of the potential of all renewable energy sources. There are many which have considerable promise but apart from the big four, PV, solar thermal, wind and biomass, it seems fair to say that none of the others is likely to be a major contributor; they might be eventually but right now we do not have good reason to bank on them. Following are some notes on the limits associated with most of the remaining contenders.

8.1.1 Tides

As with most renewables there are vast quantities of energy in this source, but that does not mean much of it can be tapped, at a reasonable cost. Large quantities of water must flow in and out through fairly narrow gaps. These days an important limiting consideration is interference with the ecology of estuaries. Heinberg (2003) says there are only 24 optimal sites in the world, most of them very remote. “It is unlikely to make a significant contribution to world energy supplies.”

8.1.2 Ocean Currents

Also promising is the prospect of harvesting ocean currents via turbines sitting on the bottom in those locations where currents are particularly strong. However the quantities that could be harvested are doubtful. For instance a recent report put British potential at 2.5 TWh p.a., the equivalent of about one-third of a power station. (http://eeru.open.ac.uk/natta/techupdates.html) It noted another report concluding that the UK had 80% of European potential.

8.1.3 Waves

Again the energies involved are huge, but so are the difficulties, especially having to do with storm damage. Unfortunately in view of the energy per metre of wave front, devices would have to be very lengthy to harvest a lot of energy. It is significant that despite many years of experimentation no commercial plant had been put into operation before 2004. The Department of Trade and Industry study estimated UK potential at equivalent to about one third of a 1000 MW power station. The UK Carbon Trust estimates that waves could theoretically generate 14% of UK electricity, if all the suitable sites could be connected to the grid (Black, 2006).

The 40 m wide device installed at Wollongong, Australia, in 2005 cost $6 million and is expected to have an average output of 57 kW (or hopefully 100 kW; personal communication). The waves at the site are said to carry 7 kW/m, meaning that the device would have an efficiency of 15%. Because this is an experimental project, costs for future versions would become much lower, but this one works out at $(A)105,263/kW(peak).

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 if sites down to 20 kW/m are used. Devices built into the shore would not be so vulnerable to storm damage but as these would take so much coast line, large scale wave harvesting would use floating devices moored out to sea. The problem then would be that these would have to be very robust, and therefore expensive, to withstand storm damage, which has prevented advancement of wave power to date.

Industry sources believe 40% efficiency can be achieved, meaning output of 12 kW/m at the best sites. If 10% of these could be used and if 40% efficiency could be achieved, output would be equivalent to 18 power stations. The equivalent of a 1000 MW power station would be 80 km long. Hayden (2004, p. 210) derives a similar figure from another experimental project; 130 km, assuming 25% efficiency. Adding the estimate for 20 kW/m coasts suggests a total 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 electricity demand. World electricity supply at rich-world rates of consumption for the present total world population would equate to roughly 9,000 power stations.

8.1.4 Ocean Thermal Gradient

This proposal involves exploiting the slight temperature difference between surface and deep waters in the tropics, via a 30 m diameter pipe. The energy efficiency is very low and it is only applicable in tropical areas a long way from rich-world populations. This might not be so problematic if hydrogen could be transported long distances. It also sets ecological problems, bringing huge quantities of cold water and nutrients to the surface.

8.1.5 Geothermal

Very large quantities of energy exist as heat in dry rock masses and it is possible to tap this by pumping water down one bore hole and up another. A study completed in 1994 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)

It will be some time before we know how practical and costly this approach will be, or what the energy return might be. 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 some European locations), meaning rather low generating efficiency. A firm is carrying out trials at a favourable site in South Australia where temperatures are relatively high, although a computer simulation anticipates use of an in-out temperature difference of only 167 degrees. It is believed generating efficiency will be 15–20% (Personal communication).

Any field of bore holes would also have to be understood as a non-renewable resource because the process extracts heat that has accumulated slowly over geological time and is not renewed at anything like the rate that it would be extracted. The information from South Australia suggests that a set of holes will last as long as, or possibly twice as long as a power station normally does. Computer simulations indicate an 11 degree temperature drop in 20 years, meaning that the in-out temperature difference would then have fallen to 156 degrees.

The main question seems to be the rate at which energy could be extracted in water flowing between the bore holes, and therefore how many holes would have to be drilled to equate to a 1000 MW power plant. A rough estimate is offered in Note 1.

The energy cost of drilling the holes, some 43,000 metres in the 280 MW simulation (corresponding to 154,000 metres for a 1000 MW power station), and of building the power plant and the lines from distant locations would have to be deducted from the gross plant output.

There are also questions having to do with what proportion of the energy lying between the bore holes might be extracted. There would be a tendency for the water to flow straight from one hole to the nearest, rather than spread out evenly through the whole rock field. From Swenson et al's., (2000) account it seems that perhaps only 25% of the rock mass in a field might be tapped.

Experiments have found that at some sites a significant amount of water can be lost into surrounding rock. The higher the pressure the faster the rate of energy recovery, but the higher the risk of loss of water. Hot dry rock sites tend to be extensively jointed and fractured, increasing this probability (Tenzer 2001, p.14). This is not expected to be a serious problem at the South Australian site.

The estimation in Note 1 is not offered as settling anything but it does indicate that the difficulties and energy costs of the pumping task are quite substantial, and they suggest that onlookers might be cautious until clear evidence from practical experience comes in. Certainly in some regions, such as South Australia, this technology is likely to be quite valuable, but despite the very large quantities of heat in dry rock it is by no means clear that it can make a major contribution to solving the general global electricity task set, especially if other countries do not have Australia's potential.

8.1.6 Solar Chimney

The published figures for the Australian proposed solar chimney seem to be very optimistic, and somewhat confusing, e.g., the $(A)800 million stated cost of building a 32 million square metre greenhouse with a 1000 metre high tower in the centre (Enviromission, 2005). That is an all up cost of $22.5/m, when 6 mm hail-toughened glass costs $(A)60/m wholesale (2005). (Enviromission's 2006 website indicates a revised proposal, for a 50 MW project.)

An experimental solar chimney built in Spain operated at about 4% efficiency. One wonders what the efficiency of the Australian project would be, sited at almost 40 degrees south, in winter. Figure 2 from Pretorius and Kroger (2005) shows that on a winter day at a good site the output of the Spanish chimney was 38% of summer output.

One merit of the chimney technology is that the greenhouse area can be used, for instance to grow algae for ethanol production. Another is that heat soaked up during the daytime would continue to provide some power at night. However, because tracking is not possible the sun is closest to a right angle to the full collecting surface only at the middle of the day and thus the power curve for solar chimneys throughout the day is much more peaked than that for solar thermal systems. (See Fig. 10, Berndes, dos Santos, Voeb and Weinrebe, 2003.) Thus an area big enough to produce 375 MW at mid-day will have a daily average output of about 100 MW. As with most other renewables average capacity is rather low and a lot of plant is fully productive for only a small proportion of the time. Winter performance could be expected to be a lower fraction of summer performance than for solar thermal systems, given that the collector cannot track the sun.

8.1.7 Geosequestration of Carbon

The core greenhouse strategy adopted by the US and Australian governments is to continue to burn coal without any thought of reducing the rate, while capturing the carbon released and burying it in the ground or deep ocean. It is not surprising that these governments have taken this stance, since it suits the powerful coal and oil industries, avoids disruptive change, does not threaten electricity supply to consumers, and makes it seem that the government is doing something significant. They can say research is under way and this defers confronting the problem for decades into the future. Following are brief notes on the problems that disqualify this option from making a significant difference to the greenhouse problem.

It is only applicable to stationary energy facilities such as power stations and therefore could capture no more than about a third of carbon released. It does not extract all the carbon generated by the plant.[2] Carbon capture is not possible in almost all existing power stations so there would be a delay of decades before it began to make a difference via new plant. Although used in some oil fields it is an untested and unproven technology for large-scale power generation.

Geosequestration is quite costly, requiring infrastructure to move and store the carbon dioxide (30 million tonnes a day in Australia). According to one estimate the separation process increases gross fuel use by some 20%, and total energy cost is increased by 40% when the sequestration process is included. By another estimate it doubles plant generation capital cost.[2]

Sites for depositing large volumes of carbon dioxide are limited and problematic. Eastern Australia does not have enough sites on land (Peacock, 2006, p. 20). Others estimate that we could store less than one-third of the carbon dioxide from the present rate of electricity production. The gas is dangerous to health even at low atmospheric concentrations, so sites must be permanently leak-proof.

Even if the technology was perfectly satisfactory, coal would not last very long if it became the main fuel for all. As has been explained in Chapter 2, if 9 billion people each used 6 tonnes of carbon p.a., the present approximate amount in Australia, annual global consumption would be 54 billion tonnes and the probably accessible 1,000 billion tonnes (or maybe 2,000) would last about 18.5 years (or maybe 39 years). Note that the rate of use would be much higher if a large proportion of the coal had to be converted to a liquid form of energy.

8.2. NOW, THE POTENTIAL AND THE LIMITS OF THE MAIN RENEWABLES?

Following is an attempt to summarise some of the main conclusions arrived at in Chapters 2 to 7.

8.2.1 Electricity

8.2.1.1 Wind

In Europe, the US and Australia, and surely many other regions, the quantity of wind energy that could potentially be harvested is quite large, e.g., comparable to electricity demand, but not likely to be so abundant as to enable transport energy to also be derived from this source.

Much more important than sheer quantity are the limits set by the variability of the wind. In most regions most wind comes in winter, and at any time of the year wind strengths vary greatly and for considerable periods there might be little or no wind. This might limit the contribution of wind to 15% of demand or less, but possibly 20% or more in favourable regions. A windmill at an ideal site will generate 33% or more of its rated peak capacity but in Germany and Denmark the variability problem has cut *system* capacity to well below this figure, indeed to around half of it. Connecting wind farms across very large areas helps to reduce the variability in system aggregate input, but does not overcome it. Large regional calms can last for days.

In Germany the average capacity figure for the more windy half of the year has been recorded at around a mere 11%, although the European annual figure has been closer to 25%. At present wind provides a very small fraction of national demand even in the countries that have built most capacity, e.g., around 5% in Germany and Denmark (where more is produced, but exported), and this capacity would have been built at the best sites available. If this fraction was increased to say 50% it is likely that most of the mills would have to be located at sites where capacities would be well below the 35%+ usually assumed, and total system capacity would surely be well under 25%. Most of the world's people do not live in the favourable wind conditions of Western Europe.

The problem is not obviously overcome by linking many mills in a large system over a wide area. Davy and Coppin's findings regarding the probable variability within a very large integrated Australian wind system 1500 km across are sobering. For a considerable fraction of the time much backup fossil fuel or nuclear power would have to be drawn on.

Another implication of variability is that if a large amount of wind-generating capacity is built, then almost as much additional coal or nuclear capacity might have to be built for use when the winds are down. In addition grids have to be reinforced to enable large surpluses from one region to be moved to others. In other words we might need capacity equal to two (or three if solar is included) separate and expensive systems with one or two sitting idle most of the time.

The usually claimed cost of wind energy is misleading. It refers to peak as distinct from average capacity, it does not include storage costs, or the costs of connecting the farm to the grid, and, most important of all, it does not include the cost of building the backup coal or nuclear plant needed when the winds are low.

It does not seem viable to use vast numbers of windmills to store large quantities of energy as compressed air, pumped water or hydrogen for use later, especially in the calmer summer months. Nor can coal be used to plug the gaps in wind power supply without exceeding safe greenhouse limits. It is difficult therefore to see how wind could be a major component in a global energy system running entirely on renewables unless some way is found for storing large quantities of energy, or we could be sure that a sufficient amount of some other renewable source would always be available when the wind input is low.

8.2.1.2 Solar Thermal Electricity

In many hot regions these systems will surely make a significant contribution, but they are not likely to meet a large fraction of demand all through the year. Even in favourable regions their performance in winter is likely to remain quite low. A significant drawback is set by the "threshold" problem, i.e., the need to reach critical temperatures before any generation begins. Dishes perform better than troughs with respect to these factors, but they are more expensive and are not being developed with heat storage capacity. The contribution of solar thermal systems in middle latitudes is not likely to be a large one, again especially in winter. European supply would probably have to come mostly from the Sahara, involving high transmission losses and costs. Winter supply from that region seems questionable. In general, supply would have to be from low latitudes to high latitudes across long distances.

The major advantage of solar thermal technology is capacity to store energy as heat at relatively low cost and losses, at least for a day or so. Nevertheless storage for several winter days is problematic, given that irregular sunshine would hinder recharging of the heat store.

Much depends on how effectively solar thermal systems can be designed for less than ideal latitudes and seasons. Chapter 3 casts doubts on these possibilities, but this is one of the areas where this book's conclusions are least certain.

8.2.1.3 Photovoltaic Electricity

PV systems are a valuable supplement to a grid powered by coal or nuclear sources, so if variability and storage limits could be overcome, PV could clearly be an important contributor to a wholly renewable system. But again no such system can exist unless there are sources that can be called on reliably to meet full demand when sun and wind are low, and it seems inevitable that much of the time there will be considerable need for input from the coal or nuclear back-up sources. Even in good solar regions PV electricity is likely to remain quite expensive, because the "balance of system" cost is considerable regardless of falls in cell costs.

8.2.1.4 Storage of Electricity

The variability problem that inevitably comes with renewable sources of energy would be greatly reduced or eliminated if very large quantities of electrical energy could be stored conveniently. The two best options, compressed air in large caverns, and water pumped up into dams when the winds are strong, seem to be much too limited.

Note the magnitude of the storage task. Sometimes there is no sun or wind over large regions for days at a time, requiring storage equivalent to several days' output from maybe hundreds of large power stations across a continent.

Some of the storage options being explored might in time turn out to make a significant difference, but at this stage we cannot assume that solutions to the problem of very large-scale electricity storage are around the corner.

It is likely that the renewables combined could make up a large fraction of total energy demand, maybe more than 50%, if coal or nuclear sources were also there to plug gaps and act as the big battery into which surpluses from the intermittents could be fed irregularly. The problem with this is that sensible greenhouse targets would be greatly exceeded. As Chapter 1 explained, sensible targets applied equitably across the planet would require almost complete abandonment of fossil fuels in rich countries.

8.2.1.5 Combining Sources of Electricity

Fortunately there is a tendency for the winds to be at their strongest in winter when the sun is weakest, and vice versa. However in the higher northern latitudes where most Europeans and Americans live there is little solar energy in winter, and there are relative low winds in summer and autumn. Consequently in these regions solar and wind sources would have to be used as *alternatives* rather than combined in the sense of *added*, meaning significant multiplication of generating plant. In regions like Australia where there is considerable solar energy in winter the overlap would be greater.

It is often claimed that the problem of the gaps left when some renewables are not producing much would be reduced by the probability that others would be producing at that time. While there are several other renewable options, there are only two major ones, sun and wind, and both can be down together for long periods. The important unknown is what would be the pattern and magnitude of the gaps left if a wide range of renewables was extensively developed, and maximum use was made of the storage options available? As has been stressed what matters here is not the average situation but the distribution; i.e., how often would aggregate supply go down how far? What we need are plots of the kind Davy and Coppin give for an aggregated wind system in south east Australia, estimating the proportions of time that supply would reach various proportions of total system peak capacity, for systems including wind, PV, solar thermal and pumped storage components. From the foregoing discussion it is likely that aggregate renewable supply would often go down a long way, because there are long periods when wind and sun are both low, and to plug these gaps using fossil fuels would be to exceed safe carbon emission limits.

The other major problem in combining strategies is that two or three (very costly) alternative supply systems have to be built, and then one or two will sit more or less idle much of the time while one or two of them functions — and at times none of them will be operating and we will have to fall back on maybe almost as much coal or nuclear power as we have in renewable capacity. As the capital cost of each of the separate renewable systems is going to be quite high, the total system cost for all components, along with their grids etc., could be unaffordable.

The capital cost per delivered kW for the options discussed in Chapters 2, 3 and 4 tend to be up to 10 times that of coal-fired plant plus fuel. This is not a precise guide to the multiple for price to the consumer, but what must be stressed again is the fact that in future the costs of everything will be significantly increased because the cost of energy will be higher. Renewable energy will be expensive and this will feed into the cost of building renewable energy plant, which will in turn multiply the cost of the energy produced. The operation of this multiplier means that the costs given and estimated in previous chapters will be much too low. In future the cost of renewable plant and energy produced will surely be far higher than the figures assumed above.

8.2.2 Liquid Fuel and Gas

Land and yield considerations clearly show the impossibility of producing from biomass more than a very small fraction of present rich-world per capita oil and gas consumption for a world of 9+ billion people. The only other option for liquid fuel is hydrogen, and its probably severe limits are summarized below.

The limits here are not set by energy return ratios or costs, but by the impossibly large land areas that would be required.

"Then let's use electric vehicles for transport." Chapters 2, 3 and 4 conclude that renewables will not be able to meet present electricity demand so there will not be significant volumes left over to run transport. Fuelling transport via electricity could require delivery of four times as much electricity as we consume now, because transport energy is much greater than electricity consumption and because of the losses between windmill and wheels.

8.2.3 Hydrogen

Solar and wind sources are likely to be fully taken up in providing electricity, and biomass cannot meet liquid fuel demand let alone provide hydrogen. Therefore we are not likely to derive anything like the quantities of hydrogen required to maintain present consumer society.

Secondly the difficulties and losses involved in large-scale hydrogen production and distribution seem to rule out the viability of a hydrogen economy, even if we could get the quantities required.

8.2.4 Remember the Growth Deamon

As will be stressed in Chapter 10, whether or not renewable energy can sustain consumer-capitalist society is not a matter of whether it can meet *present* demand. The crucial question is can it sustain the demand generated by growth of the economy? Can it provide for about four times as much output and consumption by 2050, and eight times as much by 2075? (See Chapter 10 on growth rates and predictions.) Can it provide the amount of energy 9 billion people would need if they were to have the "living standards" we in Australia will have by 2075 given the continuation of the present rate of economic growth? If so it would be providing around *30 times* as much energy as the world uses now. Assume that technical advances cut the energy to GDP ratio to one quarter of the present figure and the multiple is 7+ times.[3]

8.2.5 Can Improved Energy Conservation and Efficiency Solve the Problem?

Along with the powerful but unexamined general assumption that renewable energy can save consumer-capitalist society, there is the equally taken-for-granted assumption that technical advances and greater conservation effort can greatly reduce the need for energy. These assumptions are core elements in the basic “technical fix” view which shores up the conviction that no change from consumer-capitalist society is needed. It is not difficult to show how seriously mistaken this general position is. The magnitude of the problems, the overshoot, is far too great.

There is no doubt that the potential for energy saving is large, both in terms of wasteful practices and the potential for developing much more energy-efficient devices. A common claim is that energy use can be cut by 50%, by eliminating waste and designing more efficient machines and ways. This is plausible. Amory Lovins has argued that a “Factor Four “ reduction is achievable, i.e., halving resource and environmental loads while doubling GDP.[4] Most of Lovins’ (valuable) arguments and cases indicate 50–75% reductions. For instance the hybrid car could cut petrol consumption in half and Lovins’ discusses future possibilities which might halve that again. So why can’t we solve the problem if we just keep up this effort?

We should note firstly that not everyone agrees with Lovins regarding the scale of the possible reductions. The Australian Bureau of Agricultural Economics (2006) offers an estimate of the overall probable conservation achievement by 2050 which is much lower than the expectation often encouraged by tech-fix optimists offering theoretical analyses of what might be done. It estimates that we are on a path to a total global carbon emission rate p.a. in 2050 that is an alarming 2.6 times as high as it is now, and that conservation effort will reduce the resulting 15 GT figure by only 23%. (In Chapter 1 the safe emission limit seemed to be around 1 GT/y.)

Optimists point to the much lower energy use rates in Europe and Japan than in Australia and the US, but those countries are far smaller and have much higher population densities, meaning shorter travel and transport and that public transport is more economically viable.

Easily overlooked is the fact that we are in an era when the easiest conservation gains are being made. We are “picking the low hanging fruit”. US oil intensity fell in the 1985–2005 period at half the rate that it fell in the previous 15 years (Lovins, et al., 2005, p. 43). Gains in aircraft flight distance per litre of fuel are falling, because the easiest gains have been made (Lovins, et al., 2005, p. 80).

Another point enthusiasts about conservation and technical advance easily overlook is the “Jeavons “ or “rebound” effect. Often technical advances enable savings in energy and therefore reductions in the price, which promptly leads to greater consumption. This has to be understood in relation to the fundamental imperative in a consumer-capitalist society, to maximise output, wealth, consumption and GDP all the time. Any firm that finds its energy costs cut by better technology will immediately increase production of cheaper goods, or pass the saving to customers who will have more money to spend on something else. If we find we can travel for half the cost, we are likely to double our travelling.

The costs of savings also have to be accounted. Often there is a significant net gain, as with insulating a house. However, although very light cars use less energy the materials they are made from are energy intensive to produce. In fact Mateja (2000) reports that mainly because of their sophisticated electrical systems, hybrid vehicles take 30% more energy than the average car to produce, and in some cases five times as much. The popular Prius takes 142% more energy than the average car. Newman (2006) says " . . . over the lifetime of a vehicle . . . hybrids actually consume a lot more energy than even big SUVs." He reports the Prius lifetime energy cost per mile at 1.4 times that of the US car fleet average.

Also the full balance sheet needs to be filled out. For instance energy used in US corn production fell 15% between 1959 and 1970, but that was only energy used on the farm. When all inputs were taken into account energy use actually rose 3% (Heinberg, 2003, p. 162).

Some seemingly notable energy reducing achievements of corporations have simply been due to either getting out of production of energy-intensive lines, or transferring these to sub-contractors in the Third World where energy use is booming and there is less pressure to minimise energy or environmental costs.

