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People's wants trump protection of natural resources. Consumption habits compound the effects of large populations. Consumption and population in excess of the carrying capacity degrade the environment. Environmental degradation shrinks the carrying capacity, so fewer people can be supported on a sustainable basis in the future. It is small wonder that numerous students of carrying capacity, working independently, conclude that the sustainable world population, one that uses much less energy *per capita* than is common in today's industrialised countries, is in the neighbourhood of 2 to 3 billion persons.

Virginia Abernethy in *Where Next?: Reflections on the Human Future.*

The Optimum Population Trust (U.K.): Manchester

October 2002

INTRODUCTION

To some extent, this introduction is an Abstract of the 38 pages which follow.

The whole of this edition is concerned, in one way or another, with the energy component of the Ecological Footprint. The narrow focus is justifiable because the energy component of the world's Ecological Footprint constitutes 49% of the whole Footprint — at least that is the figure which applies to the *Living Planet Report 2002* (*LPR 2002*), and it is in line with previous assessments, including the earlier *LPR 2000*.

The *2nd Footprint forum, Part I*, conducted over the last year, concludes that the 'carbon absorption paradigm' is misleading — as critics have long held to be the case. The paradigm serves to blur the reality of the magnitude of the problem of excessive carbon emissions. Thus the paradigm needs to be abandoned as a *logical basis* for dealing with the energy component of the Ecological Footprint. By far the most likely contender for replacing it, to provide a rational basis for dealing with energy, is the 'renewable energy paradigm'.

A survey of the whole renewable energy field (pages14 -18) concludes that the best current estimate for an energy/land ratio, based on renewable energy, is 3 kW/ha (95 GJ/ha/yr). This is fairly close to 2.5 kW/ha — the energy/land ratio used in *LPR 2002*, based primarily on the carbon absorption paradigm. *Thus changing the logical basis of dealing with the energy component of the Footprint does not significantly change the numbers which have emerged in previous eco-footprinting studies* (see page14).

A large part of this issue is devoted to dealing with renewable energy, in particular photovoltaics (PV) and wind turbines. The extensive focus on photovoltaics can be justified because the figure that the 'renewable energy paradigm' needs to establish — a *mean* energy/land ratio — would be entirely different were photovoltaics able to play a substantial part in providing renewable energy. The net energy-capture (amount of useful energy captured per hectare) from photovoltaics is of the order of 200 kW_{th}/ha (kW_{th} units represent the primary energy equivalent of the electrical output). The question is whether it will be viable to use this energy collection method on a large scale. The answer, see pages 23-37, is that the cost of photovoltaics is likely to remain sufficiently high to exclude this technology from playing anything but a minor role in providing renewable energy.

Accounting only for the land monopolised by wind turbines, wind power has a net energy-capture that is about five times that of PV, and the economics are better. The problem with wind power is of another kind, namely that the amount of power which could be gained from this source is limited. The April 2002 *OPT Journal*, pages 11-13, showed the limitations of hydrogen production. In this issue, pages 38-40, we look at another limitation on wind power — variability of output, and the implications of needing to have time-independent 'back-up' power (in the renewable category that means biomass) to deal with this variability.

A lighter, less academic tone is adopted in *A Plain Man's Questions Concerning PV* (pp. 22-30 & 33-37). This *'Plain Man* ... ' series will return in future issues.

My own role in this issue may appear somewhat oversize, but in preparing it I have received valuable input from several people, in particular, Jill Curnow, Edmund Davey, David Pimentel and Yvette Willey. I thank them all for their help and encouragement.

Lastly, OPT have an announcement. Edmund Davey, until recently our chairman, managed to entice Professor John Guillebaud (on retirement from his professional life) into taking over the OPT chair; John has chosen as his co-chair Rosamund McDougall. She was responsible for setting up our website <www.optimumpopulation.org>.

A 2nd FOOTPRINT FORUM, PART I

Introduced and moderated by Andrew Ferguson

A Forum on Ecological Footprints appeared in the March 2000 edition of *Ecological Economics*. Henceforth we will refer to this Forum as simply 'the Forum', with a capital F; page numbers given for contributors to the Forum refer to this March 2000 issue. Some fundamental issues were raised in the Forum, but they were not resolved. That is the context in which a '2nd Footprint forum' appears in these pages. In this forum, I intend to raise the two most important issues in eco-footprinting. In *Part I* we will deal with one of them. *Part II* will follow later.

It was in September 2001, that those with an interest in eco-footprinting were invited to respond. They were Mathis Wackernagel, Nicky Chambers and Craig Simmons — the last two at Best Foot Forward — all three co-authored *Sharing Nature's Interest: Ecological Footprints as an Indicator of Sustainability* (Chambers et al. 2000); William Rees; and Rod Simpson, who wrote *An Ecological Footprint Analysis for Australia* (Simpson et al. 2000). We also asked three people who are knowledgeable about eco-footprinting but who do not have a position to defend, because none of their work has hinged on the subject, namely Jill Curnow, Robert Herendeen, and David Pimentel.

Ecological Footprints: the energy component

In the Forum, Robert Herendeen succinctly elucidated the main problem of what I call 'the carbon absorption paradigm', that is basing the energy component of the Ecological Footprint on carbon absorption. He said, p. 357: "Net CO_2 uptake is overestimated; it saturates to zero as succession is completed, unless there is a scheme to harvest the wood and prevent it from decaying. Thus EF underestimates energy land." One response to Herendeen's point would be that *the carbon absorption paradigm is not meant to be realistic*: namely the proponents readily accept that such carbon absorption would not actually happen; the concept is useful purely as a measure of the amount of forest that *would* be needed to absorb excess carbon dioxide *were* it possible to find some way of locking up the carbon in perpetuity.

If that is the case, how successful have the proponents of eco-footprinting been in making their position clear? Not very, judging from another contributor to the Forum, Robert Ayres, who said, p. 347, "The hidden implication, which is not sufficiently clearly spelled out by the EF proponents, is that in a sustainable world, energy would be obtained from fossil fuels but the latter would be burned — in any given country — in just such quantities as to permit the resulting carbon dioxide emissions to be absorbed by vegetation within the country." No mention there of the whole thing being based on an unrealistic proposition, requiring that after the forest has finished doing its job of absorbing carbon, the wood is to be whisked away, never to be seen again!

Moreover Simpson et al. (2000) appear to imagine that eco-footprinting is dealing with the real world when they say, p. 15, "The use of carbon dioxide emissions also links the indicator directly to the very topical issue of global warming." Would they have said that if they understood that the carbon absorption paradigm was unrealistic?

However, it has to be said that a careful reading of Wackernagel and Silverstein's (2000) contribution to the Forum does make it clear that the paradigm is unrealistic, for they say, p. 392, "Therefore, the footprint includes fossil fuel in terms of ecological capacity necessary to reverse its waste impact, namely, CO_2. The only eco-systems that can remove significant amounts of CO_2 from the atmosphere, at least for their first 30 - 50 years, are growing forests

— and using them to sequester CO_2 is still the prevailing technology. As our calculations show, such absorption forests would require absurdly large portions of the bioproductive surface of this planet." Careful consideration of the words, "at least for their first 30 - 50 years," provides a *reasonably clear* indication that the whole concept is unrealistic.

However, the proponents of eco-footprinting have rarely been as lucid as that. Wackernagel and Rees (1996) state, p. 72, "Data on typical forest productivities of temperate, boreal and tropical forest show that average forest can accumulate approximately 1.8 tonnes of carbon per hectare per year. This means that one hectare of average forest can sequester annually the CO_2 emissions generated by the consumption of 100 gigajoules of fossil fuel." No reference there to the fact that the "sequestering" will only happen during the period up to 30 - 50 years after the forest has been planted. (To avoid confusion later it should be mentioned that subsequent reappraisals changed the carbon absorption rate to 0.95 tC/ha/yr). Chambers et al. (2000), when explaining their methodology, are also cryptic about the energy footprint, and the related "sequestering," saying only, p. 67, "This portion of the calculation is used to derive the energy footprint — usually the amount of forested land necessary to sequester the CO_2 emissions."