If the magnitude of our overshoot were not so great, these often remarkable conservation and efficiency efforts might be capable of solving the problem, but we have to make perhaps 90% reductions. Let us assume that energy use and other resource and environmental impacts must only be halved (. . . although solving the greenhouse problem would require a far bigger reduction.) Now as has been explained, if by 2070 we have 9 billion people on the "living standards" we in Australia would have by then given 3% growth, total world economic output would be 60 times as great as at present. How plausible is it that by then we can also reduce impacts by 50%, meaning a Factor 120 reduction in the rate of impact per unit of GDP, not a Factor 4 reduction?

Clearly system change is needed. The problems cannot be solved by more conservation effort on the part of individuals and firms *within* consumer-capitalist society. They are being caused by an overshoot that is far too big for that, and they are being caused by some of the fundamental structures of this society. Consequently much of what is said under the heading of "sustainability" is nonsense and much of the effort being made to "save the planet" is a waste of time. Most irritating are the "What you can do in your own home" campaigners. "Buy biodegradable wash up liquid, use a low-flow shower head, recycle your bottles, buy a smaller car, etc." Such efforts can make no more than a negligible difference to *household* impact, when we need something like a 90% reduction in *national* consumption. Nothing remotely like this is possible within a consumer-capitalist society committed to affluent lifestyles and limitless economic growth. It is only possible through dramatically reducing the volume of production and consumption and therefore by *changing from* such a society to one that is about frugal but adequate "living standards", as little production and consumption as possible and a stable economy.

8.2.6 Forget about Renewables?

None of this constitutes an argument against renewable energy sources. We must move to full dependence on them as fast as we can. Chapter 11 will show how well they could fuel a sustainable and just society. But the general conclusion from the foregoing discussion has been that they cannot sustain consumer society.

CHAPTER 9

WHY NUCLEAR ENERGY IS NOT THE ANSWER

If it became generally accepted that renewable energy resources cannot substitute for fossil fuels, this would surely be taken as a convincing case for the adoption of nuclear energy. Following are the reasons why nuclear energy is incapable of solving the energy problem, and unacceptable even if it could.

9.1. FUEL

Leeuwin and Smith (2003, 2005) have analysed global Uranium resources and energy costs, finding that there is far too little Uranium at a sufficient grade to sustain a nuclear era for more than a few years. Even this richer fuel enables an energy return ratio of only about 5, meaning that in its 35 year lifetime a reactor would be producing net energy for about 28 years. (See also Mortimer, 1991.) If the world's present electricity demand was met by nuclear reactors, the high-grade ores, over 0.2% uranium oxide, would be used up within about twelve years.

Larger quantities of Uranium exist in low grade ores, e.g., 0.01–0.02% concentration, but Leeuwen and Smith conclude that extracting these would require more energy than they would provide. Even larger quantities exist in sea water, but the concentration is around 1/1000 that in the earth's crust so even worse energy budgets would be involved. They conclude that Uranium from seawater " . . . can't be considered an option." (p. 22).

The nuclear industry disputes Leeuwin and Smith's analysis of reserves but unless it can show that there is something like 100 times as much Uranium retrievable as Leeuwin and Smith believe, there would not be enough for a nuclear era including all people to last more than a few years; see below.

What about using Thorium instead of Uranium? This would probably treble fuel availability, so would not make a big difference. Some of the possible processes require fuel reprocessing and the use of Plutonium and the reasons against getting involved in these are noted below.

9.2. THE NUMBER OF REACTORS NEEDED

A largely nuclear era would involve a huge number of reactors. To provide 9+ billion people with present rich world energy consumption per capita would require 100,000 reactors each of 1000 MW (many more when conversion to liquid fuels is taken into account). Thus we would have about 500 times the present scale of accidents, waste, safety violations, etc. To provide 9+ billion people with the energy we in rich countries will be using in 2070 if the current rate of growth in energy demand continued would multiply these numbers by perhaps 5.

If the 100,000 reactors were all breeders with 4 tonnes of Plutonium in the core of each, the amount in the French Superphenix breeder, about half to a million tonnes of it would be continually recycling through reactors and reprocessing plants. We would have to bury about 4,000 old reactors every year.

9.3. SAFETY: THE ACCIDENT RATE

Especially significant is the fact that just one accident could have devastating global consequences for a very long time, i.e., seriously affecting billions of people over thousands of years until radioactivity had been taken out of natural circulation.

The consequences of a radiation accident would continue to accumulate for a very long time. The half-life of Plutonium is 24,000 years. It is sometimes misleadingly said that coal-fired power causes more harm than nuclear energy. The undesirable effects of coal power will all have ceased within say 100 years of the last coal-fired generation, but the full effects of nuclear energy will not have accumulated until many thousands of years after the last reactor ceases to operate.

A powerful argument regarding safety is the fact that the US government's Price - Anderson Act imposed an upper limit to insurance payouts that might result from a reactor accident. Without this provision there would probably be no reactors at all, because insurance companies would not insure them. If reactors were generally regarded as relatively safe, they would.

9.4. TERRORISM AND NUCLEAR WAR

A nuclear industry adds to the dangers of terrorism, e.g., via theft, corrupt diversion of Plutonium, or use of reactors as terrorist targets. By increasing the amount of nuclear material in circulation, a nuclear energy era would greatly increase the chances of some of it being diverted into arms production, either by governments or subversive groups. If fuel is to be reprocessed, then large quantities would have to be in the temporary control of trucking and other companies, with considerable scope for corruption of drivers etc. To repeat, just one accident could have globally catastrophic consequences for a very long period.

9.5. SOLVES THE GREENHOUSE PROBLEM?

Nuclear energy generates a lot of carbon dioxide, not from the operation of the reactor, but from the mining of the fuel. Fleming (2006) claims the output to be 1/3 that of coal-fired power stations (although others regard this as perhaps true of coal-fired plant but too high for gas). In any case nuclear reactors only produce electricity so they can make no difference to the carbon emitted by the 80% of the end use that is not in the form of electricity. If all electricity was generated by nuclear reactors, carbon dioxide emissions might be reduced by 30%.

9.6. THE WASTE PROBLEM

There is no agreed solution to the waste problem. That there are potential storage sites where no geological activity has been observed for a long time does not mean we can be certain there will not be any activity there in coming millennia. Especially uncertain are the possible effects of the coming greenhouse problem of changing rainfall patterns and therefore on hydrology. Many areas that have been dry for a long time will experience, in coming millennia, new and unpredictable ground water flows. The Synroc process, fixing high level wastes in a kind of insoluble glass, requires waste reprocessing, which is problematic because it involves the risk of contamination, and terrorist diversion of quantities of highly radioactive material.

No one will want the world's wastes buried near them. This means the best sites, which are probably in the desert regions of the US and Australia, are unlikely to be used. Desperately poor Third World countries will undertake to have them buried on their soil as a source of income. The rich countries generating the wastes will leave the monitoring and safety concern to impoverished Third World governments, who will skimp on design, safeguards, monitoring, etc. The rich countries will argue that these issues are the responsibility of the host governments, just as they say the poor conditions in the plantations that supply the supermarkets in rich countries are not their responsibility. As the best available sites are used up they will move to less suitable sites.

In an era of deregulation, privatisation and reliance on market forces, there will be a strong tendency to minimise state monitoring and control, accountability and public disclosure, freedom of information etc. States are increasingly prepared to do what suits corporations. The agencies dealing with the wastes will be private corporations whose interest will be to minimise costs, and therefore safeguards, and to conceal information and problems. Their sole interest will be profit maximisation, as distinct from the welfare of the public, the ecosystems of the planet, or future generations. The dominant neo-liberal ideology will ensure that governments will tend to allow the corporations to do what they want, insisting on the need to avoid interfering with market forces.

All the waste the nuclear industry has created over several decades is in temporary storage and is yet to be dealt with permanently. This will take a lot of energy which will reduce the overall energy return of nuclear energy. So will the energy needed to decommission existing reactors.

9.7. NUCLEAR ENERGY PROVIDES ONLY ELECTRICITY

Nuclear energy produces only electricity, plus waste heat which sometimes can be used. Only about 20% of rich-world energy use is electricity. Nuclear energy therefore cannot meet most of our energy demand anyway, except via hydrogen, which as Chapter 6 explained would multiply the number of reactors needed for any task by a factor of 3 or 4, given the inefficiency of hydrogen production.

9.8. THE INTER-GENERATIONAL MORAL PROBLEM

Nuclear energy sets a huge moral problem in that people living in the next few hundred years at most would get all the benefit from nuclear energy while leaving the risk and costs to be borne by thousands of coming generations, and by all the other species on the planet, who would get none of the energy. (Nuclear advocates say that future generations would benefit from the "development" that nuclear era made possible.)

9.9. THE ENVIRONMENT?

Access to vast quantities of energy would actually be a death-knell for the ecosystems of the planet. It would increase capacity to deal with environmental problems, but at nothing like the rate of increase in global resource extraction, production and waste generation that would be associated with raising all people to rich-world affluence, and then insisting on limitless economic growth.

9.10. THE TOTAL ACCUMULATED LONG TERM HEALTH, GENETIC AND MORTALITY EFFECTS?

Whether or not nuclear energy is worth the cost cannot be judged until we have some reasonably confident estimate of what the total biological effects are likely to be. Nuclear energy releases radioactivity into the environment, even if there are no accidents. In routine operation the quantities from one reactor are small. More worrying is the release from mine tailings which are too "costly" to deal with properly (Fleming, 2006. p.1).

We have almost no idea what the effects will add up to. Some of the elements involved can circulate through ecosystems and bodies for hundreds of thousands of years and still be radioactive. A very low rate of damage over a very long time could accumulate a very high toll. It is generally agreed that we should not assume any threshold for effects, i.e., we do not know that exposure to radioactivity below a certain level will cause no damage. Monson (2004) repeats the commonly stated conclusion, "The scientific research base shows that there is no threshold of exposure below which low levels of ionizing radiation can be demonstrated to be harmless or beneficial."

This means we should proceed as if any exposure to radioactivity is likely to have some health effect and therefore we should think about the possible total effect in a population of perhaps 9 billion accumulated over many thousands of years into the future. For example if a very small release rate caused only one death per year in a million people exposed to a typical dose, in a population of 9 billion exposed over 1000 years the toll would be 9 million deaths.

Coal-fired power stations have serious health effects and the nuclear advocates rightly say these must not be overlooked when comparing coal with nuclear energy. However as, has been explained, the effects of generating one kWh from coal would cease within say a generation of the power station ceasing to operate, but the effects of radiation from nuclear reactors could continue to be felt and to accumulate for hundreds of thousands of years. (Coal-fired stations also release some radioactivity, from within the coal, but not much.)

The effects we are concerned with here include illness, genetic damage and the birth of disabled beings, and death, among humans, animals and plants. So what we would need to know is, what total health, genetic and mortality effects might accumulate over all future time, from the generation of one kWh of electricity? We have no idea what this total is likely to be and until we do it is grossly irresponsible to impose that toll on others and to assume that it is "worth the benefit", all of which we will get here and now.

9.11. BREEDER REACTORS

The scarcity of Uranium means a nuclear era would have to be based on breeder reactors, (or fusion reactors, below). Breeder reactors are more complex and dangerous than the reactors in use today, involving the reprocessing of fuel and the extraction of Plutonium. The history of experiments with them has been problem-ridden and they are not being developed enthusiastically. The option seems to be far too problematic for us to embrace on the scale that a nuclear era would involve. Vast amounts of very dangerous material would have to be shipped around all the time. Just consider the scope for penetration of shipment systems by organised crime and the diversion of material into the construction of "dirty" terrorist bombs. A Plutonium bomb can be made from about 10 kg of the material. Each of the reactors in use today produces about 200 kg of it every year.

Reprocessing of reactor fuel involves several problems about which we would have to be reassured, in addition to waste storage and reactor safety. Present reprocessing plants such as Sellafield have been plagued with problems, leaving many worries about contamination of local land and seas and health effects. A breeder era would involve reprocessing of enormous quantities of spent fuel from thousands of reactors.

In any case it is not clear whether the rate at which Plutonium is "bred" in the material around the core can become fast enough to start up many breeders in coming decades (Leeuwen and Smith, 2003, p. 23).

9.12. WHAT ABOUT FUSION REACTORS?

Despite decades of costly research, Leeuwin and Smith argue that in recent years doubts have emerged as to whether controlled fusion power will be achieved. If the reaction can be sustained, reactors will certainly be very complex and costly and will be unlikely to yield cheap energy for all. Leeuwen and Smith (2003, p. 24) say that the process whereby sea water might be used as a source of Deuterium fuel is now understood to be incapable of producing net energy.

9.13. HUMANS PRESS THE BUTTONS

Finally, no reactor or system design, or fail-safe provisions, can protect against the fundamental flaw that cannot be removed from nuclear energy, i.e., the fact that humans operate the plants and are always capable of making mistakes, including overriding the fail-safe mechanisms or not following set procedure. This is what happened at Chernobyl. Claims about the fail-safe nature of Fourth Generation reactors make no difference to this point. In a coal-fired plant, human errors might not matter that much, but with nuclear energy, one mistake could be globally catastrophic.

CHAPTER 10

THE WIDER CONTEXT: OUR SUSTAINABILITY AND JUSTICE PREDICAMENT

It is now necessary to widen the context of this discussion. Energy is only one of several gigantic problems that consumer–capitalist society is rapidly running into. For some forty years a large "limits to growth" literature has been accumulating, documenting the grossly unsustainable and unjust nature of this society.

The core "limits to growth" claim is that the huge global problems we are facing cannot be solved in a society that is driven by obsession with high rates of production and consumption, affluent living standards, market forces, the profit motive and economic growth. The resource demand generated by this society is the direct cause of ecological destruction, Third World poverty, resource depletion, conflict and social breakdown. These problems cannot be solved unless we move to simpler lifestyles, more self-sufficient and cooperative ways, and a very different economy. Chapter 11 will detail what many see as "The Simpler Way."

Again energy depletion is only one of the alarming problems we are running into, and our limits to growth predicament would still exist even if renewable energy sources could provide all the energy we need. Indeed the more energy we get our hands on, the more enthusiastically we will dig up minerals, log forests, mine the sea floors, dam rivers, develop cities, clear land, travel, and buy.

There are two major faults built into our society causing the main problems facing the planet. The first is the obsession with affluent living standards and economic growth, i.e., the insistence on high and ever-increasing levels of production and consumption. The second fault is allowing competition within the market to be the major determinant of what is done in our society.

10.1. FAULT 1: WE ARE FAR BEYOND SUSTAINABLE LIMITS TO PRODUCTION AND CONSUMPTION

Following are some of the most forceful limits-to-growth arguments.

- Rich countries, with about one-fifth of the world's people, are consuming about three-quarters of the world's resource production. Our per capita consumption of assets like oil is about 15 to 20 times that of the poorest half of the world's people. World population will probably stabilise around 9 billion, somewhere after 2060. If all those people were to have the present Australian per capita resource consumption, then annual world production of resources would have to be eight to ten times as great as it is now. If we tried to raise present world production to that level by 2060, we would by then have completely exhausted all probably recoverable resources of one third of the basic mineral items we use. All probably recoverable resources of coal, oil, gas, tar sand oil, shale oil, and uranium (via burner reactors) would have been exhausted by 2050 (Trainer, 1985, Chapters 4 and 5).

- Petroleum appears to be especially limited. As was noted at the start of Chapter 1, a number of geologists have concluded that world oil supply will probably peak by 2010 and be down to half that level by 2025–30, with big price increases soon after the peak. None of the limits-to-growth themes is as potentially terminal in the short term for consumer society.
- If all 9 billion people were to use timber at the rich-world per capita rate, we would need 3.5 times the world's present forest area. If all 9 billion were to have a rich-world diet, which takes about 0.5 ha of land to produce, we would need 4.5 billion ha of food-producing land. But there is only 1.4 billion ha of cropland in use today, and this is not likely to increase.
- Recent "Footprint" analysis (Wachernagel and Rees, 1996) estimates that it probably takes 7+ ha of productive land to provide water, energy settlement area and food for one person living in Australia. The US figure is close to 12 ha. So if 9 billion people were to live as we do in rich countries, we would need about 70 billion ha of productive land. But *that is about 10 times all the available productive land on the planet*.
- As was explained in Chapter 1, the Inter-Governmental Panel on Climate Change estimates that if the carbon dioxide content of the atmosphere is to be kept to sensible levels, and carbon use was shared equally among the world's people, then rich-world per capita carbon release would probably have to be reduced to somewhere under 5% of the present amount.

These are some of the main limits to growth arguments which lead to the conclusion that *there is no possibility of all people rising to anywhere near the living standards we take for granted today in rich countries*. We can only live the way we do because we are taking and rapidly using up most of the scarce resources, and preventing most of the world's people from having anything like a fair share. Therefore we cannot morally endorse our affluent way of life. We must accept the need to move to far less resource-expensive ways. Few people seem to grasp the magnitude of the required reductions.

10.1.1 Population

It follows from the foregoing discussion that the world is over-populated. However the most serious problem we have is not over-population. It is over-consumption.

10.1.2 The Environment Problem

The reason why we have an environment problem is simply because *there is far too much producing and consuming going on*. (For a detailed argument see Trainer, 1998.)

Our way of life involves the consumption of huge amounts of materials. More than 20 tonnes of new resources are used by each American every year. To produce one tonne of materials can involve processing 15 tonnes of water, earth or air. (For gold the multiple is 350,000 to 1.) All this must be taken from nature and most of it is immediately dumped back as waste and pollution.

One of the most serious environmental problems is the extinction of plant and animal species. This is due to the destruction of habitats. Remember our footprint; if all 9 billion people soon to live on earth were to have rich-world "living standards", humans would have to use about ten times all the productive land on the planet. Clearly our resource-intensive lifestyles, which require so much land and so many resources, are the basic cause of the loss of habitats and the extinction of species.

Most green and sustainability rhetoric totally fails to grasp the significance of this magnitude, proceeding as if it is possible to make manufacturing and lifestyles and the economy sustainable without any need to reduce the volume of production and consumption, "living standards", or the GDP. It ignores the glaring fact that perhaps 90% cuts in resource use are required and these cannot possibly be made without phasing out most industrial activity, trade, travel and commerce . . . without, in other words, extreme and historically unprecedented social change.

10.1.3 Third World 'Development'

If the basic limits analysis is valid, then conventional development for the Third World is totally impossible. There are nowhere near enough resources for 9 billion people to rise to current rich-world "living standards", let alone to the resource consumption rates that growth will generate. Yet the vast development literature takes it for granted that the goal of development is to achieve rich-world ways.[1]

10.1.4 Armed Conflict

If all nations go on trying to increase their wealth, production, consumption and "living standards" without limit in a world of limited resources, then we must expect increasing armed conflict. Rich-world affluent lifestyles require us to be heavily armed and aggressive, in order to guard the empire from which we draw more than our fair share of resources. Many people within the Peace Movement fail to grasp that there is no possibility of a peaceful world while a few are taking far more than their fair share and the rest aspire to live as the rich few do. If we want to remain affluent we should remain heavily armed, so we can prevent others from taking "our" oil fields etc. (For a detailed argument see Trainer, 2002.)

10.1.5 Now Add the Absurdly Impossible Implications of Economic Growth

The foregoing argument has been that *the present* levels of production and consumption are grossly unsustainable. They are far too high to be kept going for long or to be extended to all people. Yet we are determined to *increase* present living standards and levels of output and consumption, as much as possible and without any end in sight. Our supreme national goal is economic growth. It is not just that people want more and more income, wealth, property and possessions, without any amount in view with which they will be satisfied. The core problem is that we have an economic system which needs and cannot function without constant growth in production and consumption.

For instance as technology advances fewer workers are needed, so unless consumption rises all the time the unemployment problem increases. More importantly, new money comes into existence as debt which is created when banks make loans, and this has to be repaid with interest. This absurd process cannot continue unless there is constant growth in production and earnings to enable repayment of the ever-increasing debt. Above all, capital is constantly accumulating in the hands of corporations and banks, which are then determined to find or create more opportunities for investing it.

Few people seem to recognise the absurdly impossible consequences of unlimited economic growth. If we have a 3% p.a. increase in output, by 2070 our economy will be producing eight times as much every year. (For 4% growth the multiple is 16.) If by then all the expected 9 billion people have risen to the living standards we in rich countries would have then given 3% p.a. growth, the total world economic output will be *more than 60 times* as great as it is today! Yet the *present* level is unsustainable.

10.1.6 Growth in Energy Demand

It is of the utmost importance to recognise that whether or not renewable energy can sustain consumer-capitalist society is not a matter of whether it can meet present energy demand. The essential question is whether it can enable constant increase in the volume of goods and services being consumed and the associated increase in energy demand.

Energy demand is rising significantly, although estimates of future demand vary. ABARE's *Energy Outlook 2000* shows that the average annual rate of growth in energy use in Australia over the decade of the 1990s was around 2.5% p. a. The *Australian Yearbook* shows that between 1982 and 1998 Australian energy use increased 50%, an arithmetical average growth rate of 3.13% p.a., and the rate has been faster in more recent years. (Graph 5.12.) However ABARE estimates that Australian energy demand will slow, reaching about 1.9% p.a. by 2040, meaning more than a doubling in annual use by then.

In July 2003 Australian electricity authorities warned that blackouts are likely in coming years due to the rapid rate of increase in demand, estimated at almost 3% pa for the next five years. (ABC News, 31 July.) Robbins (2003) reports NEMMCO predicting electricity growth over the next 10 years in NSW, Queensland and Victoria as 3.1%, 3.5% and 2.6% p.a. respectively. Poldy (2005) shows that over the past 100 years Australian energy consumption has followed GDP growth closely, and he estimates that in recent years it has approximated a growth rate of 3.6% p.a. In 2004 world energy use jumped, growing at 4.3% p.a. (Catan, 2005.)

Thus the commitment to growth greatly exacerbates the problem, and in turn all of the other resource supply problems, because all involve an energy component. For instance if the cost of fuel increases significantly, then so will the cost of food and minerals, and even university courses, because fuel is needed to produce them. It has been argued above that renewables are not likely to be capable of meeting present electricity and liquid fuel demand, but given the inertia built into growth trends, the demand to be met will probably be three or four times as big as it is now by mid century . . . and doubling every approximately 35 years thereafter.

To summarise regarding Fault 1, consumer-capitalist society is obviously grossly unsustainable. We have far overshot levels of production, consumption, resource use and affluence that are sustainable for ourselves over a long period of time, let alone extended to all the world's people. Yet our top priority is to increase them continuously, without limit. This is the basic cause of the many alarming sustainability problems now threatening our survival.

10.2. FAULT 2: THE MARKET SYSTEM IS INHERENTLY UNJUST

Markets do some things well and in a satisfactory and sustainable society there might be a considerable role for them, but only if carefully controlled. It is easily shown that the market system is responsible for most of the deprivation and suffering in the world. The basic mechanisms are most clearly seen when we consider what is happening in the Third World. (For detail see the web addresses in Note 2.) In general the enormous amount of poverty and suffering in the Third World is not due to lack of resources. There is for instance sufficient food and land to provide for all. The problem is that these resources are not distributed at all well. Why not? The answer is that this is the way the market economy inevitably works.

The global economy is a market system and *in a market scarce things always go mostly to the rich*, e.g. to those who can bid most for them. That's why we in rich countries get most of the oil produced. It is also why more than 500 million tonnes of grain are fed to animals in rich countries every year, around one-third of total world grain production, while 1.2 billion people are malnourished and 830 million chronically hungry.

Even more important is the fact that the market system inevitably brings about *inappropriate* development in the Third World, i.e., development of the wrong industries. It will lead to the development of the most profitable industries, as distinct from those that are most necessary or appropriate. As a result there has been much development of plantations and factories in the Third World that will produce things for local rich people or for export to rich countries. Their cities have freeways and international airports. But there is little or no development of the industries that are most needed by the poorest 80% of their people. In a market economy the Third World's productive capacity, its land and labour, are automatically drawn into producing for the benefit of others. This is most disturbing regarding export crops. In many poor and hungry countries most of the best land is used to grow crops to export to rich world supermarkets, while the plantation workers are among the world's most deprived people.

These are inevitable consequences of an economic system that produces whatever is most profitable to the few who control capital, as distinct from what is most needed by people or their ecosystems. The Third World problem will never be solved as long as we allow these economic principles to determine development and to deliver most of the world's wealth to the rich.

Conventional economics basically defines development as economic growth. Thus what is developed is little more than whatever promises to maximise the profits of those who have capital to invest, i.e., transnational corporations and banks. These institutions *never* invest in the production of the things most needed in the Third World, such as cheap basic food, clean water and housing for the poorest. Their investment puts Third World land and labour into supplying rich-world supermarkets. The large amount of productive capacity a poor country has is therefore devoted to enriching others, or left idle.

In other words development has been highly inappropriate. Obviously it would be far better for people in Bangladesh who are paid 15c an hour to make shirts for export if they could put that time and energy into local farms and firms to produce basic necessities for themselves.

Our rich-world affluence and comfort are built on massive global injustice. Look at the labels on the goods we buy. How much would we pay if the workers who produced them received a satisfactory wage? What would we pay for coffee if most of the land producing it was transferred to growing food for hungry people? Few people in rich countries seem to understand that they could not have their high "living standards" if the global economy was not enabling them to take far more than their fair share of world wealth and to deprive Third World people. We can go to supermarkets to buy the coffee from land that should have been producing food for Third World people. One billion people live in appalling conditions primarily because we are taking their wealth and gearing their land and labour to supplying our supermarkets. (This is not the only causal factor of course.) For these reasons, conventional Third World development has to be seen as a form of legitimised plunder. (Goldsmith, 1997, Chossudovsky, 1997, Rist, 1997, Schwarz and Schwarz, 1998.)

These processes and effects are not accidental or unwitting. They are the outcome of conscious, deliberate policy. We must recognise that the rich countries have and control an empire. The global economy functions as an empire which the rich countries run mostly for their own benefit, resorting to the use of power and repression when necessary to keep Third World countries to the sorts of policies the rich want.

Consider firstly the brazen hypocrisy of the rich countries. They insist that Third World countries should eliminate subsidies to exporters, yet the rich countries pay hundreds of billions of dollars in subsidies to rich world agricultural exporters every year. Rich countries insist on freedom for capital to go where it wishes to invest in the Third World, but there is no question of labour from the Third World being free to work wherever it likes in the rich countries. They inflict draconian conditions on indebted poor countries but there is no question of these being applied to the most highly indebted of all countries, the USA.

Then there are the "Structural Adjustment Packages" which force Third World governments to give transnational corporations maximum freedom to take over their economies.[2]

Ultimately there is the support of dictatorial and brutal regimes. The rich countries assist client states in the violent repression of those people who object to the economic injustice enriching us. They enable and engage in terrorism, they invade and attack and kill thousands of innocent people, in order to ensure that regimes and regions keep to the sorts of policies that suit the rich countries. This intervention used to be described as countering "communist subversion" but is now more likely to be masked as "humanitarian intervention" and as countering terrorism.[3]

Thus reflecting on the Third World problem makes clear how grossly unsatisfactory and unjust the world market system is. It allows investment, jobs and incomes to flow to where the most profit can be made, ignores the rest, and allocates the Third World's scarce resources to the rich few. It deprives the majority of a fair share. It draws the productive capacity the poor once had into producing for the rich, it uses up Third World resources at negligible benefit to Third World people, and it devastates the ecosystems of the planet, which cannot bid in the market.

Conventional development economists point to regions of the Third World where rapid growth is taking place, such as in China and India, implying that this shows how the consumer-capitalist path can work. Of course in a competitive global economy some regions will be among the winners, beating the rest because they can bid the lowest labour and other costs. But ask the two billion in Africa and the fifty smallest and most impoverished nations how globalisation is working for them. Above all what is the future for the Chinese and Indian resource-ravenous approach to development in view of the coming age of savage scarcity. And what future does all this promise for global peace and security?

The crucial conceptual mistake underlying conventional development theory and practice is the never-questioned assumption that development cannot take place unless capital is invested. The corollaries are, one must sell and trade to earn the money with which to purchase, development must be of whatever will maximise returns to capital, one must plunge into the global economy and trade whatever one can at whatever price one is offered, extreme inequality is inevitable, and satisfactory development takes generations. The Simpler Way vision outlined in the next chapter flatly contradicts these assumptions. If people have control over their own land, labour and local resources, they can achieve satisfactory, appropriate development quickly and easily. (See Note 1.)

There is no possibility of satisfactory Third World development until the rich countries stop hogging far more than their fair share of the world's resources, until development and distribution begin to be determined by need and not by market forces and the profit motive which automatically allocate them to the rich, and until Third World people can devote their local resources to meeting their own needs. Thus there is no possibility of satisfactory development until we create a very different global economic system. There is in other words no possibility of solving this problem without transition to The Simpler Way.

10.2.1 Globalisation

We have entered a period in which all these problems are rapidly accelerating, because of the globalisation of the economy. In the 1970s the world economic system ran into difficulties after a remarkable period of boom. It became much more difficult for corporations and banks to invest their constantly accumulating volumes of capital profitably. As a result the big corporations and banks have now pushed through a massive restructuring of the global economy, the development of a more unified and de-regulated system in which they are sweeping away the controls that previously hindered their access to increased business opportunities, markets, resources and cheap labour.

The supreme, sacred principle now is to "free market forces". Consequently the pressure is on governments to remove the protection, tariffs and controls which they once used to manage, regulate, stimulate and protect their economies and to guide development. These changes are enabling the transnational corporations to come in and take more of the businesses, resources and markets local people once had, and to gear "development" to whatever suits them rather than to what is needed by most people.

The now heavily documented consequences are devastating the lives of millions of people, especially in the Third World. Globalisation is eliminating the arrangements which used to ensure that many little people could sell and work and trade, and that local resources such as land would produce things they need. Now the corporations are able to take over those opportunities to increase their sales. Thus globalisation has involved a gigantic takeover of economic wealth by the big corporations and banks.[4]

Corporations are able to minimise their tax payments, especially through the "transfer payments" they put on shipments between their subsidiaries. Governments must lower taxes on corporations, i.e., make their tax regimes "more competitive", or the corporations will locate their plants in some other country. (In one recent year half the transnational corporations with branches in Australia paid no tax at all.) Therefore governments are under pressure to cut their expenditures on welfare, education and health and shift tax burdens from corporations to workers.

Globalisation constitutes a crushing triumph for the corporations, the banks and the rich. Inequality is rapidly worsening. A few are becoming much richer, the poor in most regions are stagnating at best and even the middle classes of the rich countries are being hollowed out. It has been a sudden and stunningly arrogant grab that has delivered greatly increased wealth to the corporations and banks and the few high-skilled professionals and technocrats the corporations need. The prospect is quite alarming; we are rapidly heading towards a world run by tiny super-rich elites doing only whatever suits themselves and their shareholders while rapidly destroying social cohesion and the ecosystems of the planet.

Why do governments willingly go along with these "neo-liberal" policies? The answer is, basically because the global economic system gives them no choice. Even if a government did not believe the neo-liberal world view, it would have to go along with it if its country was to survive in a globalised world. In the competitive global economy we have now, governments must seek to cut production costs, free corporations to do more business, make national exports cheaper and more competitive, and attract more foreign investment. If a government does not do these things, its economy will not survive in the increasingly open and competitive global economy. The country will not attract foreign investment, its credit rating will be dropped so the increased interest companies would have to pay to borrow capital to invest there will rise, and its exports will not be able to compete in the global market.

Some aspects of globalisation, such as the internet, would seem to be unquestionably desirable, but a) the globalisation of the present economy inevitably accelerates global injustice and b) the limits to growth analysis show that a sustainable world cannot be economically globalised. There will not be anywhere near sufficient energy and resources for all that transport, travel and trade. A sustainable world must be mostly made up of small and localised economies, with relatively little long distance trade.

10.3. CONCLUSIONS ON OUR SITUATION

It should be obvious from the foregoing discussion that the present socio-economic system is extremely unsatisfactory and cannot solve our problems. It has many valuable elements of course but some of its core principles are profoundly and irredeemably flawed. There is no possibility of having a just, morally satisfactory and ecologically sustainable society if we allow it to be driven by market forces, the profit motive and the quest for higher "living standards" and economic growth. In a satisfactory economy the needs of people, society and the environment would determine what is done, not profit. (This does not mean "big-state" socialism, nor that a satisfactory society could not have markets and private enterprise; see Chapter 11.)

Above all it must be stressed how far beyond sustainable levels of production and consumption we are. The foregoing figures show that we must develop ways of living in which we can have a good quality of life on per capita resource rates that are a small fraction of today's rates.

Overall, consumer society shows a stunning inability to respond to the alarming challenges now facing it. Most people seem to be totally unaware of and indifferent to the fact that their high "living standards" are delivered by a massively unjust global economy which so severely deprives the majority that tens of thousands of people die prematurely every day, and to the fact that their "living standards" are grossly unsustainable. The fact that their supreme values remain raising “living standards” and the GDP testifies to the overwhelming failure, refusal, to recognise the fundamental problem. Indeed among governments, academics, the media, educational institutions and the general public there is an almost universal and impenetrable mentality of delusion and denial.

Again, the energy problem is only one element of the bigger picture of our alarming global situation. When the nature of the general sustainability and justice predicament is grasped it is obvious that we cannot hope to solve global problems unless we face up to the need to develop ways of living well on far lower rates of resource consumption. This cannot be done without extreme and radical change from the core principles of consumer-capitalist society. Yet it could be done, and done easily and quickly . . . if enough of us wanted to do it. Chapter 11 details the vision and indicates the role of renewable energy sources within it.

CHAPTER 11

THE SIMPLER WAY

If the foregoing arguments are basically valid, then we have to face up to huge and radical change in some of the fundamental ways, ideas and values of consumer-capitalist society. Whether change of this magnitude is likely is not central here; the question is, given our situation what must be the core principles for a sustainable society? The argument in Chapters 10 and 11 is that these principles are clear and indisputable. It will be claimed in this chapter that an extremely low footprint and energy use can be achieved, but only if there are vast changes in lifestyles, economies, political systems, settlement geographies and values. It is important therefore that these new ways be detailed first, otherwise the energy claims will not make much sense.

Many people who have examined the global predicament are more or less saying that we cannot hope to solve the big global problems unless we embrace the following basic principles.

- *Material living standards must be far less affluent*. In a sustainable and just world, per capita rates of resource use must be a small fraction of those in Australia today.
- *A very different economic system must be developed*, one which is geared to the needs of people and ecosystems and is therefore not driven by market forces or the profit motive (although it might have a place for them). It must be an economy operating with the minimal levels of production and consumption necessary for a high quality of life, with a much lower GDP than the present economy, and without any growth.
- *There must be mostly small scale highly self-sufficient local economies*.
- *There must be mostly cooperative and participatory local systems* whereby people in small communities control their own affairs, largely independent of the state and of the much-diminished national and global economies.
- *We must shift to some very different values, especially away from competition, individualism and acquisitiveness and towards frugality, self-sufficiency, cooperation, participation and non-material satisfactions*.

The alternative way is well described as The Simpler (but richer) Way. We can all live well on a much reduced volume of production, consumption, work, resource use, trade, investment and GDP than we do now. Unfortunately any suggestion of a move to less affluent ways is usually met with horror, or completely ignored. The main problem here is that people do not understand that The Simpler Way is not a threat to a high quality of life or to the benefits of modern technology. The following discussion will show that in fact The Simpler Way is the key to a greatly improved quality of life, even for those who live in the richest countries. It will allow us to escape the economic treadmill and the looming catastrophes, and to devote our lives to more important and more satisfying pursuits than producing and consuming.

The Simpler Way could be easily and quickly achieved — if enough of us opted for it. It thrives on materially simple technologies. To save the planet we do not need miraculous technical breakthroughs, or vast amounts of capital. Essentially we need a radical change in our thinking and behaviour.

Following is a brief sketch of the changes many now recognise we must make in our attitudes and day-to-day activities. Only after this has been established will it make sense to assess the implications of radically reduced energy needs and the way renewables could satisfy them.

11.1. MY CREDENTIALS

But first it is important for the reader to know that the following vision is not a theoretical proposal made without much practical understanding of The Simpler Way. The vision in this chapter is based on a lifetime's experience of living as a fairly self-sufficient and frugal homesteader, in so far as this has been possible within consumer society. In addition, it reflects many years of association with the Global Eco-village Movement in which hundreds of small groups are now striving to live more or less according to the principles of The Simpler Way, many of them in a deliberate effort to demonstrate the kinds of social practices that must be adopted if global problems are to be resolved.

From these sources I am willing to claim that I *know* that the ways outlined below are workable, easily practised, and rewarding. I know from my own experience and from observation of intentional communities that we have all the alternative ways we need to provide a very high quality of life. I know that we do not need elaborate technologies to solve our problems. I know that ordinary people and local handymen can make and maintain small windmills, waterwheels, solar passive heating, 12 volt electricity systems, methane digesters, reed bed water recycling systems, water tanks and supply systems, and greenhouses. I know that one can build a perfectly adequate, resource-cheap, beautiful house out of earth and with hand tools for a negligible dollar cost, that perfect and abundant food can be grown without chemical fertilizers, pesticides or tractors, that you can keep a jumper going for 35 years and hand tools for at least 60, that you can easily make good furniture and pumps and pottery and baskets and windmills without factories, and that you can easily develop settlements in which people don't need cars, and that you can live with great riches on a below poverty line income. I know that large amounts of income, wealth and possessions are unnecessary and unimportant. And I know that living frugally and self-sufficiently can be immensely satisfying. What's more, I know that we could easily and rapidly transform our existing suburbs and towns into the technically simple forms that are necessary, with little capital, professional expertise or government involvement — if enough of us saw this as necessary and desirable.

However several of the themes discussed below go well beyond my own experience to suggest arrangements and systems that seem to be necessary, but precisely how it will be best to organise in these areas will need to be explored in a trial and error way.

11.2. SIMPLER LIFESTYLES

Given that the essential factor in our global predicament is over-consumption, the most obvious principle for a sustainable society is that we must move to far more materially simple lifestyles. This does not mean deprivation or hardship. It means focusing on what is *sufficient* for comfort, hygiene, aesthetics and efficiency. Most of our basic needs can be met by quite simple and resource-cheap devices and ways, compared with those taken for granted and idolised in present society.

Living in ways that minimise resource use should not be seen as an irksome sacrifice that must be endured in order to save the planet. These ways must become regarded as important sources of life satisfaction. We have to come to see as enjoyable living frugally, recycling, growing food, "husbanding" resources, making rather than buying, composting, repairing, bottling fruit, giving surpluses and old things to others, making things last, and running a relatively self-sufficient household economy. The Buddhist goal is a life "simple in means but rich in ends."

11.3. LOCAL SELF-SUFFICIENCY

We must develop as much self-sufficiency as we reasonably can at the national level, meaning far less trade, and at the household level, but most importantly at the neighbourhood, suburban, town and local regional level. Obviously in a world of severely limited energy resources the distances over which resources, goods and workers travel must be minimised, and this means we must develop mostly small scale *local* economies. We need to convert our presently barren suburbs and dying country towns into thriving economies which produce most of what they need from local resources and local labour.

The domestic or household economy already accounts for about half the real national output, although this is ignored by conventional economics which only counts dollar costs. Households can again become significant producers of vegetables, fruit, poultry, preserves, fish (from tanks and ponds), repairs, furniture, clothing, education, health care, entertainment and leisure services, and community support.

Neighbourhoods would contain many small enterprises such as the local bakery. Some of these could be decentralised branches of existing firms, enabling most of us to get to work by bicycle or on foot. Much of our honey, eggs, crockery, vegetables, herbs, furniture, fruit, nuts and meat (e.g., rabbits, fish and poultry) production could come from households, backyard businesses and small firms. Much output could come from craft and hobby production. It is much more satisfying to produce most things in craft ways than in industrial factories, but it would make sense to retain some larger mass production factories and sources of materials, such as mines, steel works and railways.

Almost all food could come from within a few hundred metres of where we live, most of it from within existing towns and suburbs. The sources would be, a) intensive home gardens, b) community gardens and cooperatives, such as poultry, orchard and fish groups, c) many small market gardens and farms located within and close to suburbs and towns, d) extensive development of commons, especially for production of "free" community fruit, nuts, fish, poultry, animal grazing, herbs, clay, bamboo and timber.

The scope for food self-sufficiency within households is extremely high. It takes 0.5 ha, 5,000 square metres, to feed one North American via agribusiness with a very high cost in fossil fuels and soil erosion. However Blazey (1999, p. 18) documents the capacity for a family of three to feed itself from less than one backyard, with almost no cost in energy, fertilizer or pesticides, via intensive home gardening, high yield seeds, multi-cropping, nutrient recycling, and mostly consumption of plant foods. Jeavons (2002) gives a similar account. In a localised agriculture all wastes can be returned to the soil. This along with use of nitrogen fixing and deep rooted plants can eliminate the need for importation of fertilizers. Blazey's figures derive from actual trials at the Diggers Seeds' site in Heronswood, Victoria. His approach yields 500 kg of vegetable food p.a. from a 42 square metre plot, a rate of food production that is almost 1000 times as great as for standard beef production.

Most of our neighbourhood could become a Permaculture jungle, an "edible landscape" crammed with long-lived, largely self-maintaining productive plants. Much food production would involve little or no fuel use, ploughing, packaging, storage, pesticides, freezing, marketing, insurance, transport or waste disposal. Having food produced close to where people live would enable nutrients to be recycled back to the soil through animal pens, ponds, compost heaps, composting toilets and garbage gas units.

There would be research into finding what useful plants from all around the world thrive in our local conditions, and into the development of foods, materials and chemicals from these. Synthetics would be derived primarily from plant materials.

Meat consumption would be greatly reduced as we moved to more plant foods, but many small animals such as poultry, rabbits and fish would be kept in small pens spread throughout our settlements. The animals could be fed largely on kitchen and garden scraps, and by free ranging on commons, while providing manure and adding to the aesthetic and leisure resources of our settlements. Some wool, milk and leather could come from sheep and goats grazing meadows within our settlements. There would be small-scale dairies, grain and timber producing areas close by.

The commons would be of great economic and social value. These include the community owned and operated woodlots, bamboo patches, herb gardens, orchards, ponds, meadows, sheds, halls, theatres, tools, machinery, tractors, workshops, libraries, leisure centres, windmills, water wheels, bicycles and vehicles. The common lands can be located in parks, beside railway lines, on old factory sites, and especially on the many roads that will be dug up when they are no longer needed. These commons would provide many free goods and would be maintained by voluntary working bees and committees. Because there will be far less need for transport we could greatly increase the land area available in cities for community facilities by digging up many roads and parking lots.

We should convert one house on each block into a neighbourhood centre, including a workshop, recycling store, meeting place, arts and crafts rooms, surplus exchange and library.