An unequivocal decision to use an unrealistic metric, *if stated openly*, would not matter if the results which emerged did not tend to mislead. Our contention is that they do tend to mislead, insofar as the carbon absorption paradigm carries an implication, rarely if ever denied by the proponents, that it really does (or would if only it were possible to plant enough forest), somehow take account of excess carbon. But when eco-footprinting is used to estimate the extent that humans have overshot the planet's carrying capacity, the result is around a 30% overshoot, as per page 1 of *The Living Planet Report*, 2000 (WWF, 2000). No one can read that *Report* without presuming that it 'takes carbon dioxide into account'. Yet the correct overshoot figure (in 1990, see below) *based on a realistic appraisal of carbon dioxide alone* is 150%.

Overshoot based on carbon dioxide alone

To express the matter as succinctly as possible, I will adopt a fanciful notion. As mentioned, the *Living Planet Report* 2000 was in line with previous eco-footprinting studies in stating that world population is overshooting biocapacity by around 30%. Like other eco-footprinting work of Wackernagel and his colleagues, the report aimed to be a snapshot of the situation at a point in time. If the overshoot is 30%, it follows that a representative reduction of world population, reducing it to 1 / 1.30 = 77%, would, at that point in time, cure the overshoot. Insofar as eco-footprinting — based on the carbon absorption paradigm — is realistic, this should guarantee that carbon emissions are brought into balance with the Earth's capacity to absorb the excess carbon that is being released by burning fossil fuels (atmospheric carbon is currently *increasing* at a rate of 3.5 billion tonnes per year, Houghton, 1997:23).

The Intergovernmental Panel on Climate Change (IPCC) stated, in 1992 (Engelman, 1998:15), that we need to reduce fossil fuel emissions to 40% of the 1990 level in order to bring emissions into balance with the absorptive capacity of the Earth. The 40% figure is not a matter of doubt, as the arithmetic appertaining to the necessary reduction — to stop atmospheric carbon levels increasing — is simple. So, with the 40% figure secure, the requirement is for a representative reduction of the population sufficient to reduce it, living in its present lifestyle, to 40% of its 1990 size. Or, to put it another way, according to the IPCC, based on carbon dioxide alone, the overshoot in 1990 was (100 / 40) -1 = 150% (a figure which has since increased to 165%).* While there are other reasons for challenging the logical basis of the carbon absorption paradigm, the gap between 30% and 150% surely indicates that the carbon absorption paradigm needs to be consigned to history without delay.

We, in OPT, are not challenging the concept of eco-footprinting. We believe it to be a valuable methodology, indeed the best method available for making a quantitative assessment of both national and global carrying capacities (Ferguson, 1998, 1999). We argue only for a change in the *logical basis* of dealing with the energy component of Ecological Footprints. In our estimation, the energy/land ratio has the right value. That ratio is in the region of 95 GJ/ha/yr, 3.0 kW/ha, not greatly different from the 100 GJ/ha/yr used initially in eco-footprinting or the mean figure of 80 GJ/ha/yr used in the Living Planet Report 2002 (WWF, 2002). Thus it is not the value that is in dispute, but the basis on which the value is to be established. We believe that basis needs to be *net* energy-capture (the amount of 'useful' energy that can be captured per hectare) from renewable resources. Work remains to be done to make the 3.0 kW/ha value secure, but progress in the field is good, and the figure looks highly plausible on present evidence.

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* These are the actual numbers for those percentages. Carbon emissions in 1990, from burning fossil fuels, were 5.95 billion t/yr (*Vital Signs*, 2000). Thus the 40% figure, which is required so as to prevent carbon concentration continuing to increase, is 2.38 GtC/yr. Thus overshoot in 1990 was (5.95 / 2.38) -1 = 150%. 1999 fossil fuel emissions were 6.31 GtC/yr, making the overshoot (6.31 / 2.38) -1 = 165%.

CONTRIBUTION TO A 2ND FOOTPRINT FORUM, PART I

From Jill Curnow, Vice-President of the NSW branch of Sustainable Population Australia Inc.
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The term Ecological Footprint (EF) can be varied to suit the context, but one useful definition is 'the area of land needed to sustain the current consumption or lifestyle of an individual, community or nation'. The elements of consumption which relate to food and fibre are generally accepted. The methodology normally employed, namely using worldwide productivity, is sensible, as it allows comparison between different lifestyles. Eco-footprinting's main problems arise from the remaining component of the consumption footprint, namely energy. That, of course, is the subject of this part of the forum.

One method of dealing with energy — not greatly challenged until this forum — has been that of relating the area to the amount of forest that would be needed to absorb all (or 65% as per page 30 of WWF, 2000) of the carbon released by a given population's consumption of fossil fuels. The uncertainties surrounding this procedure are manifest. There is no need for me to expatiate on what has already been said in Ferguson's introduction.

Some people have advocated excluding an energy component from the EF because of the many uncertainties, including the fact that a few academics continue to argue that human actions are not significantly responsible for climate change, so no action to restrain emissions is necessary.

However, there are almost irrefutable arguments from petroleum geologists (Campbell, 1997; Youngquist, 1997) telling us that the peak of world oil production will occur before 2020, and natural gas not long thereafter. Thus it is of prime importance to account for the energy component of the EF. This is especially true for rich nations, because without a high per capita energy consumption, 'modern' agriculture, manufacturing, transport, waste disposal, health and education services cannot function.

Thus it is essential for there to be an energy component to the EF. Assessing an energy/land ratio based on renewable energy is beset with difficulties, for instance: (1) determining the area which is available for siting wind turbines; (2) determining the 'capacity factor' likely to be achieved when making full use of the available sites; (3) determining the energy inputs required to build and maintain the infrastructure needed to distribute the energy gathered from the wind; and (4) determining the energy needed to build and supply the power stations for providing energy when the wind is inadequate.

That example outlines the difficulties associated with *just one aspect* of renewable energy. Despite the difficulties, because of the importance of having a realistic (which carbon absorption is not) energy component to the EF, I accept the need to base the energy component on renewable energy and, until some more persuasive analysis is available, I am ready to accept 95 GJ/ha/yr (3 kW/ha) as a sensible basis for dealing with the energy component of the EF.

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CONTRIBUTION TO A 2ND FOOTPRINT FORUM, PART I

From David Pimentel of Cornell University. <dp18@cornell.edu>

My response to the forum can be brief. Ferguson's introduction clarifies the confusion which has been undermining the concept of eco-footprinting, namely the 'net CO_2 uptake'. I endorse his analysis. The alternative method of dealing with the energy footprint, namely the area of land which is needed to provide energy from renewable sources, remains somewhat speculative, since every aspect of renewable energy generation is subject to hot debate. Nevertheless, the energy/land ratio used in eco-footprinting is a fair approximation to the correct figure; at least it is not excessively optimistic. For this reason, both the essential concept of ecological footprints, and the published footprint and biocapacity figures, remain substantially valid. That assertion requires amplification.

It seems to me unfortunate that eco-footprinting has become more complex than it need be. The complication stems mainly from incorporating the sea into ecological footprints. Actually this is hardly necessary, as the sea provides less than 5 percent of the total food protein consumed by the world's human population and less than 1 percent of the overall caloric intake (Pimentel and Pimentel, 1996). The sea's relatively low productivity, per hectare, necessitates the introduction of equivalence factors. The assumptions needed to establish equivalence factors introduce further uncertainty, and they make eco-footprinting opaque for those who have not made a study of the subject. Despite these shortcomings, so great is the difference between the biological capacity available to individual nations, that the essential eco-footprinting messages are hard to refute.

For instance, Afghanistan and its bordering nations have on average 0.7 global hectares (formerly known as Area Units) of biocapacity per person; this compares to 2.9 global hectares per person for Western Europe, and 6.1 global hectares per person in North America (WWF, 2000). Incidentally, the figure for North America is misleadingly high, in that it ignores *unsustainable* irrigation and damaging agricultural intensity (note eco-footprinting does not currently attempt to take sustainability into account, though it could do so by adjusting biocapacity).

While I would prefer to see these figures presented without the complications of equivalence factors, nevertheless I think that the uncertainties that have been introduced are not great enough to make the figures useless; there are easily observed facts which give credence to the figures. For example, Afghanistan not only has a lower per capita biocapacity than any nation bordering it, but it is equal to that of Rwanda, 0.4 global hectares per person (WWF, 2000). Experience tells us that Afghanistan and Rwanda are both in ecological peril, and intermittently unable to support their populations.