Settlement design will focus on these basically Permaculture principles, such as the intensive use of space, complex, self-maintaining ecosystems, nutrient recycling, local water harvesting, stacking and use of all available niches, multiple cropping and overlapping functions e.g., poultry provide meat, eggs, feathers, pest control, cultivation, fertilizer and leisure resources. These techniques will enable huge reductions in the present land area and energy costs of food provision and of many materials and services.

It will not be necessary for many people to be involved in agriculture. Providing food now takes perhaps one-fifth of work time, when transport, packaging, marketing and retailing are added to the farm work. That's about eight hours a week per worker. Intensive home gardening requires about four person-hours per week per household (Blazey, 1999). Averaged across the town and including small farm work, food production would probably require well below the present amount of "work" time. The difference derives from the far greater productivity of home and small farm production, and the elimination of much intermediary work, such as transport, tractor and fertilizer production, marketing and packaging.

Many materials can come from within these settlements and close by, including leather, oils, dyes, timber, chemicals, medicines, earth and clay, reeds and rushes for baskets, bamboo and energy crops. Some of these would be input crops for local firms but many would be freely available from commons for craft production.

One of the most important ways in which we would be highly self-sufficient would be in finance. Firstly The Simpler Way requires little capital. It will not be an expanding economy and most enterprises will be very small. Virtually all neighbourhoods have all the capital they need to develop those premises, stores, energy sources etc. that would meet their basic needs. This does not happen when our savings are put into conventional banks. Our capital is borrowed by distant corporations, often for undesirable purposes, and it is therefore not used to improve our neighbourhoods.

We would form town banks from which our savings would only be lent to firms and projects that would improve our town. These banks could charge "negative" interest, or make grants for socially desirable ventures. We will couple the banks with "business incubators" which provide assistance to small firms, such as access to accountants, computers and advice from panels of the town's most experienced business people. Having the bank and the incubator will give us the power to establish in our town the enterprises and industries it needs, as distinct from being at the whim of distant corporations and foreign investors who will only set up in our town if that will maximize their global profits. In any case they will not set up firms to produce what we need. We can therefore take control of our own development and make sure that it is determined by what will benefit the town, cut its imports, minimize ecological impacts, eliminate waste and provide livelihoods.

These many and diverse structures, firms and activities will make our locality into a leisure-rich environment. Most suburbs at present are leisure-deserts. The alternative neighbourhood would be full of familiar people, small businesses, industries, farms, lakes, common projects, artists, ornaments, animals, gardens, forests, windmills and waterwheels, and therefore full of interesting things to do, observe or participate in. Consequently people would be far less inclined to travel on weekends and holidays, and this in turn would greatly reduce per capita energy consumption. This shows how the solution to many problems will mostly involve carrots rather than sticks. For instance we will reduce travel not by penalties but by eliminating the need for most of it, by ensuring that work and leisure sites are close to where we live.

This high level of domestic and local economic self-sufficiency will cut travel, transport and packaging costs, and the need to build freeways, ships and airports etc. It will also enable our communities to become secure from devastation by distant economic forces, such as depressions, interest rate rises, trade wars, capital flight, and exchange rate changes and devaluations.

Local self-sufficiency means we will be highly dependent on our region and our community, and the significance of this for several important themes cannot be exaggerated. Because most of our food, energy, materials, leisure activity, artistic experience and community will come via the soils, forests, people, ecosystems and social systems close around us, we will all recognise the extreme importance of keeping these in good shape. If we do not do this our water catchments, energy systems, working bees and committees will not function well, and then we will have to pay dearly for goods and services brought in from further away. This will force us to think constantly about the maintenance of our ecological, technical and social systems. This will be the main reason why we will treat our ecosystems well – because if we don’t we will soon be sorry.

11.4. MORE COMMUNAL, PARTICIPATORY AND COOPERATIVE WAYS

The third essential characteristic of the alternative way is that it must be very communal, participatory and cooperative. Firstly, we must share many things. We could have a few stepladders, electric drills etc. in the neighbourhood workshop, as distinct from one in every house. Many goods and services would be produced by cooperatives.

We would be on various voluntary rosters, committees and working bees to carry out most of the windmill maintenance, construction of public works, child minding, and basic nursing, educating and care of aged people in our area. These activities would also deal with many of the functions councils now carry out for us that would remain, such as maintaining our parks and streets, and in fact energy, water and “waste” systems. Working bees and committees would maintain the many commons. We would therefore need far fewer bureaucrats and professionals, reducing the amount of income we would have to earn to pay taxes. (When we contribute to working bees, committees and community activities, we are in effect paying some of our tax.)

Especially important would be the regular voluntary community working bees. Just imaging how rich your neighbourhood would now be if every Saturday afternoon for the past five years there had been a voluntary working bee doing something that would make the locality a more productive and pleasant place for all to live.

These arrangements and activities would generate strong community bonds. People would know each other and be interacting on communal projects and committees. Because all would realise that their welfare depended heavily on how well we looked after each other and our ecosystems, there would be powerful incentives for mutual concern, facilitating the public good, and making sure others were content. The situation would be quite different from consumer-capitalist society where there is little incentive for individuals to care for others, for their community or their ecosystems.

One would certainly predict a huge decrease in the incidence of personal and social problems and their dollar and social costs. The new neighbourhood would surely be a much healthier and happier place to live, especially for older and disadvantaged people. All would have interesting, worthwhile things to do, important purposes, and much time for artistic and personal development.

Our life experience would mainly be enriched not by our personal wealth or talents, but by having access to public things such as a beautiful landscape containing many forests, ponds, animals, water wheels, gardens, bamboo clumps, little farms and firms, projects and leisure opportunities close to home, a neighbourhood workshop, many cultural and artistic groups and skilled people to learn from, community festivals and celebrations and a thriving and supportive community. This much more “collectivist” orientation need not have any negative implications for important personal freedom. There is no reason why we should not also retain much freedom for individuals to pursue their own private interests.

11.5. GOVERNMENT AND POLITICS

The political situation would be very different compared with today. There would be genuine participatory democracy. This would be made possible by the smallness of scale, and it would be vitally necessary. Big centralised governments could not run our many small and wildly different localities. That could only be done by the people who live in them because they are the only ones who would understand the ecosystem, know what will grow best there, how often frosts occur, how people there think and what they want, what the traditions are, what strategies will and won’t work there, etc. They have to do the planning, make the decisions, run the systems and do the work. The community will not function satisfactorily unless social cohesion and morale are in good shape, which means people must be happy about the decisions being made, and the only ones who can make that happen are those who live there.

Most of our local policies and programs could be worked out by elected unpaid committees and we could all vote at regular town meetings on the important decisions concerning our small area. There would still be some functions for state and national governments, and there would be a role for some international agencies and arrangements, but relatively few.

Thus our dependence on our ecosystems and social systems will also radically transform politics. The focal concern will be what policies will work best for the town and region. Politics will not be primarily about individuals and groups in zero-sum competition to get what they want from central government. There will be powerful incentives towards a much more collectivist outlook, to find solutions all are content with, because we will be highly dependent on good will, concern for the public interest and eagerness to contribute. Without these people will not conscientiously and eagerly turn up to committees, working bees, celebrations and town meetings. We will therefore have an incentive to find and do whatever will contribute to town solidarity and cohesion.

The core governing institutions will be voluntary committees, town meetings, direct votes on issues, and especially informal public discussion in everyday situations. In a sound self-governing community the fundamental political processes take place informally through discussions in cafes, kitchens and town squares, because this is where the issues can be slowly thrashed out until the best solutions come to be generally recognised. The chances of a policy working out well depend on how content everyone is with it. Consensus and commitment are best achieved through a slow and sometimes clumsy process of formal and informal consideration in which the real decision-making work is done long before the meeting when the vote is taken. So politics will again become participatory and part of everyday life, as was the case in Ancient Greece, Medieval towns and New England USA. Note that this is not optional; we must do things in these participatory, cooperative ways or the right decisions for the town will not be found.

11.6. MODERN TECHNOLOGY?

The Simpler Way is not opposed to modern technology. In fact there will be more resources available for research and development of the things that matter, such as better medical services and windmill design, than there are now, when the vast sums presently wasted on unnecessary products, and arms, cease being spent.

However it is a mistake to think better technology is important in solving global problems, let alone the key. Most of the things we need in The Simpler Way can be produced by traditional technologies. Hand tools can produce excellent food, clothes, furniture, houses, etc., and craft production is in general the most satisfying way. Of course we will use machinery where that makes sense and many basic items could be mass produced in automated factories. There would also be intensive research into improving crops and techniques, especially for deriving chemicals, drugs and materials from local plant sources. There will also be more resources than at present to invest in realms that have “spiritual” significance rather than economic value, such as astronomy, history, philosophy, the arts and humanities.

11.7. THE NEW ECONOMY

These changes cannot be made while we retain the present economic system. The fundamental principle in a satisfactory economy would be to apply the available productive capacity to producing what all people need for a good life, with as little resource consumption, work and waste as possible, in ecologically sustainable ways. Our present economy operates on totally different principles. It allows profit maximisation for the few who own most capital to determine what is done, it therefore does not meet the needs of most people or of the environment, and it seeks to increase consumption and GDP constantly. (For a detailed critical analysis of the economy and of the required new economy see Note 2.)

11.7.1 The Primary Determinant: Need, Not Profit and Market Forces

In a satisfactory society the basic economic priorities must be decided by discussion and debate and deliberate, rational decision. Chapter 10 emphasised that market systems cannot meet the most urgent needs or produce just or ecologically sustainable development, because they inevitably allocate resources to the highest bidder. It is axiomatic that if there are to be sustainable and just outcomes in the coming situation of intense scarcity, the basic economic processes will have to be under social control. If they are left to market forces then the rich will quickly take everything of value through their superior purchasing power and there will very likely be rapid descent to a new feudalism, soon followed by terminal chaotic breakdown.

However, in the near future we might choose to leave much of the economy as a form of private enterprise carried on mostly by small firms, households and cooperatives . . . under the umbrella of social control. Market forces might be allowed to operate in many relatively unimportant sectors. For example the kinds of bicycles on sale might be left entirely to the market. Local market days could enable individuals and families to sell small amounts of garden and craft produce. In other words market forces might be allowed to make most of the economic decisions – but none of the important ones! They would never be allowed to settle the distribution of income, basic development issues, access to livelihood or the way the environment is treated.

In the present economy the notion of having firms under social control is taken to mean big centralised bureaucracies and states. These can be entirely avoided by devolving most of the control to small localities where citizens can deal with issues through direct and participatory procedures. Again, because local conditions and resources, skills and traditions are the important factors determining how local economies can best function, local people are the ones who are familiar with these and they are in the best position to make the decisions most likely to satisfy local needs. It will make no sense for distant governments to decide what is best for your town to plant when another of its parking lots has been dug up. Thus the form of social control envisaged here has nothing to do with "big-state socialism" as socialism is usually conceived and has mostly been practised. What we must strive for is a radically participatory democracy. Without this the town will not arrive at decisions that work.

In making these decisions, communities can take into account all relevant moral, social and ecological considerations, not just dollar costs and benefits to those with capital or to purchasers. If a development would be costly and "inefficient" but ecologically important or good for the town, we could still opt for it. If a firm was struggling, or becoming inefficient we would not let market forces dump those workers and owners into unemployment, although we might need to phase out the firm. We would have to grapple with finding the best rearrangement for the town, knowing that if we don't, then the town will be weakened.

Our chances of running our local economies satisfactorily will be increased by the fact that they will be far less complex than present economies. There will be less producing and consuming, there will be no growth, there will be no interest payments (if there is interest there is growth) and there will only be a small finance sector. As time goes by people will increasingly come to see the economy not as the arena where all compete for as much wealth as possible, but as the system we maintain for routinely providing us with those relatively few goods and services we need in order to live well while we get on with important things like rehearsing for our next festival.

It is conceivable therefore that early in the transition process much of the economy will still be made up of private firms but as time goes by we will see the sense of reducing and eventually eliminating the role for market forces as we develop more satisfactory ways of ensuring efficiency and innovation. Many firms might remain privately owned, but serve the town under the watchful but helpful eye of its citizens. A key assumption here is that efficiency, "work" motivation and innovation can eventually come from a) the good will of citizens who understand the importance of contributing to their local economy and find that enjoyable, and b) via extensive monitoring and feedback and adjustment systems, rather than market forces. Crucial for this would be the development of elaborate systems (which might be run mostly by volunteers), constantly making clear how well various agencies, including firms, were performing and what innovations seemed desirable. These monitoring systems would also focus on indices of social cohesion, quality of life and footprint, and would be in touch with similar agencies and information sources all around the world.

There are only two ways of determining what happens in an economy. Either a society tries to determine outcomes via rational, deliberate processes, which can vary between authoritarian-totalitarian and participatory-democratic, or it is all left to market forces. The second option allows your fate to be determined by what will maximise the wealth of the richest few and a glance at the state of the planet shows where that option is taking us.

If the transition gathers momentum it is likely that people will in time come to see that there is no need for the remaining elements of the market system. To retain any element of the market system is to retain forces which generate and reinforce selfishness, inequality and injustice, and more important it is to subvert the crucial collectivist values on which our survival will depend. In the long run economic success will cease to be important to people, because it will have diminishing significance for their quality of life. That will derive mainly from the spiritual and ecological wealth of their community, and how well people get together to provide for their collective welfare. Obviously none of this is possible without immense cultural change (. . . which of course might be too difficult for us.)

11.7.2 Provision of Livelihood

Above all, these strategies will enable us to ensure that all have a livelihood. This is of central importance. The conventional economy sees no problem in allowing those who are most rich and powerful to take or destroy the business, markets and livelihoods of others, and thus accumulate to a few the wealth that was spread among many. The market system constantly worsens this problem. Globalisation is essentially about the elimination of the livelihoods of millions of people and the transfer of their business to a few giant corporations. A satisfactory society will not let this happen. One of its supreme priorities will be to ensure that all have the opportunity for worthwhile work and contribution, and clearly this is only possible if local communities have control of their own local economic development and can operate contrary to market forces.

11.7.3 Overlapping Sectors

One sector of the new economy would still use cash. In another, market forces could be allowed to operate. One sector would be fully planned and under participatory social control. One would be run by cooperatives. One large sector would not involve any money, including household production, barter, mutual aid, working bees, gifts, e.g., just giving away surpluses, and the free goods from the commons. Many people will derive most of the things they need from the household and the community (including commons) sectors, with little need for money. Those who need more money to acquire things, such as professionals who specialise full time and therefore do less in co-ops, would generate the demand that is met by the firms that produce items for sale.

11.7.4 Only One or Two Days a Week Working for Money

When we eliminate all that unnecessary production, and shift much of the remainder to backyards, local small business and cooperatives, and into the non-cash sector of the economy, most of us will probably need to go to work for money in an office or a factory for only one or two days paid work per week. We could spend the other 5 or 6 days working-playing around the neighbourhood doing many varied, interesting and useful things everyday. Some of that time would be spent in contributions to working bees, producing the “free” fruit etc. from the commons.

In The Simpler Way there will be far less emphasis on work and production and economic affairs, and therefore much less stress and worry, and attention can shift to more important things.

11.7.5 Unemployment and Poverty

Unemployment and poverty could easily be eliminated. (There are none in the Israeli Kibbutz settlements.) We would have neighbourhood work coordination committees who would make sure that all who wanted work had a share of the work that needed doing. Far less work would need to be done than at present. (In our present society we probably work three times too hard!)

11.7.6 There Would be No Economic Growth

We would produce only as much as is needed to provide all with a high quality of life. There would be no increase in the amount of producing and consuming over time. In fact we would always be looking for ways of reducing the amount of work, production and resource use.

The average dollar income and GDP per person would be far lower than they are now, people would be far less wealthy in conventional dollar terms, but the quality of life of all could be far higher than the average now. People will need very little money to live well in the communities described. Their money income or wealth will be an insignificant determinant of their quality of life. Again this will derive primarily from the “wealth” of their surrounding society, including the landscape, commons, festivals, solidarity, community facilities and social networks.

11.8. THE NEW VALUES AND WORLD VIEW

The biggest and most difficult changes will have to be in values and outlooks. The foregoing changes in lifestyles, economy, geography, agriculture and politics cannot work unless people think and act according to some quite different attitudes and habits compared to those dominant today. It is not possible to design a sustainable and just society made up of competitive, acquisitive individualists! It is a serious mistake to say, “But we want a path to sustainability that will work for us, for ordinary people.” The point is there isn’t one! That’s like asking for a path to slimness for people who refuse to even think about reducing their gluttony.

The crucial point here is that some of the fundamental elements in Western culture are not viable. They are like an evolutionary mistake that leads to the extinction of a species. The Simpler Way is a head-on contradiction of the Western commitment to competitive, individualistic acquisitiveness. Thus the present desire for affluent-consumer living standards must be largely replaced by not just a willingness, but a desire to live frugally, cooperatively and self-sufficiently. Most people must be conscientious, caring responsible citizens, eager to cooperate, think about social issues, come to working bees and participate in self government. They must find satisfaction in nurturing, in helping other people, neighbourhoods, societies and ecosystems to flourish. They must be sociologically sophisticated, acutely aware of the crucial importance of cohesion, cooperation, conflict resolution, and careful and responsible and active citizenship. They must have a strong collectivist outlook. They must understand and care about the global situation. If people don't have these kinds of dispositions, the new communities will not work well and will not fit within their strict ecological limits.

This does not mean that there can be no room for individual differences or that we must be nothing but collectivist, or that there will be a threat to privacy and private property. We could have wildly different religious beliefs, artistic preferences, personalities, hobbies etc., and we could still have private houses, property and businesses. It just means that there has to be much higher value put on cooperation, the collective good, the public interest and helping others than there is now.

Nor is it that everyone has to become a saint before we can save the planet. It is a matter of degree. The Simpler Way can't work unless the general level of cooperation, responsibility, frugality etc within society is lifted to a sufficient level. This does not mean everyone must always attend all working bees. It means that in general there must be a considerable willingness to do such things. In fact many could be less than ideal citizens so long as the average commitment is good enough. This means that the town's fate will not be jeopardised by those who do not pull their weight, so long as enough do.

Effective incentives can only be positive. Either people will come to working bees because they enjoy them and want to improve the town, or they will not come and the town will not function well. There is no possibility of forcing people to do the things that are crucial for the town to thrive.

Again we should appreciate the positive effect of our dependence on our local ecosystems and community. This situation will powerfully reinforce good values. It will be obvious to all that it is in their interests to cooperate, come to working bees and meetings, be responsible, think about issues, and care for their local ecosystems. If we don't do these things the local ecosystems and social systems we depend on will deteriorate and we will all be in serious trouble. More importantly, doing these things will be enjoyable. It's nice to give to others and to help out on working bees. It will not be a matter of forcing ourselves to practice the right values. The new society will not work unless people find it enjoyable to behave in socially beneficial ways, and the situation will be conducive to this.

These conditions will restore the "earth-bonding" that has been lost in consumer-capitalist society. We will be much more aware of and appreciative of our land and the local ecosystems that will provide many things we need. We will feel that we belong to and depend on our “place”, and therefore we will be much more inclined to care for it.

The difference between these values and those dominant today is so great that at first one might conclude there is no possibility of achieving a general shift to The Simpler Way. However it is again best seen not as a need to forego satisfactions in order to save the planet, but as the substitution of new and different sources of life satisfaction. The Simpler Way will constantly deliver many deeply rewarding experiences, such as a much more relaxed pace, having to spend relatively little time working for money, having varied and enjoyable and worthwhile work to do, experiencing a supportive community, giving and receiving, growing some of one’s own food, keeping old clothes and devices in use, running a resource-cheap and efficient household, living in a supportive and caring community, knowing you are secure from unemployment, violence and loneliness, practising arts and crafts, participating in community activities, having a rich cultural experience involving local festivals, performances, arts and celebrations, being involved in governing one’s own community, living in a beautiful landscape, and especially knowing that you are no longer contributing to global problems through over-consumption.

Only if these alternative values and satisfactions become the main factors motivating people can The Simpler Way be achieved. Our main task is to help people to see how important these benefits are, and therefore to grasp that moving to The Simpler Way will greatly improve their quality of life. This understanding will be the most powerful force we can develop for bringing about the transition. If it is not developed, then the transition can not be made.

11.9. LAND AREAS AND FOOTPRINT

It should be evident now that a meaningful discussion of the role of renewable energy in the alternative, sustainable society could not have been undertaken effectively before giving the foregoing account of the global predicament and thus of the radically different general form the new society must take. Those prerequisites establish the need for great reductions in resource consumption and therefore for enormous and radical change in structures, geographies, systems ways and values. Only when all that has been outlined does it make sense to finally explore the way renewable energy sources might enable the new society.

The following discussion assumes a very frugal and self-sufficient strategy, more so than is necessary as the footprint discussion below will show, but one which I would be happy to pursue. The point is to indicate how low a land and energy footprint could be achieved within the kind of systems sketched above.

Firstly, the Simpler Way will be a stable economy so maintenance of frugal structures will generate very much lower resource demands compared with a growth economy, in which construction and development are intensive and make up a large part of the GDP.

In general, solar passive building design will greatly reduce the need for space heating and cooling. As explained above, very little non-human energy will be needed for food production. Only a little will be needed for pumping clean and waste water as these will be collected and dealt with locally. The need for transport, packaging and marketing will be greatly reduced. Most leisure needs will be met within the settlement at little energy cost. Industrial production will be greatly reduced, and most manufacturing will take place in small local enterprises mostly operating in labour-intensive ways. Only a little heavy industry will be needed, e.g., basic steel, railways, buses, and thus mining and timber industries will be small. There will be little need for shipping, car or air transport. Many entire industries will be largely or entirely phased out, including advertising, cosmetics, security, finance, "welfare", "justice", tourism, fashion, aviation, car production and arms.