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IMPLICATIONS OF THE 2ND FOOTPRINT FORUM, PART I

By Andrew Ferguson, 11 Harcourt Close, Henley-on-Thames, Oxon. RG9 1UZ, U.K.

Abstract
Sections 1 to 4 of this closing paper of the *2nd Footprint forum, Part I,* set out the primary conclusion: the 'carbon absorption paradigm' is often misleading, and it is troublesome to use in conjunction with other paradigms which produce stable, rather than escalating overshoots. It needs to be abandoned rather than reformed. Section 5 takes a brief look at two alternative paradigms for evaluating an energy/land ratio. These are extreme simplifications of the renewable energy paradigm; possible further debate about them is left for the future. Sections 6 and 7 derive an energy/land ratio for the 'renewable energy paradigm', arriving at a figure of 95 GJ/ha/yr, or 3 kW/ha. This is tolerably close to the 80 GJ/ha/yr energy/land ratio used in the recent *Living Planet Report 2002*. Section 8 gives an overview of the important uses to which eco-footprinting can be put after it has been dissociated from the carbon absorption paradigm. Section 9 considers some unjustified objections to 'standard' eco-footprinting.

1. Introduction: how the forum was managed

Every effort has been made to see that this forum, which took place over about a year, starting September 2001, was conducted with scrupulous fairness. All those on the side of the 'defence', Chambers, Rees, Simmons, Simpson, and Wackernagel, and those for the 'prosecution', who in addition to myself were Curnow, Herendeen, and Pimentel, were assiduously kept up to date with the progress of the forum. Curnow and Pimentel quickly made their contributions. Herendeen, who was quoted in the introduction as an example of one of those who had drawn attention to the misleading nature of the carbon absorption paradigm, also responded early. The essence of his contribution was confirmation that he adhered to his view, that absorption of carbon by biomass must be only a temporary phenomenon unless a method can be found to store the periodically harvested biomass so that it does not decay or burn. He also remarked that he continued to like the ecological footprint as a method of bringing home the effect of off-site impacts. He added that he was content to watch more zealous colleagues thrash out the details. In order to keep fairly strictly to the points under discussion in this forum, it was deemed appropriate not to reproduce Herendeen's contribution in full.

It took more time to extract responses from those on the side of the 'defence'. Rees was first to contribute a paper. It contained this key statement:

> Typical carbon sink forests have a useful life of about 50 years, after which they should be retained as carbon stores. While not long, 50 years is sufficient to span the expected life expectancy of recoverable conventional petroleum and natural gas.

With those words, Rees confirmed the assertion by Wackernagel and Silverstein mentioned in the introduction. Wackernagel reiterated the same point in his July 10 contribution to the forum:

> There is no alternative to reducing the fossil carbon load of the human economy if we want to stabilize the carbon concentration in the atmosphere. The sequestration is only transitory and will run into saturation as ecosystems mature.

Also Wackernagel, in a paper written with ten co-authors (including some well known names — Norman Myers, Richard Norgaard, and Joergen Randers), *Tracking the ecological overshoot of the human economy* (Wackernagel et al, 2002), made this comment:

> CO_2 sequestration rates may decrease as more and more forest ecosystems reach maturity. Eventually afforestation will saturate so that the net rate of CO_2 uptake goes to zero.

So the stance of the 'defence' can be summed up thus: it is acknowledged that carbon absorption capacity will saturate, but they argue that this is made adequately clear, so that carbon absorption can be used as a measure without misleading people. It is a defence we will need to bear in mind.

Rees reiterated to me, in an email dated 20 June 2002, that he never intended that the carbon-sink should be regarded as permanent. Nevertheless he made it clear that he was not ready to abandon the carbon absorption paradigm, saying:

> In thermodynamic terms the carbon-sink approach . . . is entirely appropriate as an accurate estimate of the energy component of the total footprint, whether or not available carbon sink forests become saturated or no sink is available. In either case the EF is accurate if calculated correctly. The deficiency in assimilation capacity then becomes a measure of overshoot.

While that is strictly true (and similar to the suggestion in the introduction, pages 3 and 5), the corollary is that it is incumbent on those using the carbon absorption paradigm to make manifest, *on every relevant occasion*, the escalating nature of the "deficiency in assimilation capacity." For if absorption capacity is admitted to be temporary, it is necessary to follow through the logical consequences. Let us look at the *Living Planet Report 2002* (WWF, 2002). The world footprint is 13.6 billion gha (13.6×10^9 global hectares) and the world has 11.4 billion gha of biocapacity, so overshoot is 13.6 / 11.4 -1 = 20% (as the report states). The mean world energy footprint is 1.12 gha per person, which works out at a total of 6.7 billion gha. Supposing no other changes were to occur, except maturation of the forests, then after 50 years, when all the sinks are full, the overshoot would become (13.6 + 6.7) / 11.4 -1 = 80%. After another 50 years, overshoot would increase again, this time to (13.6 + 6.7 + 6.7) / 11.4 -1 = 140%. *LPR 2002* fails to say that under the carbon absorption paradigm the 20% figure is merely the *start* of an escalating overshoot.

The carbon absorption paradigm could be used as a measure without misleading people, *but only if two conditions are met*: (1) in any definition or description of the meaning of ecological footprint, the temporary nature of the absorption capacity is made clear; (2) whenever an overshoot is mentioned, reference is also made to the escalating nature of that overshoot. It will be our main task to consider how far those criteria are met.

Neither has Wackernagel abandoned the carbon absorption paradigm. He titled his contribution *Fixing the Footprint's Fossil Fuel Fallacy*, but it turned out that the 'fix' he had in mind was to show that the figure for the land/energy ratio was similar to other possible methods of assessment. His 'fix' involved essentially asking and answering the wrong question, since *it has never been a contention that the carbon absorption paradigm produced an inappropriate energy/land ratio* — only that it is misleading in its implications that it is unambiguously measuring the 'wastes' that humans produce.

Wackernagel's proposed alternatives are only extreme simplifications of the 'renewable energy paradigm'. It could be that there are reasons for adopting them, rather than the renewable energy paradigm, but since Wackernagel proposed them some ten months into the forum (he was of course tremendously busy producing *LPR 2002*), there was insufficient time left to get comments on them from other members of the forum. Thus these alternatives will be mentioned only briefly in Section 5, and possible discussion of them will be postponed.

Perhaps a word about peer review is appropriate here. This is difficult to achieve in the context of eco-footprinting. My solution was to send out the whole of the present forum, including this article in draft form, to all participants, asking them to point at any suspect data or flaws in logic. Let us return to the other participants.

Chambers repeatedly indicated that it would be immensely difficult for her to find time to defend the carbon absorption paradigm, whereupon I asked her to enlist the help of her fellow author (in *Sharing Nature's Interest*), Simmons. Between them they could only contribute an intimation that, in general, they agreed with Wackernagel, and, off the top of their heads, they thought the energy/land ratio was numerically about right. As already mentioned, whether the figure is numerically correct, as judged by other paradigms, is not the issue.

Simpson had indicated from the outset that he would like to be kept advised of the forum's progress (which was duly done), while indicating that he did not anticipate making a contribution. From this, it will be apparent that any lack of balance in this *Part I* of the forum is not from want of trying to activate those with a 'duty' to defend the carbon absorption paradigm (a duty insofar as their work assumes that the paradigm is not a misleading measure).

We have seen that the carbon absorption paradigm would not be a misleading measure provided that certain conditions are satisfied. We must now enquire whether they are.

2. Definitions of ecological footprints

Although similar statements occur throughout eco-footprinting literature, let us take two quotations from Wackernagel et al., 2002:

> The ecological impact of humanity is measured as the area of biologically productive land and water required to produce the resources consumed *and to assimilate the wastes generated by humanity*, under the predominant management and production practices. [my italics]
>
> Burning fossil fuel adds CO_2 to the atmosphere. We calculate the area required by estimating the biologically productive area needed *to sequester enough carbon emissions to avoid an increase in atmospheric* CO_2. [my italics]

In the last section, we have already quoted the words that occurred in the same paper relating to the *temporary* nature of the carbon absorption capacity, but can we blame people for being misled by the above statements, when it would be so easy, and appropriate, to introduce a qualification to them. For instance the last statement would have no tendency to mislead were the words in square brackets to be added, thus:

> Burning fossil fuel adds CO_2 to the atmosphere. We calculate the area required by estimating the biologically productive area needed to sequester [so long as the putative forest is growing] enough carbon emissions to avoid an increase in atmospheric CO_2.

In his contribution, Wackernagel was forthright (as is Rees) in mentioning the lack of realism in the carbon absorption paradigm:

> We fully acknowledge that the sequestration approach is not really a feasible mitigation method . . . Indeed, it is absurd to believe that sequestration is the solution.

But those qualifications are missing from other statements and crucial definitions. In his July 10 contribution, Wackernagel said:

> The Ecological Footprint measures the amount of biosphere necessary to renew what people use. More precisely, it calculates the area necessary to produce what people consume and *absorb the waste they generate under current ecosystem management schemes and using prevailing technology*. . . . [my italics]
>
> *How much space would humanity need if we were to stabilize atmospheric CO_2 concentrations?* This is the area measured through the first method of the fossil fuel Footprint. [my italics]

The general reader can surely be excused for taking these statements at their face value, rather than mentally adjusting them according to the aforementioned caution that absorption capacity will "eventually" become saturated.

3. References to overshoot

So much for definitions. Now let us consider how clear it is made, in the literature, that the assessments of overshoot are only *initial* estimates of the areas needed to absorb human wastes. This is how Wackernagel et al. describe their results in their July 2002 paper:

> The calculation provides evidence that human activities have exceeded the biosphere's capacity since the 1980s. This overshoot can be expressed as the extent to which human area demand exceeds nature's supply; whereas humanity's load corresponded to 70% of the biosphere's capacity in 1961, this percentage grew to 120% by 1999.

And this statement comes from *LPR 2002* (WWF, 2002):

> The productive quarter of the biosphere corresponded to an average of 1.9 global hectares per person in 1999. Therefore human consumption of natural resources that year overshot the Earth's biological capacity by about 20%.

There is no mention there — or in fact in any references to overshoot that I have seen — that these are only *initial* estimates of an *escalating* overshoot: for it is escalating whenever the energy footprint is based on the carbon absorption paradigm (which of course it claims to be).

While appropriate qualifications are missing from definitions, and from statements about overshoot, since there are cautionary words elsewhere (at least in more recent publications), concerning the temporary nature of the absorption capacity, it can hardly be said that the statements quoted are wrong, but they do not meet the two aforementioned criteria: (1) in any definition or description of the meaning of ecological footprint, the temporary nature of the absorption capacity is made clear; (2) whenever an overshoot is mentioned, reference is also made to the escalating nature of that overshoot.

A second alternative criticism of the carbon absorption paradigm, besides its tendency to mislead readers, is that it would require excessive complication to use it unambiguously in harness with another paradigm which does not produce an escalating overshoot. And usually, in eco-footprinting literature, reference is made to some alternative paradigm (of which there are two examples in Section 5). The impression is usually given that the energy component of the footprint could just as well be determined by one of these alternative paradigms, which thus acts *in support of* the carbon absorption paradigm. However, none of these alternative paradigms (including the renewable energy paradigm) suffer from the problem of producing escalating overshoots. Thus every definition, and every statement about overshoot, requires two sets of qualifications: one to deal with the escalating overshoot of the carbon absorption paradigm, and the other one to deal with the stable overshoot of the alternative paradigm. Thus, for example, to avoid being misleading, the last quote should read:

> The productive quarter of the biosphere corresponded to an average of 1.9 global hectares per person in 1999. Therefore human consumption of natural resources that year overshot the Earth's biological capacity by about 20%. As far as the carbon absorption paradigm is concerned, this is only an initial figure, which will escalate as the carbon sink capacity is exhausted. As far as the alternative paradigm is concerned, the 20% figure will remain constant provided all the other factors, population size, average consumption per person, the kinds of production system and the biocapacity, remain unchanged.

Of course other forms of words are possible, but some formulation is required in order to show that the 20% figure is not in conflict with the 150% overshoot (in 1990, see page 5) which is apparent from considering excessive carbon dioxide emissions alone. In the absence of suitable explanatory words, eco-footprinting, so long as it says that it is linked to carbon emissions, will serve to conceal the 150% overshoot. So important is that point that we must study it further.

4. Untenability of the carbon absorption paradigm.

In his contribution, Wackernagel claimed that the carbon absorption paradigm linked "the results effectively to the currently quite prominent CO_2 debate." How good is that linkage when eco-footprinting indicates a 20-30% overshoot, while the carbon dioxide emissions situation alone indicated, in 1990, a 150% overshoot? Let us take another look at this from a slightly different perspective.

The point is best seen by a thought experiment. As assessed in *LPR 2002*, the world has 2.6 billion hectares of forest available for carbon absorption. *LPR 2002* indicates the need for a 20% expansion in the size of the Earth in order to accommodate humans. If, by a magic wand, we were to expand the cropland, grazing land, and the total forest area, by 20%, the world would have available a further 1.8 billion hectares. Were we to plant that with forest, then there would be a total of 2.6 + 1.8 = 4.4 billion hectares of forest available for carbon absorption.

The requirement, at the rate of carbon absorption that is assumed in *LPR 2002*, 0.95 tC/ha/yr, and taking account of the 35% assumed to be absorbed by the oceans, is for 4.3 billion hectares of freshly growing forest. The mooted 4.4 billion may or may not be sufficient: it depends how much of it is mature forest, and whether the mean absorption rate approximates to 0.95 tC/ha/yr. We need not speculate on that point, because what is fairly certain is that when 50 years have passed, the world will need another 4.3 billion hectares of freshly planted forest; and 50 years after than yet another 4.3 billion hectares (at present emission rates). In short, under the carbon absorption paradigm, the measurement of a 20% overshoot is merely an initial figure for an escalating overshoot.

That argument has already been deployed in a slightly different form, but such is the indomitable spirit of the besieged defenders of the carbon absorption paradigm — I have been laying siege to it for about five years — that there is no alternative but to pound their fortifications into rubble!

Rees hinted, in the first quotation above, at another line of defence, namely that after 50 years, so much fossil fuel would have been burnt up that fossil fuel emissions would consequently drop by the required 3.5 Gt/yr, and renewable energy would then supply the energy needed. One weakness in that argument is that it is far from clear that we will have *sufficiently* used up fossil fuels in fifty years time, but letting that pass, if that is to be the argument, then it is imperative for us to verify that the energy/land ratio that is used for carbon absorption is also a sound estimate for a sustainable use of renewable energy resources.

In Section 6, we return to the renewable energy paradigm — which everyone concedes to be *realistic*, albeit difficult to quantify. Now, as promised, we will digress briefly to state the simple alternatives to the ‘renewable energy paradigm’ mentioned by Wackernagel in his July 10 contribution.

5. Alternatives to the ‘renewable energy paradigm’

The ‘energy replacement’ alternatives suggested by Wackernagel, in his contribution, are of the same kind as indicated in *LPR 2002*, where it states, pages 31 and 32:

> **Burning fossil fuel** can be translated into a bioproductive area through either CO_2 sequestration or . . . . Alternatively, the fossil fuel footprint can be calculated by determining the amount of biologically productive area that, left alone, is able to replace the consumed energy. This approach, using fuelwood as nature’s energy currency, leads to roughly the same area requirements.

We have already commented on the difficulties which arise from having two paradigms in tandem — one producing escalating overshoots and the other one stable overshoots. But our task now is briefly to look at the details of the two paradigms mentioned in Wackernagel’s contribution.

Let us repeat, these paradigms are *not* misleading in the same way as the carbon absorption paradigm, because they do *not* produce escalating overshoots (with a tendency to masquerade as stable ones). In fact, they are extreme simplifications of the renewable energy paradigm. The basis for arguing that they are superior would seem to be confined to saying that they are simpler; however further thoughts on that will be postponed to another issue. In presenting them, we will give the land/energy ratios they imply, which may be compared with the current *LPR 2002* mean figure of 80 GJ/ha/yr. Hopefully it will be helpful to give the numbers, but giving numbers does not at all imply that we should judge the paradigms on the basis of the figures they produce.