The basic settlement model can be thought of as a landscape in which very small towns and suburbs of something like 250 households and 1000 people are located on average 2 km part, centre to centre, and therefore within an area of 400 ha. This size is taken for illustrative convenience and obviously the ways discussed would be applicable in a range of larger and smaller settlements. Every 10 km throughout the settled countryside there might be a large town, on a railway line, and very small cities might be 100 km apart. Their suburbs would be more or less like the town being described.

If the settled area of our town is 700 m across it will occupy 50 ha. If the typical area occupied by roads in an outer Sydney suburb is assumed, but reduced by 75% in view of the much lower need for vehicles, roads would occupy about 2 ha, and railways about 1 ha. About 6.5 ha of roads would be converted to commons. Commons within the settlement would occupy about 10.5 ha, and there would be much greater common areas outside it, for instance in town forests.

As has been explained above, virtually all food needs except grain and dairy could be met from within the 50 ha settled area, but there could be small farms, orchards, fish farms and plantations just outside it. These would supply grain, fibre, wool, timber, dairy products, and energy. Much of the fish production could be via recreational fishing in lakes and streams, but many small fish farms could be located within the settlement. Scrupulous recycling of nutrients and use of nitrogen-fixing and deep rooted plants would eliminate the need for imported fertilizers.

If each household had on average 15 useful trees, and these were also planted on half the commons at 4 m × 4 m spacing, there would be 7,000 trees within the settlement. If half of these were fruit and nut trees yielding 10 t/ha/y, annual per capita production might be 110 kg, plenty for people and animals. (Some tree crop food yields are higher than this.) The per capita footprint for food produced within the settled 50 ha might be 0.036 ha according to Jeavons (2002) and far less according to Blazey (1999, p. 18.)

If produced from wheat or corn, flour might require 17 ha just outside the settled area, assuming 100 kg per capita consumption p.a., and 6 t/ha yield. However it can be produced from tree crops such as Chestnut and Oak, and at a yield of up to 20 t/ha from Carob and Algaroba, without the energy cost of annual crops.

Timber requirements in a stable economy would be very low. If 50 kg per capita per year is assumed, 7 ha would be required, at 7 t/ha/y harvest. Half of this might be located on commons within the settlement. Firewood for heating and cooking within well insulated solar passive houses might double this area.

Water is assumed to come mostly from local sources, including rooftop collection of rainfall, and from small dams. There would be intensive mulching, recycling, and use of low water demanding crops. There would be much use of tree crops, reducing somewhat the need for vegetable garden area and watering.

Town dairy products might require 45 ha, assuming consumption of 100 kg per person p.a., 110 cows, 900 kg output per cow p.a., and 2.5 cows per ha. However sheep and goats tethered or herded on the commons within the settlement might contribute a significant fraction of this demand. Some of the dung would be collected to generate methane for cooking and fridges before the slurry was returned to gardens and fields.

The foregoing ways would greatly reduce the energy needed for food production. In the US economy it takes about 1.6 kW to provide one person with food, 50 GJ/y, when the tally includes irrigation, tractors, fertilizers, pesticides on the farm, and perhaps 2,000 km of transport, then factory processing, packaging, advertising, supermarket overhead costs, and the trip to the supermarket in the SUV. The total energy cost from the alternative food production system described above would be almost zero.

Wool might require 25–30 ha of grassland, assuming 2 kg per person p.a., 25 sheep per ha, and 3.2 kg clean wool per sheep p.a. All of this area might actually be found within the settlement and the surrounding plantations. Note that overlapping uses complicate footprint calculations but reduce the areas needed. For example land used for food can also be used for grazing, timber production water collection, and other materials production and leisure.

Another almost negligible area would be required for cotton and other fibres, assuming a 5 tonnes per ha yield. Need for new clothing would be very low as garments would be worn out, patched and recycled.

The area per town to be set aside for its share of the regional industry, hospitals, colleges, universities, and services would be very small. For example, a tertiary educational institution of 3 ha serving 10 towns averages only 3 square metres per person, or 0.3 ha per town.

Adding these areas indicates that 133 ha, 33% of the 400 ha area the town is set within, would be used for purposes other than energy supply.

Energy sets the biggest problems. First let's consider the land area that would be required to meet present Australian per capita oil plus gas demand of 128 PJ. If this all came from biomass at 7 t/ha via ethanol produced at the equivalent of 7 GJ (net) per tonne of biomass input, then our town situated in 400 ha would need to harvest 2,610 ha of forest! That is, the per capita footprint for this item alone would be 2.6 ha. An additional area would be needed to fuel electricity generators (below).

Let us therefore explore a very austere energy budget, derived from 100 ha devoted to plantations for energy production, plus where possible PV, wind, garbage gas, micro-hydro, solar heating panels, within the town, and a share of the high cost national renewable energy supply from without. This discussion applies to Sydney's latitude, 34 degrees south, so for colder climates the problems would be significantly greater.

Space heating and cooling would eventually have negligible energy costs as solar passive house design and earth-built housing, business premises, animal sheds, etc. became the norm.

Electricity supply would not be so difficult, if extremely frugal use is assumed. Based on records from my homestead, a family of three could meet its electricity needs on about 0.4 kWh/day. (Lights, computer, TV, duct fans, some workshop machinery, but no air-conditioning, electric stove, electric fridge or washing machine.) This is under 2% of the typical rich-world household consumption. The town would therefore need let us say 500 kWh/d for domestic purposes. The half of this that does not have to be stored might come from a combination of solar PV, solar thermal and wind. One quarter might come from hydro and one quarter from the burning of wood, both via generators that can be turned up quickly when intermittent inputs are not available. To meet this demand via a 22% efficient wood burning system (i.e., taking in energy used in growing and harvesting as well as generating efficiency) the town would need 5 ha of forest harvested at 7 t/ha/y.

In hilly areas the many small dams could all be generating some electricity, and helping with the energy storage problem. Chains of small dams along creeks can function as high and low storage ponds, where once more the greatly reduced scale of the electricity demand and therefore storage task makes pumped storage much more viable. Presently existing grids would be adapted to augment local sources when necessary, from more centralized and distant renewable sources. Much machinery could be powered by solar concentrating or wood-powered steam or Stirling engines.

Gas for refrigeration and for some of the cooking would come from biomass, mostly wood, but it would also come from the perhaps 800 tonnes p.a. of kitchen, toilet, garden and animal wastes from within the settlement flowing through methane digesters on their way back to gardens. In addition we would be able to use a significant fraction of the at least 1.5 tonnes of manure a day produced by the 110 dairy cows located just outside the town. The gas might best be used for generating electricity at night, for fridges and for light or rapid cooking.

Because use of gas refrigerators would have to be very frugal, community facilities might be used, such as neighbourhood freezers. However most food can come fresh from fields and animal pens so relatively little storage would be needed. Extensive use could be made of cool rooms, cellars, and solar-passive evaporative coolers ("Koolgardie safes") and of fruit and vegetable drying and bottling. A less intensive agriculture would enable potatoes and root crops to be left in the ground until needed.

The greatly relaxed pace and lack of pressure to maximise output and "efficiency" would enable any energy-intensive tasks to be carried out when most appropriate. For instance heavy woodcutting might be done by solar powered Stirling engines when the sun is high. Light firewood is best cut by hand late on a winter afternoon—that way it warms you twice. Water wheels might mix clay and recycle paper when the creeks are at their best.

Liquid fuels are the big problem. If the remaining 90 ha of the 100 ha allocated to energy produced liquid fuel at 7 GJ/t and a 7 t/ha/y yield, then 4,410 GJ would be produced p.a. Averaged over the 1000 people in the town this is around 3.5% of the present Australian per capita oil plus gas use. Many people could probably live well on such an extremely low amount of liquid fuel from village resources. This is because there will be relatively little transport, international travel, car travel to work, construction of roads, houses or infrastructure, industrial manufacturing, agricultural energy use, packaging, international shipping of resources, or energy-intensive leisure, and there will be far less professional and bureaucratic provision of services, government and administration. There would also be far less international transport, tourism and trade, lowering town per capita average consumption.

However there would also be some national biomass (and electricity) production and distribution of the resulting liquid fuels and this would probably add considerably to these figures deriving from the town level. If Australia could harvest biomass from 10 to 25 million ha (a debatable figure) this could provide fuel equivalent to 20%–50% of the present per capita liquid plus gas fuel. However few other countries could find this 0.5–1.25 ha per person, and it would make the national average footprint greater than the available world average.

The above figures for land use within the 4 square km town area yield a remarkably low overall footprint per capita of around 0.25 ha. However the national average footprint would be slightly larger than in the example town, because people living in bigger towns and in the cities would be more dependent on imported goods, materials and energy, and the above tally does not include things like heavy industry, railways, steel and more centralised services such as higher education. However the much-reduced amount of this does not need to be located on productive land. Even if we assume another 250 ha per town for these distant from the town, a highly implausible figure for the new economy, this would raise the per capita footprint to 0.5 ha, still under the 2050 globally available figure of 0.8 ha, so there is scope to make some of the above assumptions and conditions much less stringent.

These numbers have been rough approximations intended to indicate the general scale of the tasks and the general feasibility of the town model presented, and the approximate footprint and energy consequences. They provide a base for others to work out the implications of different assumptions. However they seem to indicate that the energy demand associated with The Simpler Way would be extremely low, and could be met without great difficulty from renewable sources.

11.10. THOUGHTS ON THE TRANSITION PROCESS

It would be very easy to establish and run The Simpler Way – if that was what we wanted to do. It does not involve complicated technology and it does not require solutions to difficult technical problems, such as how to get a fusion reactor to work. lt does not require vast bureaucracies or huge sums of capital.

If enough of us wanted to, we could make most of the basic geographical, structural and economic changes in towns and suburbs within a matter of months, using mostly hand tools and working bees. The Simpler Way is essentially about *reorganising* to harness *existing* and *abundant* resources, now largely wasted. In any neighbourhood there are huge resources of labour, skill, advice, humour, technical capacity, care, and community that could be contributing to community well being, but at present they are not. People who could be helping each other, developing and running community facilities, dropping in on old people, organising festivals, etc., are sitting in their isolated boxes watching TV (. . . four hours a day in the US).

However, the Simpler Way constitutes such a head-on contradiction of consumer-capitalist society that the chances of successful transition to it must be rated as very low. My own feelings on the matter have become increasingly pessimistic in recent years, given the failure of the mainstream to even recognise that the pursuit of affluence and growth could be a problem. The transition would require the development of households, neighbourhoods, economies, technologies and political systems that flatly contradict some of the fundamental elements in Western culture.

As has been noted, the transition cannot be imposed by an authoritarian state or an authoritarian revolutionary group or through the use of force. There will not be enough resources for centralised authorities to do what's necessary, but more importantly, the new local societies can only be made to work by the willing effort of local people who understand why The Simpler Way is necessary and who want to live that way. Only they know the local conditions and social situation and only they can develop the networks, trust, cooperative climate, etc. The planning, producing, maintaining and administering will not be done unless by local people, eager and happy to do it. Getting the transition going therefore has to be about helping ordinary people to move towards willing acceptance of the new ways, towards enthusiastic participation in the long process of working out for themselves how best to organise in their own town or neighbourhood. This clarifies the nature of the required revolution and rules out many options.

The first obvious implication is that there is no value in working to take state power, either within the parliamentary system, or by violence. Even if the Prime Minister and cabinet suddenly came to hold all the right ideas and values, they could not push these changes through against public opinion. If they tried they would be instantly tossed out of office. The changes can only come from the bottom, through gradual profound change in ideas, understandings, and values among people in general. There must be a lengthy process of learning the new values and in developing the new arrangements in the places where people live.

We do not have to get rid of the present society before we can begin to build The Simper Way. We must begin developing elements of the new society, here and there within the old, in little ventures led by small groups who have the required vision. The classic Marxist theory of revolutionary change involves a very long and painful struggle to get rid of the old system before anything can be done to begin building the new one. Fortunately when we understand the need for transition to The Simpler Way we can see that the very different view of transition held by the Anarchists is the right one. We can "prefigure" the new way, i.e., begin building bits of it here and now in order to eventually replace the old. There is no other possible way. The Simpler Way cannot be given or imposed from the top, by totalitarian states or benign social-democratic states. It can only be constructed slowly, built by people who are learning their way in the development of the systems that will enable them to run their own thriving communities.

It follows that the main target, the main problem group, the basic block to progress, is not the corporations or the capitalist class. They have their power because people in general grant it to them. The problem group, the key to transition, is — people in general. If they came to see The Simpler Way as preferable, consumer-capitalist society would be more or less immediately replaced. The Simpler Way cannot come to be unless and until people in general willingly adopt it. The task is therefore to help ordinary people to see the merits of building The Simpler Way where they live. The battle is therefore to do with the ideology, world-view or vision held by ordinary people.

We will be greatly assisted in this revolution as the faults in consumer-capitalist society become more obvious and impossible to ignore in coming years. People are likely to become increasingly aware that their quality of life is falling. If a significant petroleum crunch occurs, as is very likely, that will concentrate minds wonderfully. We are so extremely dependent on petroleum that any significant increase in scarcity or price will surely jolt people into the realisation that radically different social arrangements must be turned to. Without petrol it will be glaringly obvious that only localised economies will make sense. Of course the wrong responses are quite possible, such as an intensified grab to control the oil producing regions, or a dash for nuclear energy. Unfortunately the window of opportunity will be brief and risky. Nothing much will change before complacency is shaken but if things deteriorate too far there will be too much chaos for sense to prevail and viable alternative systems to be established.

The chances of consumer-capitalist society turning in the right direction before it is too late will depend primarily on whether we have built enough impressive examples showing that there is a better way. Thus the top priority for anyone concerned about the fate of the planet must be to contribute to the establishment of elements of The Simpler Way, here and now. In the last 20 years a "Global Alternative Society Movement" has developed in which many people all around the world have begun to build, live in and experiment with new settlements which enable simpler ways.[1] If the analysis of our situation sketched in Chapter 10 is more or less valid, then the fate of the planet will depend on whether this movement can develop a sufficient number of impressive examples of The Simpler Way in the near future.

11.11. SO WHAT CAN WE DO HERE AND NOW?

The first thing everyone can do is to talk about these issues as much as possible. We urgently need to get the limits analysis of our situation and the desirability of The Simpler Way onto the agenda of public attention.

But the most effective contribution will be to initiate in our localities some of the new ways and systems. Again as consumer society crumbles nothing will be more effective than people being able to see around them examples of alternative social arrangements which make more sense.

Following are brief notes on the first steps that could be taken in a dying country town and in normal city suburbs, towards their eventual conversion to the new kinds of economies.

The focal institution is the Community Development Collective (hereafter referred to as CDC.) Ideally the CDC will eventually develop into a mechanism for the participatory self-government of the town or suburb, but at first it might involve only a handful of people seeking to do a few quite humble things.

Their best initial goal might be to set up a community garden and workshop which will enable some of the locality's unused productive resources of skill, energy, experience and good will to begin to be applied by local people to meeting some of their own needs. Especially important is involving low income receivers in the production of food and other items for their own use. This enterprise might best be approached as a cooperative "firm" in which participants contribute ideas, time and labour, and share in the produce.

The CDC could then look for areas in which additional cooperative production could be organised to meet local needs. A promising early possibility would be bread baking. Once or twice a week a cooperative working bee might use the community earth oven to produce most of the bread etc. the group needs, selling some to outsiders.

Other early possibilities would be the repair of furniture, bicycles and appliances. The workshop could become a shop where surpluses are sold. Scavenging from the locality, especially on council waste collection days, will provide furniture, appliances, bicycle parts and toys to be repaired and materials for use in the workshop. Other possible areas of activity would be cooperative house repair and maintenance, nursery production, herbs, car repair, poultry, honey, preserving and bottling fruits and vegetables, toy making, slippers and sandals, hats, bags and baskets, and the "gleaning" of local surplus fruit from private back yards.

Later the CDC could explore somewhat more complicated fields in which it could organise productive activity, such as planting orchards, fast growing trees for fuel wood, aquaculture, earth house building, insulation, recycling and planting "edible landscapes" on public land. The most successful of these activities could become separate small cooperative or private firms.

These activities would also provide important intangible benefits, such as the experience of community empowerment and worthwhile activity. The involvement of local people other than those who are low-income receivers would be important, especially gardeners, handymen and retired people. Ideally the garden and workshop would become a lively community centre with information, recycling, leisure and celebratory functions. Specific times in the week should be set when all would try to gather at the site for the working bees, followed by a meal, discussions, entertainment and social activities.

What we would have done at this point is establish a radically new economy, one geared to need not profit, cooperative, independent of market forces, and under participatory social control. The longer-term goal is to expand this out into the locality.

One early step must be to enable people in this new sector to trade with the firms that have been operating within the locality before the CDC began. It must find out what things our new sector can start providing to some of these older firms. For instance in the case of restaurants the answer is likely to be vegetables from the CDC's cooperative garden.

We would not set up firms that compete with the existing firms in the town. There is no net benefit in us setting up a bakery that wins all the scarce bread sales opportunities and therefore just puts people in the old bakeries out of work. Our focus must be on creating sales and jobs in a new economy, putting to work those people previously excluded from economic activity.

It is in the interests of the old firms to join in enthusiastically, because this will enable them to increase their sales and their real incomes. They will be able to start selling to that group of people previously not involved in much economic activity.

The development of the gardens and workshops would have been carried out through cooperative working bees. Before long the CDC should organise voluntary neighbourhood or town working bees, perhaps occasional at first but eventually occurring at set times aimed at developing the locality in desirable ways, e.g., planting fruit and nut trees in local parks, or building simple premises for new cooperatives or family businesses. This might be the beginning of the development of productive commons throughout the region.

A market day could be organised mainly to sell CDC produce and products, and so that many people who do not operate firms or work full time for wages can gain income by selling items they produce in small volume through home gardens, craft activity or family produce.

At a later stage it is important to explore how many imports to the town can be replaced by local production. The proportion of the town or suburb's consumption that is met by imported goods is typically very high. When goods are produced somewhere else and imported, this means that the jobs that were involved in their production are not located in the town, and it means that money is flowing out of the town. The CDC should explore what items the town could begin producing to replace imports. Food is the first such item. Other possibilities are fire wood, and insulation, as replacements for imported energy, and timber from woodlots and earth for building, and some services, including entertainment.

The CDC must constantly focus attention on the importance of reducing the need for money in the first place, i.e., of living simply, making things yourself, home gardening, repairing, preserving fruit, sharing and re-using. The fewer goods people consume, the less that the town will have to import or provide. The more simple its demands are the more likely that these can be met from local resources. The more we do without or make for ourselves the less money we need to earn in order to buy things. Every dollar we can cut from our expenditure the less produce or labour the town needs to export.

The CDC could develop craft groups to increase home production. It might organise classes, skill sharing and display days for gardening, pottery, basket making, cooking, woodwork, sewing, preserving, sandal making, weaving, leatherwork, blacksmithing, etc. It could list skilled people willing to give advice or run classes. It could also list sources of materials, especially from the commons such as bamboo clumps, reeds, vines, herbs and clay pits. The CDC could develop recipes for nutritious but cheap meals mainly using plants that grow well locally or grow wild.

One of the committees within the CDC should focus on the possibilities for providing local entertainment, including regular concerts, dances, visiting artists, drama groups, craft and produce shows, art galleries, picnic days, celebrations, rituals and festivals.

Eventually a town bank (or credit union) and business incubator should be formed, creating the power to set up the kinds of firms the town needs.

The most important functions for the CDC are to do with research and education. After all, the main point of the exercise is to help local people to understand the need for and the rewards offered by the new ways. All the CDC's activities provide opportunities for increasing awareness within the surrounding region.

If we do make it to a sustainable and just world order, then the transition will have been begun by tiny groups of people who at some point in time have taken on this task of working out how they could start to move their towns and suburbs towards eventually being highly self-sufficient and cooperative local economies. The goal must be to work patiently at this process of gradually extending the functions of the CDC so that in time we have transformed the locality.

At present it is likely that initiatives of this kind will find it difficult to attract participants. But as the problems consumer-capitalist society is running into become more intense and people increasingly realize that the old system will not solve their problems, and if people can see groups in their neighbourhoods living in much more satisfactory ways, they will be more likely to come and join us. A serious petroleum crunch, or collapse of the global financial house of cards, will do wonders for our cause.

The approach outlined is positive and immediate. It is not about destroying before we can start to build. It enables living in and enjoying the new ways, to some extent, here and now, long before the old system has been transcended. There is nothing to stop us starting this work immediately. Above all, given our global situation, what other action strategy makes as much sense? Is any other more likely to get us to The Simpler Way?

The question to ask when we are recruiting co-workers is –

"What shape would you want your locality to be in when petrol becomes very scarce and the renewables can't substitute for it?"

NOTES

CHAPTER 1

[1] Professor of Engineering, Hobart University, A.B.C. Science Show, 12th Dec. 2004.

[2] My previous attempts to partially explore the field have been, Trainer, F. E.: 1995: ‘Can renewable energy save industrial society?’, *Energy Policy*, 23, 12, pp.1009–1026, and Trainer, F. E.: 2003: ‘Can solar sources meet Australia’s electricity and liquid fuel demand?’, *The International Journal of Global Energy Issues*, 19, 1, pp. 78–94.

CHAPTER 2

[1] Czisch (2004) says Germany is “ . . . already approaching its installation limits . . . ” and wind power there “ . . . cannot be expected to grow significantly”, even though wind meets less than 6% of demand. (However the Dena study envisages expansion to 13%, but see Note 4.)