The first proposed paradigm is the ‘energy replacement with wood paradigm’. According to this paradigm, the measure is to be based on keeping available, for energy purposes, the amount of forest that would sustainably provide the current usage of energy. The assumption of this paradigm is that fuelwood would be harvested at the growth rates occurring with the current age distribution of forests. These growth rates are estimated to be 2.6 t dry wood per hectare per year. The calorific value of dry wood is about 20 GJ/t, so this paradigm gives an energy/land ratio of 52 GJ/ha/yr.

The other paradigm that Wackernagel proposed for consideration might be termed the ‘energy replacement with improved-wood-harvesting paradigm’. It is the same as the first paradigm except that it assumes that a 60% increase in growth rate could be achieved by keeping the forest young — through harvesting at 20 year intervals or less. On this assumption, the growth rates are 4.1 t dry wood /ha/yr, giving an energy/land ratio of 82 GJ/ha/yr.

This last energy/land ratio is close to the 80 GJ/ha/yr used in *LPR 2002* but, I repeat, *the numbers should be of no consequence to our discussion*: what we need to do is to establish which paradigm is most closely related to reality (thus gaining public approbation), and least likely to mislead. We will round off this section with some comparisons with the renewable energy paradigm — which clearly *is* based in reality, and suffers only from the problem of uncertainty about the actual figure to use. Since the rest of this paper will argue the need to adopt the renewable energy paradigm, it is perhaps appropriate to consider here what effect adopting it would have on the figures which appear in the most comprehensive, and recent, eco-footprinting analysis, namely *LPR 2002*.

Changing to the energy/land ratio which is here proposed for the renewable energy paradigm, 95 GJ/ha/yr, would reduce the world energy footprint to 80 / 95 = 84% of its *LPR 2002* value. And reducing the *energy* footprint to 84% of its *LPR 2002* value would reduce the world footprint to 92% of its *LPR 2002* value. We may thus note that adopting the renewable energy paradigm would have little effect on the *LPR 2002* results, because other errors in the system are such that accuracies of 20% to 30% are probably the best we can expect (that assertion will be explored in more detail in other papers); anyhow, an 8% adjustment is unlikely to change any important conclusions.

With the 'carbon absorption paradigm' severely battered, some alternative is required. Since *I have no wish at all to undermine eco-footprinting* — only the 'carbon absorption paradigm', I must now take upon myself the task of defending the renewable energy paradigm.

6. The 'renewable energy paradigm'

There is, as I hope to show, a sound case to be made for accepting a 95 GJ/ha/yr energy/land ratio. For many years, Pimentel, with colleagues and assisted by his students at Cornell, has studied renewable energy sources, so his observation, on page 7, carries considerable weight. He said, "the energy/land ratio used in eco-footprinting is a fair approximation to the correct figure; at least it is not excessively optimistic." What follows mainly brings out a few salient points from the work of Pimentel and his colleagues; it also uses research into renewable energy gathered from many sources by Trainer (2002). All of their work has been subject to my critical scrutiny, and where there have been disagreements between us, we have always understood why the other party makes a different judgement over a difficult point.

For the following exposition, it may be easier to change the units of *energy per year* into more familiar units of *power*, the precise equivalence being 31.54 GJ/yr = 1 kW. Thus 95 GJ/ha/yr becomes 3 kW/ha. Then the question is whether, when considering the need to capture energy from renewable resources, a net 3 kW/ha is a reasonable estimate.

Let us start with the most difficult problem, namely producing 'liquid' energy from renewable resources. Smil (1993, p. 189) refers to the low net energy gain of the process in these words: "Even choosing the most efficient option — cultivation of sugar cane for distillation of ethanol [achieves] a net energy gain of about 0.3 W/m^2 [3 kW/ha]." Other estimates have been made which put the figure at 2.1 kW/ha (P&P 1996, Ferguson 1999), or using the same data, but with the most optimistic assumptions, 2.6 kW/ha. But both these estimates are made with a flagrant disregard for the fact that sugarcane production is associated with serious soil erosion (Pimentel 1993). Such net energy analyses are open to many questions, a fact which is even more clearly seen with the production of ethanol from corn (maize).

Growing corn requires large energy inputs and — as it is conventionally grown — is accompanied by rapid soil erosion (of the order of 18 t/ha/yr). Pimentel has frequently pointed out that to produce ethanol requires considerably more energy input (not counting the feedstock) than is contained in the ethanol produced (e.g. P&P, p. 261). Comparison of the input to the output involves various matters of judgement about how the task is to be done, in particular:

1. The extent to which 'by-products' of the feedstock should be used to supply the processing heat (retaining 5 - 10 t/ha/yr of biomass on the soil is important to reduce loss of soil, P&P, p. 154).
2. The amount of the input that has to be in *liquid* form.

Different ways of looking at the problem produce a range of figures for net energy-capture (the amount of *useful* energy that can be captured per hectare). Interpreting Pimentel's figures the way he judges them gives a figure of 0.3 kW/ha; however, by *ignoring sustainability altogether*, it would be possible to arrive at a figure of 1.6 kW/ha. Smil (1993, p. 190) confirms Pimentel's low figure, saying, of corn grown in temperate regions, that with the "distillation subsidized by coal power, densities for ethanol as stand-alone fuel would be no more than 0.2 W/m^2 [2 kW/ha]. Power densities of a fully solar operation (fuelling the machinery with ethanol, distilling with phytomass heat) would drop to about 0.04 W/m^2 [0.4 kW/ha]."

The literature produces some apparently contradictory figures regarding the inputs and outputs of ethanol production. However, there is no need to weigh up these arguments and choose between them, because the simplest overview makes the *essential* position clear. All experts agree that, (1) it takes about 1 t of corn to produce 370 litres of ethanol (calorific value about 21.3 MJ/litre); (2) That the energy required to effect the conversion to ethanol, including the distillation, is about 16.7 MJ/litre; (3) that 7.5 t/ha is a good yield of corn in the United States. This gives a net gain of 21.3 - 16.7 = 4.6 MJ/litre, and the net energy gain, according to this highly simplified assessment, is 12.8 GJ/ha/yr = 0.4 kW/ha. There is little chance of improving the fermentation process significantly (the process produces ethanol at a concentration of 8%). Thus the energy inputs *counted so far* — needed to produce concentrated ethanol — are substantially irreducible.

To see the quintessential message that net energy-capture is low, there is no need to include all the elements that a careful investigator, such as Pimentel, would take into account, namely, gasoline, diesel, nitrogen, phosphorus, potassium, lime, seeds, insecticides, herbicides, drying, transport, electricity, and that embodied in the machinery and plant used. Note, too, that it is possible for input to substantially exceed output, as Pimentel has assessed to be the case, and still have a positive net energy-capture, because in a net energy-capture calculation the energy in the feedstock is taken into account. Moreover, the stover which is left from the corn harvest provides about 3.8 kW/ha, so there is plenty of scope — at least nominally — for reducing inputs. It is this possibility, and the difficulty of deciding how much of the input needs to be in liquid form, which allows the different outcomes, as mentioned above, from the same data set.

Trainer (2002) quotes a variety of figures for methanol production (Pimentel and I have both found wide scatter in methanol data). Taking a fairly optimistic estimate from Foran and Marsdon (1999), assuming a dry biomass yield of 3 t/ha/yr would indicate a net energy-capture of 0.4 kW/ha. In some places, suitable biomass yields could be as high as 10 dry t/ha/yr, but this would only push up *net* energy-capture to 1.3 kW/ha. 10 t/ha/yr was the high end of the range used by Giampietro et al. (1997) in their study of large-scale biofuel production, but they noted that it would require substantial energy inputs to sustain, and obviously adequate rainfall too, so it is unlikely that such yields could be sustained over large areas. Not even in Canada, with its abundant forests, have sufficiently large methanol plants been constructed to test methanol production at the scale at which, it is believed, there may be considerably improved yields.

The general conclusion emanating from these figures is supported by consideration of the low efficiency of photosynthesis in capturing solar energy. Pimentel calculates that the average conversion for all natural vegetation in North America is about 0.1%, and says that this is the average, too, for U.S. agriculture (P&P, p. 36). Of course there are special cases. Pimentel calculates that a 15,000 kg/ha biomass yield (approximating the total biomass from a good corn crop) would represent a 0.5% capture of insolation. The likely average yield of sugarcane, 74 (fresh) t/ha/yr (Ferguson, 1999), is equivalent to an energy capture of 11.9 kW/ha. Since sugarcane is grown in areas of high insolation, say 220 W/m^2, = 2200 kW/ha, conversion is again 0.5% (i.e. 11.9 / 2200). Higher biomass yields are mooted for certain crops, such as switch grass, but they are crops for which yields over time and large areas have yet to be demonstrated. Neither should one forget the need to maintain biomass in the soil, and the energy costs of replacing vital nutrients after heavy continuous cropping.

If neither ethanol nor methanol can make much of a contribution, then how about liquid hydrogen produced from biomass? The electrolytic production process essentially needs electrical energy. A reasonable sustainable yield over a wide area from biomass, 60 GJ/ha/yr, would produce about 20 GJ/ha/yr of electricity. Even after making allowance for the fact that, in an internal combustion engine, hydrogen burns 33% more efficiently than gasoline, this would produce the gasoline equivalent of only 16 GJ/ha/yr (0.5 kW/ha). Note, moreover, that this is not a fully net figure; for instance, no allowance has been made for that part of the liquid hydrogen output which would be needed to harvest the wood and transport it to the power plant.

It could be argued that it is not sensible to try to produce liquid hydrogen from biomass. That is true, yet we saw in the *OPT Journal*, April 2002 pages 9-13, that the possibilities of producing liquid hydrogen from other renewable energy sources are severely limited, except for nations with Iceland's ample hydroelectric and geothermal energy resources.

Perhaps the most debatable aspect of seeking a datum for the renewable energy paradigm is in deciding the part that each energy resource can contribute to the whole. Now we must turn to that.

7. Integrating the resources

Although a band of uncertainty remains, the broad picture is fairly secure, which we can see by starting with a simplified situation in which we take just 100 kW as a representative sample of the whole. Suppose that 35 kW can be generated from solar thermal panels and photovoltaic cells on roof tops, thus using *no* biocapacity. Suppose also that 15 kW can be generated from wind turbines which are either off-shore or are situated on unproductive land, thus again using *no* biocapacity.

The fact that the remaining 50 kW is likely to require biocapacity is supported by the following considerations:

a) The mean capacity factor (output as a proportion of the rated capacity) of photovoltaic cells is about 15%, and the mean capacity factor of wind turbines is at best 25%, so considerable 'time-independent' back up is needed.

b) Even today, electricity is too expensive to use extensively for heating; that will be true to a greater extent when it has to be generated from renewable sources. Thus the *heat* source of choice will be to burn biomass.

c) A substantial demand for liquid fuels will exist, and it is unlikely that this will be fully satisfied by windpower, so some ethanol and methanol will probably be derived from biomass.

Based on a sustainable yield, and using wood for heat, energy-capture is about 2 kW/ha, or say 90% of this after inputs have been taken into account. Combining this with the low figures applicable to 'liquid' fuels, we will not be far out in assuming that 1.5 kW/ha is an approximation to the mean net energy-capture applicable to this remaining 50 kW.

We can now combine the 50 kW requiring zero biocapacity, with the 50 kW requiring 1.5 kW/ha, and thus achieve a mean *net* energy-capture of 100 / (0 + (50 / 1.5)) = 3.0 kW/ha. Crude though this analysis is, it gives an indication of why, at the present state of knowledge, 3 kW/ha is in the right ball park for an energy/land ratio from renewable sources.

We should now ask how realistic are the assumptions regarding wind turbines and solar panels. Wind is limited in scope. If all inland and offshore sites in the U.S. were developed, the electricity produced would only replace 8% of fossil fuel use. Actually it would replace considerably less than that, because the $355 billion investment needed to build the required, for example, 355,000 wind turbines of 1 MW capacity would use up a substantial part of the energy output, probably as much as a fifth, reducing the useful output to 6.5%. Note, incidentally, that present growth in U.S. energy would overtake this in six years.

Photovoltaic panels are far more efficient than photosynthesis, capturing about 9% of the insolation (independently of the level of insolation) falling on a horizontal surface of equivalent area, but there are two problems with them: (1) intermittency; (2) cost.

The first of these problems is apparent from the fact that even in a sunny site (200 W/m^2), high efficiency panels (with cells of about 17% rated efficiency) can make available to the grid only about 14% of their rated capacity (data based on the experimental station at Toledo, Spain). That is, for example, an installation of 1000 MW capacity gives a mean power output of 140 MW (with the power not necessarily being delivered when wanted). That is only about 25% of the output of a coal power station of 1000 MW (a moderate size) which would probably operate at a capacity factor of 60%, giving a mean output of 600 MW (and always available to satisfy varying demand).

The second of the problems is amplified by the first. The 14% 'capacity factor' means that to deliver a given amount of electricity, about seven times as much rated capacity is required. We can see the extent of the problem most clearly by estimating the cost of supplying the same amount of electricity as could be supplied by wind with all available sources being exploited. We can reasonably estimate a cost of $5 per watt in order to cover both the module cost and the 'balance of system' costs (*wholesale* module prices in 1998 were about $3.5 per watt). At this $5 per watt price, the total cost of supplying 777 billion kWh/yr (estimated at $355 billion for wind) would amount to $3200 billion for photovoltaics. The same caveat, about the fact that the electricity supplied is not exactly available for use, applies even more strongly to PV. A main reason for the high cost of the panels is the energy used in their manufacture. I once estimated that for the insolation at Toledo (200 W/m^2) it would take 25% of the output, over a 30 year lifetime, to provide the energy for manufacture; in the U.K., it would take 38% of the likely output. Thus the $3200 billion investment would probably not manage to supply the aforementioned six years of growth in U.S. energy demand. A $3200 billion investment is hard to visualise, but it amounts to about $11,000 for each American man, woman and child. Perhaps the obvious point should be made that building either wind turbine or photovoltaic capacity has the initial effect, for many years, of *increasing* the demand for energy.

This somewhat extensive analysis of wind turbines and photovoltaics is justified by the fact that some prestigious organizations, such as the *World Watch Institute*, and *Friends of the Earth*, appear to be equally unacquainted with these cold realities as they are about the large amount of energy that is needed to produce liquid hydrogen (for that, see the April 2002 issue of the *OPT Journal*).

It has to be admitted, therefore, that the foregoing assumption of satisfying half the energy demand from roof top solar thermal and photovoltaic panels, and from wind turbines, is unlikely, especially with present levels of energy use in the United States. However, it will be a long time before we actually use up all economically viable coal, especially if underground coal gasification proves successful (see *New Scientist*, 1 June 2002, pp. 42-45) , so provided that one is not too absolutist about using only renewable energy, the earlier calculation can be seen to be plausible. It is for such reasons that Pimentel affirmed that 3 kW/ha is not an excessively optimistic figure. What all eco-footprinters need to realise is that the foundations of their work rests not on the unrealistic (which is freely admitted) and misleading concepts of the carbon absorption paradigm, but rather on the difficult, but *realistic*, 'renewable energy paradigm'.

8. Eco-footprinting under the 'renewable energy paradigm'

The carbon absorption paradigm has long been a millstone around the neck of eco-footprinting. It has thrown doubt on the validity of all eco-footprinting analyses, and made it hard to demonstrate — without engaging in a full scale critique — that carbon dioxide emissions set separate and far more stringent limits. Thus, far from being weakened by having shuffled off the carbon absorption paradigm, eco-footprinting is strengthened, although it does put eco-footprinting in a new light.

Under the 'renewable energy paradigm', eco-footprinting results tells us the carrying capacity of a given region of the Earth *when humans have only renewable resources to rely on*. While the robustness of eco-footprinting is enhanced, there are new challenges. To strengthen eco-footprinting further — under the renewable energy paradigm — we need to establish, with the greatest possible certainty, the validity of the 95 GJ/ha/yr (3 kW/ha) energy to land ratio. An even more important task, *though this is not exclusive to the new paradigm*, is to estimate the loss of productivity (and hence biocapacity) when agriculture is required to be *sustainable* (a point made by both Pimentel and Herendeen). For instance, wind erosion is so serious in China that Chinese soil can be detected in the Hawaiian atmosphere during the spring planting period; and soil eroded by wind in Africa can be detected in Florida and Brazil

(Pimentel et al., 1999). *Sustainability* implies agricultural practices which eliminates these problems.