It seems that on-shore sites in Denmark are close to the limit due to these exclusion (and other) problems. (*Country Guardian*, 2002). A number of others have also estimated that only a very small proportion of technically suitable sites could be used. A 1997 US EIA/DOE study came to the remarkable conclusion that “ . . . many non-technical wind cost adjustment factors . . . result in economically viable wind power sites on only 1% of the area which is otherwise technically available . . . ” Mills (2002, p. 188) quotes one authority saying that up to 90% of suitable land might not be accessible. In general he puts the exclusion factor, even in low population density Australia, at 30–50%.

Elliott (1994, p. 8) and Grubb and Meyer (1993, p. 194) estimate that siting constraints would limit wind to providing 10% of UK electricity demand. They believe that in densely populated Europe only a remarkable 1.5% of the area technically suitable for siting windmills could actually be used. Elliott, Wendell, and Gower (1991) state that 75% of the class 7 wind area of the US would have to be excluded from use. Sorensen (2000, p. 311) reports surprisingly that even for offshore wind areas only 10% can be used in view of other uses, such as shipping lanes.

[2] In areas where the winds always blow from the same direction the sideways spacing might be reduced towards 10 × 3 rather than the usually assumed 10 × 5 diameters. Hayden says this situation is rarely reached, and that where winds are not clearly from one direction spacing will be 10 × 10 diameters. Mills (2002) discusses spacing and areas in terms of a 1.25 MW mill with 77 m diameter blades, and arrives at area conclusions similar to Hayden. Sorenson (2000, p. 195) points out that for most of the US and Denmark, 10 × 5 spacing is necessary. Californian winds are atypical in being unidirectional, enabling closer sideways spacing. Existing farms will have been established at the very best sites and we cannot be certain what the average spacing will be for large-scale wind harvesting from less than ideal sites and therefore lower capacity factors.

Sorensen (2000, p. 435) says at 10 diameter spacing 10% of capacity is lost due to array disturbance. However for large-scale use of wind farms mills will tend to be densely packed over large areas, and Sorensen points out that in such a situation a higher overall loss occurs, because wind disturbance effects tend to compound if many mills are sequenced. Grubb and Meyer, (1993, p. 186) say the array loss could be 25%, but assume 13% in general.

As wind power spreads, mills will be built on decreasingly favourable sites. If it is to make a significant contribution in the US in summer, many mills will probably have to be located where speeds average 6.5 m/s (and many windmill *sites* in such regions will have much lower means). It is not clear how this might affect average capacity, but it is argued below that in such regions *system* capacity, as distinct from that of a single mill, would probably be under 16%.

At present the total electrical consumption in Europe and the US is 42 and 250 times as great as the amount coming from windmills. Therefore if wind power was increased to the point where it provided, say half the electricity consumed, the areas used would have to be greatly increased, and the average quality of sites would probably be much lower than it is now, and therefore the average capacity would be much lower.

[3] What we want here is not the theoretical "power curve" for the mill; we want to know what average monthly output in the field actually was and what mean monthly wind speed at that site was. The power curves given by makers assume ideal conditions, and to take the output for a 7 m/s site for instance and multiply it by 8,760 hours in a year to get a yearly output from a 7 m/s site would be misleading. For instance wind speeds at the site will rise and fall and thus the mill will often be accelerating, with output lagging behind speed. More importantly most of the energy a mill generates is from the higher winds it gets (see below), so the mean is less significant than the distribution about the mean.

[4] The Dena study explicitly states that German wind energy can be increased to 13% of demand by 2020 without the need for significant increase in grids or any increase in back-up capacity. However the study by the German Energy Authority (heavily

committed to wind) seems to at least give some misleading impressions. For instance it says 400 km of the grid would have to be upgraded and 850 km of new grid would have to be built. This is not insignificant since it means that for wind to supply another 10% of national electricity the national grid would have to be enlarged by about 5%.

Most of the difficult and costly development, including providing grids for the 27% of wind energy to come from offshore, are not included in the report which only deals with Stage 1 development to 2015.

The argument that no more back-up capacity will be needed seems to be mistakenly based on the stated expectation that better forecasting will eliminate the need. As is explained below this is not so. Even perfect forecasting could not solve the problem set by periodic low wind events. The report's Table 2 indicates that their conclusion derives from a plot of *mean* wind speeds and that *on average* supply would only be 19% from the expected 36 GW output from the wind system, a mere 7 GW in a 250 GW national electricity system. This is not the important point. It is indeed likely that there is already sufficient slack in such a large, mostly fossil-fuelled, system to cope with a mere 7 GW shortfall, but what about a shortfall of 36 GW, i.e., what about the times when there is no wind blowing anywhere? The point is that the plot gives means but does not tell us what the variation about the mean is and thus how often supply would be how far below the mean.

The Study's Table 5 actually provides some information on this question. The "statistically guaranteed power" from wind will be 2.3 GW in winter and 1.8 GW in summer, a mere 6.4% and 5% of the capacity of the wind system, i.e., at times supply will fall a long way below the average shortfall of 19%. These figures are also significant for the discussion of "capacity credit"; see below.

[5] The report bases its conclusions on winter wind system performance, when surely it should have been based on the time of the year when winds are weakest. Its capacity credit claim (0.2–0.3 of wind capacity installed) is difficult to understand. Virtually no windmill, let alone any entire system, always performs above 0.2 capacity. The 2003 average capacity for the entire UK system was only 0.24 and the Danish system often falls to around 0.05 for long periods. No reference is made to seasonal variations, when Czisch reports European winter wind energy at 4.7 times summer energy. The important p. 37 conclusions derive from only four studies, one being the challengeable DENA grid study (see Note 4), and one is based on the Nordic countries with quite different conditions to the UK (most electricity from hydro sources and thus much pumped storage, good inter-connectors to other countries, and a very large area including four countries.)

[6] Those events in which mills would be functioning at under 40% of their mean capacity would last on average five hours. Aggregation of all sites into one big system spanning the three states would reduce this period to two hours.

[7] The probability of a wind under 5% of capacity in the state is 13.3%. In addition for 4.6% of the time there are very high wind events meaning that many mills would shut down in these periods.

For South Australia and Victoria the situation is better, but in these states the 5% and 95% capacity level would be reached 6% and 4% of the time respectively.

[8] Strong winds often raised capacity greatly in summer (p. 19), e.g., going from 40% to 70% capacity about 12 times in one month, for all states combined. Variation in NSW was much greater than in the aggregate from the three states.

[9] Czisch and Ernst (2003, Fig. 3) report 12 hour correlations around 0.2 if mills are 500 km apart, but 0.62 at 200 km

The variability of supply from the whole Western Denmark wind system has been reported as one-third of that from any one site, again a considerable reduction but one that leaves a large amount of variability (*Windpower Monthly*, Feb., 2004, p. 37).

The ESCOSA Report on South Australia (Planning Council, 2005, Table C2, p. 70) sets out surprisingly high correlations between five sites, which range between 0.32 and 0.67. The average of the correlations (for half hour periods) is 0.52. The Report found that combining input from 12 sites would reduce variability 50% (p. 14).

[10] Let us assume a system delivering only 25% of peak capacity, about the European figure, and needing backup equal to 26% of peak capacity. For each MW of wind power we added enough windmills to deliver, we would also need to add enough coal fired capacity to deliver 1 MW. However if we take the 16% infeed factor for Denmark and Germany in a recent year, then for each MW *generated*, additional coal or nuclear capacity of 1.82 MW would also have to be built.

[11] Coppin, Ayotte and Steggle (2003, p. 46) provide a useful overlying plot of wind speed distribution for a 7 m/s site, mill power curve and mill energy output. The speed at which this mill generates most of the electricity it produces over time is 10 m/s, although in such winds it is only operating at about half its peak output. Only 19% of the energy it generates comes from winds under the site mean of 7 m/s. Half the energy it generates comes from the relatively few winds over 11 m/s. Indeed 26% of it comes from the mere 7.5% of winds over 13 m/s. In other words the output of a mill over time is mostly due to the few quite high winds it gets at its site.

Figures from Sorenson (2000, p. 164) show the same effect. For a mill at a 7 m/s site, only 11% of the energy generated came from winds under 7 m/s. Half of it came from the 1.5% of the time that winds were 16.5 m/s or more.

Thus mean wind speed is not all-important. What matters a great deal is the variation about the mean, and therefore the occurrence of higher winds. From the plot given by Coppin, Ayotte and Steggle it can see seen that had this mill been located at a site with a 7 m/s mean, but at which all wind was at that speed, then it would have generated only half as much electricity compared with the amount it would have provided given the distribution of wind speeds received at the site.

Inspection of the distributions in the Victorian Wind Atlas confirms this point. The regions in which wind resources were identified as “moderate” or “limited” often have means quite close to the state average, indeed some have means above it. Similarly about half of the best sites actually had the same mean as for the state as a whole, but had slightly more wind at high speeds. For instance Baw Baw, probably the best site in the state, actually had the same mean as the state but had very slightly more wind at higher speeds. At this site the frequency of winds of 7, 7.5, 8, 8.5 m/s were greater than the state average by a mere 2%, 1.5%, 1% and 3% respectively. In other words these tiny differences in the amount of higher winds received made this site into one of the best in the state.

Thus the fall off in power likely to be harvested is greater than the "cube law" would suggest. A 6 m/s wind has only 67% of the power in a 7 m/s wind, but it seems that a mill at a 6 m/s site would generate significantly less than 67% of the energy that a mill at a 7 m/s site would generate.

This is evident when the distributions from the Victorian Wind Atlas for moderate and low wind regions are superimposed on the plot from Coppin, Ayotte and Steggle referred to above. It can be estimated that at a 6 m/s site the 660 kW mill they refer to would have generated not 67% of the power it generated at a 7 ms site but only about 50%. This in turn roughly indicates that 6 m/s sites would deliver about 1/3 of the energy that an 8 m/s site would yield.

Brief comments by Coppin, Ayotte and Steggle (2003, p. 46) confirm this effect. " . . . locating at slightly higher wind speed sites can have major economic benefits." The converse, a rapid fall off in energy for sites at lower speeds is evident in their Figure 24. At a site with a mean of 8 m/s a 660 kW mill would generate 1.7% less energy with each 1% drop in wind speed. However the same mill at a 6 m/s site would drop 2.4% of its energy output for each 1% drop in speed. That is, this graph shows that the rate of fall off accelerates as wind speed falls.

[12] Note also the resolution issue. Only about half the sites in the area marked with a mean of 6 m/s on large-scale maps would have a mean speed of 6 m/s or better.

[13] Hansen's (2004) figures for the present loss rate correspond to about a 19% loss for a 1000 MW power station transferring power 1,000 km. Bossel (2004, p. 56) says that an optimised electricity supply system loses 10% of energy, and the US system is not close to optimal. This comment refers to relatively short transmission distances. Much higher estimates can be found, e.g., 25% loss (Enxiv, 2005) and 20% for South Australian transmission a few hundred kilometres to the Snowy dams (Ferguson, 2005c). Lillies (2005) reports a loss on the 3 GW line from Dalles Oregon to Sylmar, California which corresponds to 44% over 4,000 km.

Czisch and Ernst (2003) estimate that HVDC transmission (at euro 70 kW/1000 km, but 10 times as much for under-sea cable) adds 30–33% to windmill costs. Arnold (2003) reports that 5 GW HVDC lines from coal powered stations would add 40% to generating cost, at $(US)2 billion for 5000 km. A report from Electronix Corporation, Western Area Power Administration (no documentation available) says that 500 KV lines capable of carrying 660 MW cost $(US)600,000 per km, sub-stations for 250 KV lines cost $160/kW, and undersea cable for 250 MW lines cost $400,000 per km. A 5 GW cable under the Mediterranean would then cost something like $(US)8 billion, or $(US)1,600/kW. This is well over the cost of the plant to generate one kW, and indicates that a 4,000–5,000 km line from the Sahara to Northern Europe would cost more than two times as much as it would to build another coal-fired plant.

Conductor size and weight also has to be taken into account. One report states that for copper the diameter of 5 GW cables would have to be 27 cm and for aluminium 36 cm. Transmission lines now have steel cores, but weight and cost implications for large-scale power transmission (e.g., tower spacing) would seem to be significant. In addition, where lines are buried provision has to be made for dissipating heat. A 10% loss of energy from a 4,000 km 5 GW line is 0.12 kW/m which must be able to escape into the surrounding environment.

[14] In NSW, Australia, the subsidy for wind energy is 100%, i.e., 4 c/kWh, which means generators are economically viable receiving 8 c/kWh, but only at very good sites, where mills average 8 m/s or better. In Denmark the wind subsidies are said to be "very large", 10 billion DKK per year, around DKK 0.45/kWh and the price of wind electricity is four to five times that of electricity from other sources (*Country Guardian*, 2002).

In Germany the subsidy for rooftop PV power is reported to be 48 Euro. cents per kWh. (50c Euro is quoted in Douthwaite, 2004, p 93.) Worldwatch (2001–2, p. 46) reports PV power in Germany receiving a 10 year interest free loan plus purchase of electricity at 50 c/kWh. Mills says wind power in Germany is subsidised 85–-90% of retail price (2002, p. 46). The E. ON Netz Report (2004, pp. 3, 4) states a higher multiple; some 2.7 times the price from other generators. One source states that the German PV subsidy for systems designed into buildings can be 81c/kWh, and is guaranteed for 20 years. (www.solarcatalyst.com/solarcircle/docs/aitken-GermanyTransition.pdf)

Figures from a proposal by Babcock and Brown for a 200 MW South Australian wind farm throw a little light on what seems to be a precarious financial situation (Sydney Morning Herald, 17.7.2003). The project will cost $450 million, and will sell electricity at 8c/kWh. Over 25 years and assuming 25% capacity, income will be $1,051 million. At the probable loan repayment rates (from personal communication) interest on capital borrowed will probably be $250 million. Operations and management (at 2% of capital cost p.a.) will be c. $225 million. Cost will therefore be in the region of $960 million, i.e., not much below total lifetime income. Annual earnings would therefore seem to be $3.6 million, or 0.8% of invested capital. Assuming a 30 year lifetime and a 30% capacity factor would improve the outlook.

Constable (2005) refers to a UK Department of Trade and Industry study finding that UK wind farms with subsidies of 50–-70% of income " . . . will struggle to be economic."

CHAPTER 3

[1] De Laquil, et al., (1993) report that costs for central receiver and dish-Stirling thermal systems are 1.14 and 1.43 times as expensive as for trough systems. Sandia (2005) state the corresponding ratios for the costs of electricity produced

are 1.6 and 2.5. Mills (2002) reports four varied estimates all of which rate trough systems as most expensive. Mills and Morrison, (n.d.) say dishes are more expensive than Fresnel systems. According to de Laquil et al. (1993, Table 15) dish cost is 1.5 times trough cost. Sargent and Lundy (2003) say that although troughs are preferable at present the cost of central receiver or tower systems will in future probably become a little lower than trough costs. (The term trough has been used at times throughout to include Fresnel arrangements.)

The figures from the Sandia website www.energyllan.sandia.gov/sunlab/PDFs/lsolar-overview.pdf "Overview of Solar Technologies", put troughs, tower and dish costs at $4,000, $4,400 and $12,600 per kW, although they predict that by 2030 dish costs will be half those of troughs. Another Sandia figure for dishes is $6,000 (News Centre). The ANU website states $6,000/kW for the big dish and for a proposed 3 MW device, $4,000 for a 50 kW dish, but predicts $2,000 for a future 20 MW system. Mancini et al., (2003) report on four dish systems, mostly around $(US)3,000 but one at $10,000/kW. These costs will be for construction of small numbers of experimental models, as quite distinct from a mass production costs. Heller's estimate of future larger scale production costs for dishes is e4,500/kW, or $(A)6,428/kW. Note that these dish figures do not include storage provision, which is included in the above cost from Sargent and Lundy.

Such figures defy generalisation and are complicated by the fact that they mostly apply to experimental models, but they seem to put dish costs substantially above those for troughs. Taking Sargent and Lundy's and Heller's estimates, the cost of dishes seem likely to be around twice that of troughs. This inquiry is informed by considerable caution re predicted cost reductions and focuses on the present situation.

[2] The figures given by Brackman and Kearney (2002) for the 1991 performance of SEGS IX, with an area of 483,960 m and 8 kWh/m/d solar incidence, indicate an efficiency of around 7%. The efficiency stated for SEGS VI is 10.7%. Quashning and Trieb (2001) report solar thermal efficiency at 10–14%. Sargent and Lundy (2003, Section 4.2.0) believe it can be raised to 15–17%. For Solar II, a tower system, it was 7.6% and output was 1.3 kWh/m/d in 1997. Table 15 from de Laquil et al., (1993) puts trough efficiency at 14% and dish at 20% (Sargent and Lundy, 2003). However Mills, et al. (2004) claim their trough design will achieve 25% efficiency.

The Sandia (2004) 1997 figures for the SEG VI 30 MW system seem to show that the capital cost per kW delivered (not "peak"; see below) is about 6 times that of a coal-fired power station ($A1.2 billion + $(A)2.5 billion for coal; see text below). Table 4A shows 57 GWh/y were generated from a plant costing $(US)119.2 million (some years ago), after subtracting 1/3 of the power delivered which was generated from gas backup. A coal-fired plant operating at 0.8 capacity would generate 7,008 GWh/y, i.e., 123 times as much electricity. This indicates that the cost of a solar trough system capable of the same output would be (somewhat less than) 123 × $119.2 million = $(US)14.7 billion (or $(A)20.9 billion). The cost would be somewhat less because the cost of the gas equipment has not been subtracted here.

The Solarmundo proposal for Spain (Haberle, et al., 2003) anticipates 10.5% efficiency in a region with an annual average 7.3 kWh/m/d. The expected capital cost is remarkably low, e1,540/Kw(e)(peak, not delivered), compared with Sargent and Lundy's estimate for near future cost of $(US)4,859/kWe(peak).

The account of the proposed Andasol 50 MW plant for Spain also anticipates a quite low 2010 capital cost, possibly due to the use of Fresnel reflectors. (Aringhoff et al., n.d.) However it is in the region of 7–8 times the pro-rata cost of a coal-fired power station. The estimated future cost of the collector field, $(US)102/m, ($(A)145 million in 2004, is quite low. The anticipated efficiency is 14% at an annual average 7.3 kWh(e)/m/d site. This would mean delivery of 1.02 kWh(e)/m/d. The plant is to have a 550,000 square metre collector which will produce 561,000 kWh/d. A 1000 MW coal-fired plant functioning at 0.8 capacity would generate 19.2 million kWh a day, so would have 34 times the output, meaning that an Andersol-type plant capable of the same performance would cost e6.8 billion (or c $(A)10 billion). The few figures reported on PV costs in Chapter 3 for one-dimensional tracking systems ranged from $(US)300/m to $800/m. The SEGS VI field cost was $(US)486/m. The Sandia website states trough efficiency at 11%, tower at 7% and dish 12%, although it says dishes could go to 25% by 2030.

Another source (www.solarpaces.org/SolarThermal_Thermatic_Review) suggests that in the long term future capital costs might fall to around half today's figures, which aligns with the estimates by Sargent and Lundy.

[3] Let us take the 400 MWe(peak) plant proposal described by Mills, Morrison and Le Lievre (n.d.), with 3.12 million metres of collector, generating 1.12 million MWh(e)/y, but let us assume it costs $(US)4,859/kW(e)(peak) as Sargent and Lundy expect, meaning it would cost $(A)1.94 billion. Its output, 128 MW, would be equivalent to that of a 160 MW coal-fired plant operating 0.8 of the time. The coal-fired plant would cost about $224 million, so if we chose to build the solar thermal plant we would be paying 8.7 times as much as for a coal-fired plant capable of the same performance. Of course several other factors should be taken into account such as the cost of coal, environmental costs and problems of intermittancy, storage and "start-up threshold" (below).

The SEGS VI 30 MW peak capacity system delivers about 6.5 MW on average, meaning that its capacity is 22%. The capital cost was $(US)119.2 million, so the capital cost per kW(peak) was $(US)3,973, but given the 22% capacity the capital cost per kW(e) delivered would be $(US)18,054, or around $(A)25,600.

[4] Following are some of the elements in their account which leave some important issues unsettled or puzzling at this stage. After pointing to a trade-off between generator efficiency and collector cost (efficiency is highest when temperature is highest, but so are heat losses and costs of more elaborate materials etc.) they conclude that it is best to collect and generate at relatively low temperature, i.e., around 270 degrees. The account seems to assume a 31.5% generating efficiency at that temperature. Coal-fired stations operating at 550 degrees commonly achieve around 37%, and Carnot's law suggests that an efficiency around 25% would be expected

from steam at 270C. Geodynamics expect only 15–20% efficiency from their geothermal plant to operate at 270–300 degrees. Contrary to Mills, Morrison and Le Lievre, the discussion of future developments by Sargent and Lundy foresees use of increasingly high temperatures, conceivably eventually above 800 degrees for towers. The proposal also assumes that 75% of the solar energy (beam) intercepted can be absorbed as heat. This compares with 50% to 55% reported for the SEG VI site. Sargent and Lundy (Table 4–3) estimate that by 2020 the figure will be 56%.

There might be quite satisfactory explanations for these figures, but they are not apparent in the overview articles accessed. It is not being implied that they cannot be achieved. The Fresnel approach does seem to have advantages over troughs and could result in significantly lower costs. Unfortunately these possibilities can't be assessed satisfactorily from the publicly available information. (It is regrettable that this study cannot provide a more informed and confident account of the Solar Heat and Power technology as it appears to be most relevant to assessing the potential of solar thermal technologies in mid latitudes, but they have not been willing to assist with this study and have prohibited use of data they initially supplied.)

[5] Jones, et al. (2001, Figs. 14 to 18) state 10%. Sargent and Lundy (2003) put the operating energy costs at 8–10% of gross output. (Table 5–20.)

Haberle et al. (2003) indicates that 8% of electricity generated has to be used in the plant, especially in pumping the heat absorbing fluid through long lengths of absorber (e.g., several hundred km of 7 cm diameter pipe.) A complete analysis of embodied energy would also take in many other factors such as the energy needed to produce the tools used to make the plant. Debates about where to draw the line are inevitable. For instance should the energy cost of worker travel to work, clothing etc. be included?

[6] The figures Mills, Morrison and Le Lievre (2004) give for concrete and steel used in a 400 MW plant indicate a pay back period of only a few months. This is at variance with the figures from Lenzen (1999) below in this Note. However the account is difficult to follow as the all-inclusive steel use figure given, 5,200 tonnes for 3.1 million square metre collector, works out at only 1.89kg/m.

The appropriate accounting for the figure given by Lenzen (1999) can be debated. If *thermal* energy used in construction is used as the input figure for the production of *electrical* energy, the energy cost is 8–11% of output, not 3%. What is the appropriate measure?

It could be argued that it is not appropriate to transform the thermal energy in the materials and construction into an electrical equivalent (i.e., divide it by 3) because the MJ measure represents the actual amount of primary energy that had to be found and put into the production of the materials, given that the present electrical economy is mostly based on heat from coal. (This procedure would not be so if say PV energy was used to produce the materials used.) Using the thermal or MJ measure is the usual procedure for calculating ER or emergy.

It is in order to measure output in electrical form, because we do not want thermal energy from the solar thermal plant; we want energy in the form of electricity, just as in an ethanol plant we want energy in the form of liquids. Energy pay back calculations for PV modules do not divide the energy in MJ going into the production process by 3 to transform it into an electrical equivalent, to weigh against the electrical energy produced. (E.g., Table 3 in Gale (2006) states input costs as MJ.)

Again this can be debated but if this argument is accepted then the energy cost of producing solar thermal plant is considerable. When parasitics are added net energy output could fall to under 80% of gross output.

[7] Haberle, et al. (2003) say molten salt storage at 307 degrees is being practised but there is no cost effective system in place for 390 degree heat. Evidently it is not currently possible to store heat in large caverns at over 360 degrees (Eren, n.d., 5.36, p. 365). The lower of these two temperatures would probably be associated with only c. 28% efficiency of generation. However Mills (n.d. c.) seems to say that 31.5% generating efficiency is possible from 370 degree fluids.

[8] For storage via generation of hydrogen from electricity and conversion back to electricity via fuel cells at the power station site the total loss would probably approach 75%, and there would be further high loses in any transporting, storing and pumping of the hydrogen for other uses; see Chapter 6.

[9] Figure 3 in Mills and Keepin (1993) sets out annual output from seven different systems. The four best show an approximately factor 5 seasonal difference. For the three others with lower summer performance there is a factor 2 difference, but all of these achieved only around 1.1kW(e)/m gross output in winter.

US National Renewable Energy Laboratory (personal communication) says SEGS VI's performance in winter is only 20% of summer output. Winter performance could be improved by realigning troughs east-west, but that would lower annual performance by 20% (discussed below).

A plot from Czisch (n.d.) shows that for sites in Portugal, Morocco and Mauritania SEGS mid-summer to mid-winter output ratios would be 10+/1, 3.6/1, and 4/1 respectively.

On a typical winter day output from SEGS VI reaches only one-quarter that of a typical summer day (Sandia, 2005), leaving out the electricity generated by the use of gas. In 2002 the mid-summer to mid-winter ratio was 9.5 to 1. In addition annual output varied significantly. In 1992 the plant's solar output was 56% of 1995 output. So year to year differences constitute another source of considerable variability to contend with.

About 41% of SEGS VI annual output occurred in the three summer months, and over the four winter months of the year cumulative output was only c. 10% of the annual total. Again it seems clear that the performance of solar thermal plants is due mostly to the relatively few most favourable periods in the year, which means the intermittency problem is much greater than a simple inspection of incident solar energy per metre in summer and winter might suggest. In this region that ratio is about 2/1, but the ratio of electricity generated at these two times of the year seems in general to have been 5/1. Note again that in one plot from Sandia it is a surprising 9.5/1.

Evidently there is a larger fall for towers. Solar One's summer capacity in summer was 15%, but in winter it was down to 2%. The plant's efficiency became negative at times in mid-winter, i.e., it consumed more energy than it produced. The fall in winter output is much greater than the fall in solar energy entering the trough or dish in winter. The figures from Renewable Resource Data Centre (n.d.) show that for north – south troughs the winter/summer ratio is about 2/1 at good solar thermal sites, and it increases with latitude or distance from the equator.

Again these would seem to be impressive illustrations of the seriousness of the winter problem for solar thermal systems. PV output in summer and winter is about the same proportion of the solar energy intercepted; i.e., efficiency is much the same. This appears not to be the case with solar thermal trough technology as efficiency falls markedly as energy intercepted diminishes.

[10] The effect is the same as that suffered by fixed flat plate PV panels set to directly face the sun at midday. These typically collect about 3/4 as much energy as panels that "track" the sun, i.e., turn to face it at right angles all day.

[11] This is not a serious problem when troughs are very long and therefore the plant has relatively few trough ends, but if troughs are 10 metres long then at a site in mid-latitudes maybe 10% of the energy entering them will be lost at the far end, all through the day during mid-summer and mid-winter. This is for troughs with absorbers only about 1 m high. For systems with absorbers 10–15 metres above the collectors as with Mills' linear Fresnel arrangement, the problem would seem to be intractable. To solve the problem by extending the absorber ends would be to lose heat through these sections at times when sunlight is not reflecting out of the end of the trough.

[12] Much the same account is given by Broesamle, et al., (n.d., p. 7). In July, the best month of the year, there was no output from the SEG VI plant at 750 W/m, it did not achieve half its peak efficiency until irradiation reached 800 W/m, and full efficiency was reached at 850–900 W/m.

Similarly graphs from Jones, et al. (2001) for a trough ST plant show that at 700 W/m there was no power generated, half of full power was reached at 750 W/m, and full power at 850 W/m.

De Laquil, et al. (1993) report that the intensity of solar energy must rise to over 300 W/m before electricity is generated, even then at a low rate and efficiency. At Sydney in winter the intensity of the solar incidence on a horizontal plane is over 400 W/m for only 2 hours a day. (Morrison and Litwak, 1988.) Even in Central Australia in winter it is above 400 W/m, 500 W/m and 600 W/m for 6, 4 and 2 hours respectively. (Evidence on DNI or beam insolation is discussed below.)

In 1992 solar energy at the SEGS VI site was 82% of that received in 1995, but electrical output was 56% as much, again reflecting the markedly disproportionate effect of reduced insolation (NREL, personal communication).

Data from SANDIA (2005), and from Solar Parabolic Trough, (n.d. b), confirm these observations from SEGS VI. In mid-summer the plant only achieved 57% of its peak output and efficiency at 800 W/m. At 560 W/m it achieved 33% of peak output and at 400 W/m it achieved only 5% of its peak. The effect seems to be a significant factor underlying table 5.37 showing how solar thermal generation declines markedly as sites receiving slightly less solar energy in total kWh/d are considered. The best, Barstow, California, received 2,725 kWh/m/y, Wadi Rum in Jordan received 2,500, 8% less but generated 11% less electricity. Jodhpur in India received 2,200, 19% less than Barstow, but generated 25% less electricity. In other words as site insolation falls, electricity generation falls at an accelerating rate.

Dishes and central receivers could be expected to have much lower thresholds because the concentration ratio is much higher, yet Kaneff's (1992) work with dishes in central Australia achieved no start up under 400 W/m, half peak output at 650 W/m and full output at 1000 W/m (Fig. 82). However SANDIA (2005) reports that dish Stirling systems, i.e., which concentrate solar energy at a point rather than along a pipe at the focus of a trough, can start up at 240 W/m. This is apparent in the evidence on European systems from Heller (2006) and Mancini et al., (2003). The relation between insolation and output for dishes is better than for troughs, but not remarkably so. (See below on dish performance.)

[13] Renewable Resource Data Centre, http://rrdec.nrel.gov/

[14] Within 1000 km of the Mediterranean coast the winter insolation is well below the summer value. The ratio of summer to winter daily energy received in Spain, Morocco, Algeria and Saudi Arabia is (3.4 to 5.1)/1, 2.6/1, 2.3/1, and 3.0/1 respectively. In addition the winter horizontal plane insolation in these countries is lower than in central Australia; i.e., 2.2, (unknown), 2.7, and 2.5 kWh/d respectively.

[15] Maps from Broesamle (n.d.) suggest a somewhat more westerly extension of this area, into the south of Libya. However the annual average insolation for the Sahara in general is 6 kWh/m/d. It reaches 6.5 kWh/m in a region only on the southern Egyptian border, equal to about 1/3 Egypt's area. Mamoudou's plots show that at 20 degrees North of the equator the ratio of average summer to winter irradiation is 1/1.65, but at 10 degrees north it is 1/1.2, i.e., 83% of the summer level. This region has a slightly higher annual average than the south west US, the best region reaching 6.5 kWh/m/d, compared with 5.5 kWh/m/d in the US. However quite large areas extending more to the west and therefore closer to Europe have 6.0 and 5.0 kWh/m/d.

CHAPTER 4

[1] Of course in future costs might be much lower (and in view of increasing energy costs they might be higher), but taking current costs will give us a mark against which to assess the situation if costs are different. Following is some evidence on costs. Hayden, (2003, p. 161, and 2004, p. 210) reports that there has been little fall since 1998.

The current wholesale cost of PV panels is approximately \$5–6(A) per watt, half the retail cost (BP Solar Australia, 2003, Largent, 2003). For the large Victoria Market project completed in 2001 the cost was \$6/W (Origin Energy, 2003). It has been claimed that the recent “Sliver Cell” technology will cut costs considerably, but others regard this as uncertain. Some think its costs could be higher. (UNSW Photovoltaic and Renewable Energy Engineering: Personal communication.)

A check on costs via BP Solar in May 2004 found that the retail cost is \$(A)10.5/W for 80 W panels, and \$(A)6.87 wholesale. Note that the 0.65 m area of this panel indicates \$(A)1,292/m, and 12.3% efficiency although the suppliers claim 16–17%. The difference might be explained by the fact that total module area includes non-cell surface. This point needs to be kept in mind when assessing PV systems.

Hayden (2004, p. 198) points out that the dramatic fall in the cost of computing power, based on silica, does not have implications for PV costs as is often assumed. It has been mostly due to reducing sizes of computer components and increasing speeds, which are not significant for PV performance.

Cost claims vary and this makes analysis difficult, especially regarding what elements have been included, e.g., manufacturer’s profit margin.

[2] See for instance Kelly 1993, p. 300, and Commissioners of the European Community 1994, p. 24. Solar Energy Systems (2003) estimate that BOS costs are around 43% of total system cost (personal communication). However they also state that the installed system cost for grid connected systems is \$12.50/W, indicating that balance of system costs make up 60% of the total. Largent (2003) says balance of system costs are 60–70% of final system cost. BP Solar, Australia, 2003 advise that balance of system costs make up 40–70% of total system costs. For the Austrian Energy Park 66.8 kWp system the balance of system cost was 63% of the total cost. Solar Technologies Sydney (2004) estimated that in May 2004 BOS costs were 50% of final costs. On the other hand Hansen (2004) says that for thin film systems BOS could become 20% of total cost (although it is not clear if all elements have been included in this figure). de Moor, et al. (2003) report BOS costs at c. 50% of system costs, and little fall over the past 10 years. Peacock (2006) reports on 112 panel and 129 panel systems recently installed in South Australia with costs of \$(A)10 and \$(A)11 per watt, i.e., about twice panel cost.

What is said to be the world’s largest PV system has recently begun operating in Germany (DW Radio, 2004). The total cost is reported as \$(US)5.3/W, or (\$(A)7.60/W. This relatively low figure is probably due in part to the use of a wooden support structure with an estimated 20 year lifetime, and especially to the effect of the extremely high subsidy to PV energy in Germany; i.e., including ten year interest free loans and a guaranteed purchase price of 50c/kWh (Worldwatch, 2002).

These figures are for non-tracking systems. Systems in which the panels change their angle throughout the day to track the sun collect some 30% more energy (at low latitudes but at high latitudes there might be no difference at all (see Reichmuth and Robison, n.d., Fig. 2, p. 3), but have much higher balance of system costs. For example each of the 15 metre diameter tracking modules in the 10 kW(e) Washington

State system (Reichmuth and Robison, n.d.) uses 6.7 tonnes of steel, and costs $(US)20,000–$25,000. Each of these supports 80 m of PV panels, indicating a cost of $250–$312/m for steel alone. Reichmuth and Robison (op.cit, p. 4) state that conventional wisdom is that tracking is not justified due to the additional mechanical complexity involved.

Again, the BOS cost is the most uncertain factor in estimating total PV costs, often because it is not clear whether all elements have been included. It is the factor most capable of invalidating the cost conclusions arrived at in this chapter. It has seemed best to be guided by cost figures for total/final installations actually completed, as noted above. These cases seem to indicate that despite some lower claims, the BOS costs for a completed system are more or less equal to the cost of the modules.

[3] The cost of the Mt. Piper power station in N.S.W., Australia, was $800 million (Pacific Power, 1993, p. 104). In 1997 the 2000 MW Loy Yang plant in Victoria sold for $4.9 billion, indicating a sale price of $2.45 billion per 1000 MW (Sydney Morning Herald, 2003). This would be greater than a current construction cost.

[4] This energy payback issue can obscure assessment of the "economic" viability of PV systems. As previously discussed, the energy cost of their establishment is paid for in dollars, which are used to purchase presently cheap energy. The energy produced is expensive, so had the dollar cost of construction been calculated in terms of the dollar price of the energy the plant produces (or the price energy is soon likely to be), the economics of the situation would appear quite different. Also, because the price that would have to be put on the energy produced for sale would be much higher than at present this would tend to reduce the demand for it and therefore the likely economic viability of the PV plant producing it.

My own home lighting system monitored in Sydney, at 34 degrees South, delivers 9.4% of incident energy to the batteries on a clear summer day. Winter performance is lower, because the sun is on a lower angle and its energy has to travel through more atmosphere. This is a tracking system. Systems involving stationary panels would be around 30% less efficient. These figures do not include losses due to the dumping of more than half the energy collected in summer when batteries are full (yet the 880 ah battery capacity is too small for reliable supply in winter). The average daily power delivered per panel is about 0.2 kWh. If this power was sold at 4c/kWh it would take about 270 years to pay back the (A)600 panel cost, if the energy was sold at the same price as coal-fired electricity is sold from the power station. The panel cost is only about 28% of the 25 year life time system cost when several sets of batteries are included, and only about 70% of energy delivered to the batteries can be drawn from them.

[5] The figures roughly align with Mills' (2002, p.28) report of costs around 60 c(A)/kWh for rooftop PV.

[6] Smeltink (2003) confirms this general account but reports that some concentrator cells cost 68c/W.

[7] Unfortunately it has not been possible to find clear and confident publicly available figures for the balance of system costs of tracking systems, either for PV or solar trough technology. The support structures for the two would be similar if the heat exchange components of the latter are excluded, because in both cases a frame supports a parabolic or Fresnel reflector and the whole assembly must be capable of movement about at least one axis (for seasonal change). Because it has a U shaped cross section the area of the trough or concentrator reflector has to be greater than the area of the solar radiation intercepted. Strebkov et al. (n.d.) states that the ratio is between 2 to 1 and 2.4 to 1. (Web pictures often seem to show lower ratios.) This effect does not occur with flat collectors and tends to increase the costs of trough systems per unit of solar energy intercepted. For the Rockingham, Western Australia project the curved glass for the reflectors cost $70–80 per square metre (Littlewood, 2003).

Some indication can be derived from the cost of solar thermal collector fields, although these usually include the cost of the absorber and so are not good guides. The SEGS VI collector cost $(US)487/m (or about $(A)700/m). Strebkov et al. (n.d.) says the cost of the collection field for central receiver solar thermal systems is $(US)200–600/m. Mills and Keepin (1993) put solar thermal field costs at $250/m. The White Cliffs dish system (Kaneff, 1992) cost $363/m, some years ago. These figures would not be sound indicators of mass production costs.

In their discussion of another proposed trough system Brackman and Kearney (2002) state that the collection field would make up 45% of the total cost. Again unfortunately this figure includes heat absorption equipment, but it indicates that the balance of system cost in PV concentrating systems is likely to be much more than the cost of the PV components.

[8] To provide storage capacity for a cloudy day for the output of a 1000 MW power station assuming 3% efficiency, storage must be (8 hr × 1000 MW + 16 hr × 670 MW)100/3 = 618,048 MWh. This is about nine times the amount of energy that a coal-fired power station would consume in one day, and about 25 times as much as it would produce.

[9] Data published in 1999 by BP Solarex (Corkish, n.d., Ferguson 2000a) on a 390 square metre system in the UK, an 805 square metre system in Switzerland, and a 7,960 square metre system in Toledo, Spain, show that over approximately three years the output of these systems was around 6–7% of the solar energy received by the respective collection areas.

The large Victoria Markets system installed in Melbourne in 2001 performs at c. 11% efficiency. A smaller, 1.26 kW system installed in Melbourne, with panels normal to the sun in mid-winter, delivered as electricity only 8% of the solar energy falling on the panels, averaged over the 2.5 mid-winter months (Renew, 1999).

An inspection of data on actual generating performance from the US Solar Electric Power Association (2002) also indicates that delivered electrical energy from recent large-scale systems is often c. 8% of the incident solar energy.

Ferguson (2000a) estimates that for the Toledo system referred to above the energy needed to produce the panels would be 0.25 of the energy the system will produce (over an assumed 30 year lifetime in this analysis).

Especially important for systems not connected to the grid is the fact that when output exceeds demand or storage capacity much of the energy being generated cannot be used and has to be dumped. A large-scale regional system capable of meeting all demand in mid-winter would have approximately twice the required capacity in mid-summer, given that in mid-latitudes winter solar energy incidence is about twice as great in summer.

CHAPTER 5

[1] Lynd, et al. (1991) estimate that idle US cropland could provide only 14%–28% of current US transport fuel, even making the extremely optimistic assumption of 21 t/ha biomass production. (US corn plant growth is 18 t/ha with intensive application of fertilizer, water and pesticides on good soils. However US average forest growth is only around 3 t/ha/y.) Di Pardo (n.d.) says that 10% of US cropland is the maximum amount that could be used to produce cellulosic biomass inputs.

Lynd et al. estimate that 186 million tonnes of waste biomass (dry) could be collected in the US, at under $(US1994)56/t, the higher of two costs examined. Lynd (1996, p. 410) says this would yield 20 billion gallons of ethanol. This is equivalent to no more than 6% of US gasoline consumption.

The Oak Ridge National Laboratory (ORNL, 2005) says US forest wastes could provide 8 Quads (8.4 EJ), whereas all US energy is around 100 Quads. This seems to be a high estimate, equivalent to almost 2 t/ha/y from the entire 250 million ha of US forest, not taking into account energy costs of harvest and delivery.

Australia's largest single source of wastes is likely to be from sugar production. If all 11 million t/y (Mills, 2002, p. 48) was collected it would be only around 2–4% of the quantity required (below). Kelleher (1997) estimates that in Australia a total of 24 million tonnes of agricultural waste could be collected each year, assuming it is ecologically acceptable to leave only 1 t/ha, 30% of growth. Bugg, et al., (2002b) estimate Australia's non-agricultural waste at about 7 million tonnes, and all agricultural production at 55 million tonnes. Some would argue that all wastes should be returned to the soil, since any removal constitutes mining of soil minerals and in the years ahead difficulties in fertilizer supply will correspond to those for petroleum.

[2] While appearing to admit that such a large area would have to be mostly degraded land, at one point (p. 636) they say such a yield could only come from "relatively high quality cropland." The Oak Ridge National Laboratory reports on switchgrass, willows and poplars in the US growing in experimental plots at 11–15 t/ha/y (McLaughlin, 1999). Hall, et al., (1993, p. 635) say the Europeans are "hoping to" raise experimental biomass yields on good farmland to 10–12 t/ha/y. However for very large-scale biomass production, enormous areas of land would be required and

it is not plausible that areas with such yields can be found in the US, let alone in Australia with its poorer soils. Pimentel and Pimentel (1997, p. 203) put overall American agricultural yields at 2.9 t/ha/y, despite the use of the most productive land and large fertilizer and irrigation inputs.

[3] ORNL state that high biomass yields are likely from only about 20 million ha of US cropland (Personal communication). Hohenstein and Wright (1994, p. 187) found that only 91 million ha of US farmland could yield an average of 5 tonnes of biomass per ha per year. Graham (1994, p, 187) concluded that 88 million ha of US farmland will be available by 2030, but 75% of this will not be suitable for bioenergy production, meaning that only 16.2 million ha will be available.

[4] The concept of forest is ambiguous. The Australian Bureau of Statistics (2000) states Australia's forest area as 164 million ha, but regards as forest stems down to 2 metres in height and 20% ground cover. By more generally accepted definition, Australia's forests total approximately 40 million ha.

[5] They give figures for "capable" and "suitable" land, although the definitions are not clear. "Capable" appears to refer to total physical capacity without regard to factors such as use for water catchment or grazing, or tenure. The "suitable" category eliminates these factors, but still includes areas that might not be useable, such as private land which owners might not want to make available, land too difficult to harvest, and land too close to creeks.