This *Part I* of the *2nd Footprint forum* has shown the carbon absorption paradigm to be misleading. That conclusion brings considerable benefits to eco-footprinters, namely:

1. Eco-footprinters are now free to acknowledge that, with the present average *per capita* carbon emission rate from burning fossil fuels, world population needs to be 40% of its 1990 level (Engelman, 1994, p. 27), *without thereby undermining the concepts of eco-footprinting.*
2. Eco-footprinters are now free to acknowledge that net deforestation is about 10 Mha per year,[1] so in reality there is little chance of net *afforestation* occurring, and they can also admit that uncertainty surrounds natural carbon releases (e.g. due to instability of sequestered soil-carbon with rising temperatures), *without thereby undermining the concepts of eco-footprinting.*
3. Eco-footprinters can now see their discipline as entirely separate from that of accounting for excess carbon, and thus they can provide an *independent* assessment of the extent to which meeting reasonable aspirations to improved lifestyles would lead to exceeding *sustainable* biocapacity.

With respect to the last item, it should be noted that at present half the world's population are suffering from malnutrition (WHO, 1996) and many people have insufficient fuelwood, as for example described by Smil (1993, p. 55):

> China's rural energy surveys put the average daily effective heat energy requirement at 16.2-18.7 MJ per family, but the actual availability was a mere 14.5 MJ a day, an average shortfall of over 20 per cent (Smil 1988). Seasonal and regional shortages are commonly more than twice as high. Other acutely affected areas include Africa's Sahelian zone and Namibia, Swaziland, Lesotho and parts of Botswana, the Nepali hills, large parts of the Indian subcontinent, and much of Central America (FAO 1980).

Thus if eco-footprinters base their calculations on the premise that everyone should have their basic physical needs met, there is evidence to show that there will be similarity between the ceiling on population that is needed to stabilize carbon dioxide concentration, and that needed to ensure that population matches biocapacity when energy is supplied from renewable sources.

Under the 'renewable energy paradigm', eco-footprinting would not only provide valuable support to the work of other scientists, but could analyse the relation between the populations and biocapacities of individual nations. The work of "other scientists," just referred to, is exemplified in the following quotation (given without references as they can be found in the original) from Pimentel et al. (1999, p. 32):

> Worldwide, balancing the population-resource equation will be difficult because current overpopulation, poor distribution of resources, and environmental degradation are already causing serious malnourishment and poverty throughout the world, especially in developing countries. Based on the estimate that 0.5 ha per capita is necessary for an adequate and diverse food supply, it would be possible to sustain a global population of approximately 3 billion humans. However, arable land is being degraded and lost at a rate of more than 12 million ha per year. At this rate of loss, in just 42 years there will be sufficient arable land for a population of only 2 billion. It is critical to adopt soil and water conservation techniques to protect the soil resources that currently produce more

than 99% of the world's food. A world population of 2 billion, in addition to having adequate food, renewable energy, and forest products, should also have adequate freshwater resources.

9. Some objections to 'standard' eco-footprinting

Although it is the narrow task of this *Part I* of the *2nd Footprint forum* to elucidate the 'energy Footprint', the result, demolition of the carbon absorption paradigm, may be misinterpreted by some as undermining 'standard' eco-footprinting, so I will now allow myself to divert from the narrow remit of this *Part I* of the forum in order to take a wider view of the value of eco-footprinting using Wackernagel's 'standard' methodology.

Various people, for example Lensen and Murray (2001), have pursued different Footprinting methodologies. Sometimes people do this because they think that there are weaknesses in the 'standard' methodology. Without doubt, there are substantial inaccuracies, and perhaps those inaccuracies have not been fully recognized, but, as I see it, other criticisms raised are invalid, except of course for those pertaining to the carbon absorption paradigm. These are the chief remaining criticisms, together with reasons why they are invalid:

a) It would be better to use 'local' rather than 'worldwide' productivity.

Response: 'Worldwide' productivity is the most suitable for what eco-footprinting does best; and it introduces no significant inaccuracies (see *The Assumptions Underlying Eco-footprinting*, Ferguson, 2002).

b) Eco-footprinting does not take all emissions into account.

Response: Even if eco-footprinting were to take *no* emissions into account (which Pimentel and I would recommend), it is still saying something important.

c) Eco-footprinting fails to take into account whether land is being used sustainably.

Response: This criticism stems from a failure to appreciate that measuring biocapacity is *at least* as important a part of eco-footprinting as measuring Footprints (see *The Logical Foundations of Ecological Footprints*, Ferguson, 1999a). Moreover, the only limitation to taking sustainability into account, when assessing biocapacity, is the availability of suitable data.

This last point is of such importance that we should dwell on it. Let us take Australia as an example. Australia's biocapacity in 1996, (WWF, 2000) was assessed as 9.42 global hectares x 18.1 million = 171 million global ha. Note, 'global hectares' are hectares with world average bioproductivity; they are referred to as 'area units' in the *Living Planet Report 2000* (WWF, 2000). In order to adjust the 171 million global ha for sustainability, at least the following would need to be taken into account:

1) The need to change land use so as to stop water tables from rising and rivers getting saltier, i.e., to eliminate 'dryland salination', and to stop the process whereby, owing to raised water levels, salts get washed into rivers.[2]

2) The need to reduce the use of fertilizers, so that phosphates and nitrates do not get washed into the rivers and cause algal blooms, with the concomitant dangers of toxin produced from cyanobacterial action.

3) The need to reduce soil erosion to zero without extensive use of no-tillage or minimum-tillage agriculture, because — particularly in view of Australia's low rainfall — there are ecological risks attached to these procedures.

Those points, and others, are dealt with more extensively in *Stop Thieving from Our Children* (Tod, 1996) and *Listen . . . Our Land is Crying* (White, 1997). But the point here is not to make an extensive list, but to note that eco-footprinting has a simple way of adjusting biocapacity for sustainability (by adjusting the yield factors and land categorisation); the difficulty is only in getting data to support any particular *quantitative* assessment. A seat-of-the-pants guesstimate that Australian biocapacity should be reduced to between a third and a half of the 171 million global ha, though quite likely to be true, would rightly carry little weight in academic circles.

The conclusion is this. With eco-footprinting freed from the misleading implications of the carbon absorption paradigm (through changing to the 'renewable energy paradigm'), 'standard' eco-footprinting — approximately as done in *The Living Planet Report 2002* (WWF, 2002) — can continue to perform an important function, namely to assess the relationship between each nation's Footprint and its biocapacity. Moreover, eco-footprinting has the potential to be much more valuable than it presently is, provided only that it could be improved with soundly-based estimates of appropriate adjustments to the yield factors (and sometimes to land categorisation too), to take full account of sustainability.

Acknowledgements

David Pimentel has remained steadfast in his belief that, (a) Ecological Footprints have an important role to play in providing a quantitative assessment of the extent to which humans are exceeding the Earth's biocapacity, and (b) that the energy component of Ecological Footprints needs to be based on renewable energy. Without his kindly and generous help, extended over many years, this forum would never have taken place.

Thanks too to William Rees, for letting me take excerpts from his contributions, and to Mathis Wackernagel, who with his usual good nature responded generously to my questions about eco-footprinting. It is a pity that his 10th July contribution arrived so late that shortage of time made it necessary for me to extract from it only those parts which were relevant to the discussion!

I am also indebted to Robert Engelman, for his superb series of booklets, produced for *Population Action International*. In particular, his booklet, *Stabilizing the Atmosphere*, stimulated my interest in carbon dioxide emissions.

Endnotes

1 10 Mha is an approximation based on PAI, 1999, p. 26, which stated, using FAO data, that 200 million ha of natural forest were destroyed in the developing world, between 1980 and 1995, while there was an increase of 20 million ha of forest and forest plantations in developed countries (net loss of 12 Mha/yr); also, page 38 of *World Watch*, Sept/Oct 2002, which, quoting FAO 2001 data, gave 14.6 Mha cleared per year, with 5.2 Mha of afforestation) (net loss of 9.4 Mha/yr).

2 A study in the USA showed that along the Colorado River, farmers irrigating their cropland close to the river were dumping 18 t/ha/yr of salt into the river.

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In the ensuing dialogue, Secretary of the Optimum Population Trust (UK), Edmund Davey, takes the role of the 'Plain Man', asking questions of interest to himself and other members of OPT.