Table 2 given by Bugg et al. lists as hardwood production under "suitable", 0.6 million ha @ 18.9 t/ha/y, 1.7million ha @ 15.4 t/ha/y, 2.3 million ha @12 t/ha/y, 4.9 million ha @ 8.6 t/ha/y, 8.7 million ha @ 4.7 t/ha/y, 31.9 million ha @ under 1.3 t/ha.

The forest area per capita for the inhabitants of the state, 1.4 ha over 8.6 t/ha and 2.53 ha over 4.7 t/ha, would be one of the highest figures for developed countries. World forest area per capita is around 0.55 ha, and world average forest growth is probably in the region of 3 t/ha/y.

[6] Sheehan states a puzzling energy production figure, which tends to be widely quoted, i.e., that 1 Quad, approximately 1 EJ, can come from 200,000 ha. This is 5,000 GJ/ha/y, which is 36 times the rate at which energy would be stored in wood growing at 7t/ha/y, and corresponds to a photosynthesis rate of 11%. Most plants have a rate around 0.07% and the highest rate Pimentel (2005) reports is a 3% rate from intensive algae production in Israel.

The general limit on biomass growth and therefore on energy production from biomass is set by photosynthesis. In natural ecosystems only about 0.07% of the solar energy received becomes stored as energy within plant material, although in special agricultural situations such as sugarcane growing the figure can rise to 0.5%. For a region averaging 5 kWh/m/d of solar energy, natural vegetation would be storing energy at the rate of approximately 1.4 kW/ha (i.e., average continuous flow over 24 hrs). This rate of solar energy capture might be compared with the average per capita US consumption rate for all forms of energy combined of approximately

10 kW. In other words 7 ha would be needed to capture the amount of energy each American uses, making no allowance for the proportion of this lost in converting it to useful forms. For liquids and electricity the efficiency of that conversion is around 33% (below), indicating that for energy alone a per capita footprint of over 20 ha would be required. (By 2070 the available global per capita amount of productive land will be 0.8 ha.)

[7] Pimentel and Pimentel (1997). See also Pimentel 1984,1991,1998, 2003, and Pimentel and Patzak, 2004a. If energy credit is given for the dry distillers grain output from the process, the deficit is still 20%. This study took into account emergy inputs, i.e., the energy needed to produce machinery and infrastructure.

Ferguson says the net energy capture of biofuels is " . . . so low that these methods are barely viable." (Ferguson, 2000b). Ulgiati (2001) concludes that the energy return from ethanol produced from maize in Italy is 0.59, rising only to 1.36 when energy credits from waste are maximised. He concludes producing ethanol from maize is " . . . not a viable alternative."

Slesser and Lewis (1979) say the return is 0.3 from acid hydrolysis and 0.125 from enzymatic hydrolysis. Giampietro, Ulgiati and Pimentel (1997) conclude from their review that the net energy return ratio reported for ethanol ranges between 0.5 and 1.7.

Lorenz and Morris (1995) argue that recent technical improvements now enable a positive net energy ratio for ethanol from corn, but only if energy credits for non-ethanol energy outputs are given.

Pimentel and Patzak (2004b) detail energy budgets for the production of ethanol from a number of biomass sources and conclude that in all cases more energy is needed than is produced. The excesses are, for corn 29%, Switchgrass 50%, and wood 57%. For the production of biodiesel from Soy and Sunflower the figures are 32% and 118%. These figures are (understandably) disputed by the US corn -growing and ethanol industries.

[8] Patzak (2005) criticises the 5.9 MJ/l energy credit Shapouri, et al. give for soy meal animal feed by-product, stressing that all output material should be returned to the field. He concludes from his accounting that ethanol from corn requires far more energy than it yields.

[9] Stewart, et al., (1979) estimates that 149 litres of ethanol net, 4.3 GJ, could be produced per tonne of wood.

Lynd (1996) argues that cellulosic inputs such as wood and grasses can have an energy return of 4.4 (1996, p. 439), and in the long term future this might be raised to over seven. This is because much less energy is used in producing woody biomass than producing plants such as corn. However Lynd's figure includes the energy output not in the form of ethanol. About 40% of the energy in the cellulosic input biomass ends up in un-fermentable lignin, which can be burnt to produce electricity. Lynd says the electrical energy produced is equivalent to 20% of the energy in the ethanol, so the thermal energy in the lignin is equivalent to about 60% of that in the ethanol. Again our concern is only with the ER for the production of liquid fuels, meaning that we are not consoled by the fact that other forms of energy might also be derived from ethanol production. (However the electricity needed in the process could be generated from co-products and it is appropriate to deduct this from the energy cost.) Thus from Lynd's account the future ER might be 4.4 overall but for ethanol production alone it would appear to be 2.75.

Lynd's figures indicate that one tonne of biomass input (20 GJ) will yield 6.6 GJ of ethanol. Given that the ER is 2.75, the energy needed to produce this ethanol would be 2.4 GJ. Thus the net ethanol output would appear to be 4.2 GJ. This is in fact the figure Lynd states in two sources for current technology. (1996 and Lynd et al., 2003.)

Table 1 from Giampietro, Ulgiati and Pimentel, (1997) indicates that 8 GJ of ethanol can be produced per tonne of input material, but with a net energy return of between 0 and 0.4 of the input energy. They conclude " . . . none of the biofuel technologies considered in our analysis appears even close to being feasible on a large-scale . . . ". (p. 593).

Foran and Mardon's Table 32.2 (1999) provides a clear estimated energy budget, concluding that net output would be 80 litres of ethanol, 2.3 GJ per tonne of wood input, with an ER of 2.13.

Some conclusions from other sources are as follows: Four ethanol from biomass plants report achieving 416 l/t, 265 l/t, 265 l/t and 125 l/t (from garbage and sludge). www.mrb.org/pdfs/pub26.pdf) The Oregon Cellulosic Study
(www.energystate.US/biomass/document/OCES/pdf)
states 227 l/t and quotes NREL as stating 172 l/t to 249 l/t for various biomass inputs (249 l/t for wood.) NREL's statement that 1 t of biomass can yield 257 l/t is often quoted. (www.eia.docl.gov/oiaf/analysisspaper/biomass.notes.html) A gross yield of 70–120 l/t is reported in
www.princeton.edu/cgi-bin/bytesery.hr/~ota/disk3/1980/8008/800805/pdf These figures vary considerably but loosely indicate an average equivalent to 190 litres per tonne of input material. Unfortunately it is not clear in all these cases whether all energy costs have been deducted or credit for co-products given.

Ferguson (2004) reports estimates arrived at by Just, a New Zealand engineer experimenting on ethanol from cellulosic inputs. One tonne of material can yield 253 litres of anhydrous ethanol. Biomass yield is assumed at 8.5 t ha/y, and ethanol production at 45.7GJ/ha. 27% of the energy in the input material ends up in the ethanol (gross output), but another 22% becomes methane, which is used as processing energy.

Ferguson takes Giampietro, Ulgiati and Pimentel's (1997) conclusions that fertilizer and pesticide required on moderately fertile land would have an energy cost of 20% of the ethanol produced, and that harvesting, transport and handling would take the equivalent of 17% of output energy. Biomass energy production might also involve fertilizer applications that are a large fraction of those in agriculture. US corn production takes about 135 kg of nitrogen per ha per year, and wheat 60 kg. Mason (1992) estimates that biomass energy plantations will require 50–60 kg of Nitrogen per ha per year.

Just estimates electricity use at equal to 8% of thermal energy used (which is questionable as Slesser and Lewis estimate 21%). Other inputs, including embodied costs for steel, cement and water, were estimated at 8.2%. The sum of these input energy costs came to 63% of the energy in the ethanol, meaning ER is 1.58, and leaving an estimated net yield of 3 GJ per tonne of input.

Pimentel and Patzak (2004b) present a detailed account including a comprehensive discussion of cost input factors. They come to the most pessimistic conclusions of those reviewed here, finding that the production of ethanol from wood takes 57% more energy than is produced.

Usually not referred to in reports is the energy cost of dealing with waste water. Giampietro, Ulgiati and Pimental, (1997, pp. 210, 591) state that there would be 13 to 37 litres of high BOD sewage for each gross litre of ethanol produced, requiring energy for treatment equivalent to 50% of the energy in the ethanol. Ulgiati (2001) says the figure rises to 33.58 litres per litre of net ethanol, i.e., after the energy cost of producing the ethanol has been deducted from the output.

[10] Ellington, Meo and El-Sayed, (1993) provide an analysis based on current energy costs, taking into account "emergy" factors such as steel and concrete used in construction of plant. They conclude that for each tonne of woody biomass input with an energy content of 18.89 GJ, 9.95 GJ of methanol can be produced (i.e., 53% of the energy in the input biomass ends up in the methanol), but it takes 5.4 GJ to produce it. The ER is therefore 1.84. Each tonne of input biomass yields a net methanol output of 4.55 GJ.

Giampietro, et al. (1997) use some of Ellington, Meo and El-Sayed assumptions in an analysis which arrives at an ER of 1.58 and a net yield of 3.3 GJ per tonne of input biomass.

[11] From the figures in Foran and Mardon's Table 4.3, for an input of 2.2 t of 80% dry feedstock wood, plus 0.4 t to meet some of the energy cost of production, 1 tonne of methanol gross can be produced. The ER of 2.4 is somewhat better than their figure for ethanol from wood. The energy in the methanol produced is equal to 33% of that in the feedstock. The calculation of an ER for the process has to take into account the 0.4 t of input material used to provide one of the energy inputs. Gross output is 8.6 GJ/t and the energy cost of production is 3.6 GJ/t, giving the 2.4 ER. (Beer, (2004), says Foran and Mardon are "very optimistic" re methanol.)

Ulgiati (2004) gives a similar account; production and processing of woody inputs yields 4.5 GJ per tonne, with an ER of 1.1.

[12] They expect that in future 55% of the energy in the feedstock will end up in methanol. The assumed energy required is one third to one half of that assumed by Ellington, Meo and El-Sayed and Giampetro et al. The difference regarding electricity required at the plant is large, 3.89 GJ vs 0.5 GJ per tonne of ethanol produced. They state that they are assuming electricity generation from biomass at 50% efficiency although in the US it is around 22% (when all energy costs are included according to Hohenstein and Wright, 1994, p, 164). Their assumed energy use in the processing, 2 GJ, is 11% of that assumed by Giampietro, et al., and by Foran and Mardon. It seems from their Table 1 that the 0.5 GJ refers to electrical energy and should therefore have been accounted as 1.5 GJ(th). The footnotes b. and c. under Table 1 dealing with how inputs are recorded are not clear, but they state that one

way of accounting that could have been used would have cut their net yield by one third. In other words their assumptions are quite optimistic and their discussion is about future technologies and efficiencies that might be achieved.

[13]This is a remarkably low figure. It is not clear if the 8% difference refers only to wood used in the processing plant to produce electricity but does not include other energy inputs such as those within the plantations. Attempts to clarify the situation have not been successful.

[14]Youngquist (1997, p. 187) reports petroleum use in the mid 1990s as approximately 6.6 billion barrels, or 277 billion gallons per year. Transport was taking approximately 212 billion gallons. The US Department of Energy, (2000) reports US transport taking 212 billion gallons. The *UN Statistical Abstract* gives 114 GJ per person for 2002, and total US oil plus gas as 203 GJ per person. The International Energy Agency (2006) states petroleum use at 145 GJ per person for 2005.

[15]The IEA, (Fulton, 2005) says that at a net yield of 112 gallons of ethanol per tonne, i.e., 9.7 GJ/t, one-third or more of world transport fuel demand could come from biofuels after 2050. (See also Lovins, et al., 2005, p.104.) Where the land is to come from is not explained. The point here however is that despite the very high yield assumption only a small fraction of demand could be met.

The US National Academy Research Council estimates that by 2020 biofuels could provide the US with the equivalent of 584 million barrels of oil p.a. (Lovins, et al., 2005, p. 103), which would be about 15% of gasoline plus diesel consumption.

Kheshgi (2000) refer to the estimate by Hall, et al. (1993, p. 632) that 890 million ha might be available globally for biomass energy crops, and that this could yield 80 EJ gross. (The yield of 10 t/ha/y is a high estimate for such a large area, much of which would be degraded land.) Global fossil fuel use in the early 1990s is given as 320 EJ, four times as high. Hall, et al. state present world forest harvest at a more realistic 40 EJ/y. They believe the average production from the estimated potential world plantation area would yield primary energy equivalent to 20% of current world petroleum consumption.

Koonin, (2006, p. 435) says studies indicate that biofuels could meet 30% of global demand.

Pimentel concludes that the mid-1990s US energy use of 85 Q is 30% greater than the 54 Q of total solar energy captured by all US vegetation (Pimentel, 1994, 1998, p. 197). (By 2003 US energy use had risen to 96Q.)

Kheshgi (2000) points out that present US ethanol production is equivalent to 0.8% of gasoline use, and is grown on 1% of US cropland, meaning that some 120% of all cropland would be needed for a gross production equivalent to US gasoline (presumably not including diesel). From this the energy cost of ethanol production would have to be subtracted. At another point they say only 14 million ha might be available for energy production in the US by 2030, and this might produce 4.8 EJ, gross. Tolbert and Schiller's (1995) conclusions align with those of Kheshgi. They estimate that the area of US cropland not likely to be needed for food production for decades to come totalled 74 million ha, but only 16 million ha is regarded as well-suited to energy crops.

Giampietro, Ulgiati and Pimentel (1997) find that to produce only 10% of US energy via ethanol would require 37 times the commercial livestock feed production. Providing US food plus energy via biomass would require 15 times the existing cropland, 30 times the agricultural water consumption, and 20 times present pesticide use. For Japan the cropland multiple would be 148 (p. 591) " . . . none of the biofuel technologies considered in our analysis appears even close to being feasible on a large scale due to shortages of both arable land and water . . . " (p. 593). Their discussion does not take into account pollution control measures required to deal with ecological impacts, notably the large quantities of nutrient-rich waste water. For these and other reasons Giampietro, Ulgiati and Pimentel conclude " . . . biofuels are unlikely to alleviate to any significant extent the current dependence on fossil energy . . . " (1997, p. 588).

[16] Australia's hay/fodder production averages about 4 t/ha, and 30 bales/tonne, i.e., 120 bales per ha, and this would sell (pre-Australian 2002 – 3 drought) for about $550 gross income per ha. Australian Bureau of Agricultural Economics figures indicate that the cost of production is around $270 – 300/ha, meaning net income is c. $(A)270/ha.

[17] Optimists do not foresee more than a doubling of yields, corresponding to the general Green Revolution achievement. See Ragauskas, et al., (2006), p. 484.

CHAPTER 6

[1] Even when compressed or liquefied a large volume hydrogen container does not hold much energy. Bossel, Elliason and Taylor (2003) state that a 40 tonne tanker delivering hydrogen will only deliver the equivalent of 288 kg of petrol. Simbeck and Chang, (2002), give the same estimate. This figure has been disputed; (LBST, n.d.) state that it is 10 times too low if hydrogen is liquefied, but even then a 40 tonne truck would be delivering the equivalent of 2.9 tonnes of petrol, and there would be a large energy loss in liquefying the hydrogen which is not taken into account here. According to Friedman (2005), if the vehicle was fuelled by hydrogen at 3,000 psi, its fuel tanks would have to be 14 times as big as when using petrol as fuel. Bossel, Elliason and Taylor conclude that trucking compressed hydrogen 200 km requires energy equivalent to 12.5% of the hydrogen delivered.

[2] The advantages Lovins claims for the hyper-car would be reduced for transport vehicles where the predominant factor is not the lightness of the vehicle but the weight of the freight. As in *Natural Capitalism*, Lovins fails to recognise any problem in providing enough natural gas to generate the hydrogen. (For a critical review of *Natural Capitalism* see Trainer, in press, or http://socialwork.arts.unsw.edu.au/tsw/D50NatCapCannotOvercome.html.) He is assuming in effect that US

natural gas consumption can be increased by some 50%, when its availability is already causing alarm in the US and many believe its future is almost as problematic as that of petroleum.

CHAPTER 7

[1] The Queensland Office of Energy estimates 70%. Ferguson (2004) reports two studies stating 70% and 80% efficiency for the pumping and 80% for the subsequent hydro-electric generation, giving an overall efficiency of 56% and 64%. (Department of Physics, University of Oregon, 2000, University for Applied Sciences, Esslingen, 2000.) If 60% is taken as the overall value, 1.7 units of electrical energy would be required to provide 1 unit after storage.

[2] Taking the figure Sadler, Diesendorf and Denniss (2003) give. 1 MJ/cubic metre at 100 m head, the area would be 38 square km.

[3] Sorensen (2000, pp. 568, 552) gives two figures, 40–50%, and 65%. Hansen (2004) says 75% of the energy used to compress the air is retrievable, without the use of added heat. (He says that if gas is used to add heat the energy return on the total air plus gas input energy can be 85%.)

CHAPTER 8

[1] A 1000 MW power station running for a day generates 24 million kWh, which equals 86 million MJ of heat energy. The temperature of the water coming up from the rock source will be 270 degrees at best. The South Australian simulation operates on an in – out difference of 167 degrees, and anticipates 15–20% efficiency of generation. Evidence from previous sites indicates an efficiency of around 8%. One quarter of the energy produced might be needed to run the plant, but there is evidence that the "parasitic" losses are much higher. Burns et al. (2000) report trials where parasitic losses were 66% of output, and regarded as "irreducible."

Let us assume that the efficiency will be 10%, after parasitic losses. Thus a 1000 MW plant will need an input of 10 × 86 million MJ of heat per day. If it takes 4,200 J to raise 1 litre of water 1 degree, then to raise it 167 degrees will take 701,400 J, i.e., 0.7 MJ. Therefore to deliver 869 million MJ will require 1,228 million litres a day, 850,000 l/minute, or 14,000 l/s. Pumping water 500–1000 metres through fractured rock at this rate is such a daunting task that one must question the parasitic loss assumption built into this approximation.

[2] (http.ftp.ecn.nl/pub/www/library6/conf/ipcc02/costs-02–06.pdf)

[3] The arithmetic is, multiply the present Australian average per capita energy use of about 200+ GJ by 6 for continuation of the present energy consumption growth rate, by 9.4 billion for population, and divide by 400 EJ for present world energy use.

[4] Lovins' main statement of the Factor Four thesis is in Von Weizacker and Lovins, (1997). For a critical analysis of the thesis, see Trainer, Natural Capitalism Cannot Overcome Resource Limits (in press) or at http://socialwork.arts.unsw.edu.au/tsw/D50NatCapCannotOvercome.html

CHAPTER 10

[1] For the alternative, appropriate path see, Trainer, (2005), "Development; The radically alternative view", *Pacific Ecologist*, Summer, pp. 35–42, also at http://socialwork.arts.unsw.edu.au/tsw/D99.Dev.Rad.View.161005.html

[2] http://socialwork.arts.unsw.edu.au/tsw/DocsTHIRDWORLD.html#STGRUCTURAL ADJUSTMENT PACKAGES. For an overview of a radical understanding of Third World "development" see http://socialwork.arts.unsw.edu.au/tsw/08b-Third-World-Lng.html

[3] For an account of the structure and functioning of the empire, see http://www.socialwork.arts.unsw.edu.au/tsw/10-Our-Empire.html For a large collection of documents on the topic see http://www.socialwork.arts.unsw.edu.au/tsw/DocsOUREMPIRE.html

[4] For much evidence on the damaging effects of globalisation see Globalisation Documents, http://socialwork.arts.unsw.edu.au/tsw/DocsGLOBALISATION.html

CHAPTER 11

[1] (Hagmaier, et al., 2000) lists more than 300 settlements. The US *Communities Directory* (Federation of International Communities, 2000) lists 700 settlements. (Discussions of the Movement are given by Douthwaite, (1996), and Schwarz and Schwarz, (1998).

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TERMS

(e) This symbol indicates that the amount of energy referred to is in the form of electricity, as distinct from heat.

Energy return on investment The ratio of the quantity of energy produced by a process to the energy used in producing it. Also indicated by **ER** and **EROI.**

Gross The total amount of energy in a source or output, without deducting the energy that has been used in producing it.

Infeed The amount or percentage of electricity fed into the supply system from a generator.

Integration A renewable energy source such as wind needs to be fitted into the existing supply system, so that supply is not disrupted by the variability of the added source.

Intermittent Most renewable energy sources change in their availability, e.g., sometimes there is little or no wind.

Net The amount of energy produced minus the amount used in producing it.

(p) This symbol indicates that the amount of energy being referred to is the peak or maximum output the device is capable of.

Peak capacity The output of a generating plane when operating at its maximum rate. The average capacity of a coal-fired power station is about 0.8 of its peak capacity. For windmills at good sites the average output is about 0.35 of peak capacity.

Penetration The proportion of supply provided by the source in question.

Ramp rate The rate at which a generating source can be brought up to greater output.

(th) This symbol indicates that the quantity of energy being referred to is in the form of heat, as distinct from electricity. It also stands for "thermal", indicating that the generating source uses heat, e.g., coal, gas or nuclear power stations.

UNITS

Kg	Kilogram	
t	Tonne	
m	Metre	In this book m is also used for square metre.
Km	Kilometre	
MJ	Megajoule, one million joules	
GJ	Gigajoule, one thousand MJ	
TJ	Terajoule, one thousand GJ	
PJ	Petajoule, one thousand TJ	
EJ	Exajoule, one thousand PJ	
kW	Kilowatt	
MW	Megawatt, one thousand kW	
GW	Gigawatt, one thousand MW	
TW	Terawatt, one thousand GW	

Changes in exchange rates and costs while this book was being written complicate conclusions to some extent. The exchange rate used has been #$(A)1 = $(US)0.7.

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