A PLAIN MAN'S QUESTIONS CONCERNING PV, PART I

Asked by Edmund Davey; answers provided by Andrew Ferguson

Edmund Although this discussion is on the subject of photovoltaics (PV), it may be as well to keep it within the context of the wind figures you mentioned. You said that according to the American Wind Association, if all wind potential in the United States were to be exploited, it would yield 777 billion kilowatt hours of electricity a year. You added that the primary energy equivalent of this would be only 8% of total U.S. energy demand. Then you said that the cost of doing the same with photovoltaics would be US $3200 billion, namely nine times the capital cost of wind turbines which could achieve the same. My mind boggles at such a large sum. Can you show me that there has not been an extra naught added on!

Andrew One quick check on the figure is to work out what, on this grand scale, the capital cost for 1 kilowatt hour (kWh) would be. Since the $3200 billion can be amortised over 30 years, the annual capital cost is $3200 / 30 = $107 billion. Dividing by 777 gives $107 / 777 = ¢14 per kWh.

We can check that figure with the output from an area of module rated at 1 kW, also known as a peak kilowatt (kW_p). For the 200 W/m^2 insolation of Toledo, Spain, the capacity factor is 14%, so panels rated at a peak kilowatt will produce, over a 30 year life span, 0.14 x 24 x 365 x 30 = 36,792 kWh. The capital cost of a peak kilowatt of fully installed module, at $5 per watt, would be $5000. So the cost per kWh would be $5000 / 36,792 = ¢14 per kWh. That checks with the previous calculation.

Edmund OK, you've convinced me, but is your estimate of a total installed cost of $5 per watt realistic?

Andrew Actually, it is probably an underestimate. In *Vital Signs, 1994*, p. 54, Nicholas Lenssen said that a coalition of more than 60 utilities had plans to install 50 megawatts of solar cells, between 1994 and 2000, at an estimated total cost of $500 million. That indicates an installed cost of $10 per watt.

In *Vital Signs, 2000*, p. 58, the wholesale price of PV modules is shown to have dropped from about $4.2 per peak watt in 1994 to $3.5 per peak watt in 1999. That's a 17% drop. A 17% fall would not apply to the *total* installation costs. But even supposing it were to, it would only reduce the total cost from $10 per watt to $8.30 per watt, so $5 per watt is optimistic. Future cost reductions are likely to come in the modules themselves and not the 'balance of system' and installation costs. For instance, if solar module costs were to fall by two-thirds, reducing by $2.30 per peak watt, it will only reduce the fully installed cost from the $8.30 per peak watt which we have calculated, rather optimistically, to $6 per peak watt.

Edmund Right, I agree that your $5 per watt is a low estimate to cover full installation costs. Taking a break from looking at costs, I would like to be clear about what you mean by saying that 777 billion kilowatts hours of electricity would replace 8% of fossil fuel use.

Andrew Electricity is a particularly valuable type of energy. It takes extra energy to produce because the efficiency of conversion is only about 33%. Thus if the electricity were to be generated by fossil fuels, the 777 billion kWh would need 777 / 0.33 = 2350 billion kWh, or 8.5 exajoules (8.5×10^{18} joules), of fossil fuel. I estimate U.S. total energy use, in

2000, in these primary energy equivalent terms, as 105 exajoules, so the 8.5 exajoules is about 8% of the whole.

Edmund Good, that's what I thought. Just checking. Something which I would like to get a picture of is what area of PV surface would be needed to supply this 777 billion kWh per year. Is it difficult to calculate that?

Andrew No. Since the average annual insolation in the U.S., 190 W/m^2, is near enough the same as the 200 W/m^2 of Toledo, we could calculate from the capacity factor figure of 14% kW/kW_p, but the more general, and simpler, method is to use the figure down at the bottom right of the Toledo spreadsheets (see p.29), which shows that the energy delivered to the grid is 8.6% of the insolation that would fall on a horizontal surface of the same area. Thus the area needed, which is what you want to find out, multiplied by the insolation, multiplied by 8.6% needs to be equal to 777 billion kWh/yr. 777 billion kWh/yr is an average power of 88.7 billion watts, which makes the area needed 5100 square kilometres.

Edmund That sounds a staggeringly large module area. It is easy to make slips with such large numbers. Could you just take me through the calculation the other way round, starting from the solar insolation on 5100 km^2, and arriving at the output.

Andrew Sure. A square kilometre is a million square metres, and 5100 million square metres, enjoying an insolation of 0.200 kilowatts per square metre, will receive 8.9 trillion (8.9×10^{12}) kilowatt hours of insolation per year. At 8.6%, the electricity captured would be 770 billion kilowatt hours per year.

Edmund OK, you've convinced me, but can you give me an idea of what 5100 square kilometres means. I seem to recall that the Clinton administration, in the U.S., launched a Million Solar Roofs program. If that were to have been carried out, would it provide the required 5100 square kilometres?

Andrew One might reasonably suppose that there would a suitably oriented area on the roof of each house for 50 m^2 of solar panels. At that rate one would need to find *100* million roofs.

Edmund That sounds a tall order, and it's going to keep a lot of window cleaners busy. I suppose, then, that many of the panels would have to be at ground level.

Andrew There are two problems with that. On sloping roofs the panels do not shade one another, but on level ground, the PV panels would need about twice the space to avoid shading one another. And, perhaps more importantly, there would be extra cost in providing suitable support for the panels.

Edmund It's beginning to look as though it would be hard to imagine a more unlikely project, but let's just pursue the cost angle a bit further. It occurs to me that with a huge capital investment, like $3200 billion, you must take interest charges into account. How do you do that?

Andrew I like to do accounting in terms of constant value money, i.e., removing the distortion of inflation. For that, a 'real' interest rate should be used, which is about 2½% a year. Thus the annual interest payable on half the sum of $3200 billion would be $1600 x 0.025 = $40 billion. Thus there would be an additional cost of $40 billion / 777 billion = ¢5 per kWh for interest charges.

Edmund So adding that to the ¢14 you calculated earlier, I get a cost of ¢19 per kWh. But you have not taken any account of the fact that PV is an intermittent supply, so spare capacity must be available from a time-independent source.

Andrew Yes, that is an important point, but unfortunately I can find no way of costing it. My seat-of-the-pants guess would be a couple of cents per kWh.

Edmund I'll accept that, to make a total of ¢21 per kWh. But you still have to add on distribution costs, for isn't it true that actual fuel cost is only a small part of the price we pay for electricity.

Andrew Yes, you are right there. Distribution is a thorny problem. While it is true that most of the electricity generated by PV could be used where it is generated, since the distribution company would need sufficient distribution capacity to send the full amount during the night, I would argue that distribution costs are not much reduced. Will you settle for another couple of cents for distributions costs?

Edmund Sure! That tots up to ¢23 per kWh, but you still have not taken into account the maintenance costs. I know that PV modules are reliable, but ancillary equipment is needed to feed the output into the grid, and there are all those window cleaners we were talking about. You can't tell me that all that is going to cost nothing!

Andrew You are right there. Will you settle for another couple of cents per kWh?

Edmund That seems reasonable to me. I note that it brings the cost up to ¢25 per kWh. But now that we have done our own calculations, may I ask if there are not experts, writing in prestigious journals like the Worldwatch Institute's *World Watch*, who present their own estimates?

Andrew Yes there certainly are experts pulling figures out of hats. For instance, Christopher Flavin, who is now President of the Worldwatch Institute, wrote an article with Molly O'Meara in the September 1998 issue of *World Watch*. One of the things they said was: "By 2002, the fully installed cost of one of these systems is projected to fall by half, to below $3000 per kilowatt. That would provide power for roughly 9 cents a kilowatt-hour which is competitive with the cost of providing power at times of peak demand." That projection provides a useful reminder that one should always beware of anything which has been "projected," especially after the due date has passed, and the projection has been shown to be contradicted by reality!

From our earlier considerations, it is clear that the cost of a fully installed system for $3 per watt is improbable. It is even unlikely by 2052, because however much the cost of the modules comes down, the other costs will not come down much. In fact, by 2052, the costs, even in constant dollars, could well increase because of higher energy costs.

Moreover, if the fully installed cost were to fall to $3 per watt, from the $5 we used, that would reduce the capital cost, which we calculated earlier as ¢19 per kWh, including interest, to 3/5, = ¢11 per kWh. If we add to that the other things you wisely forced me to take into account — that is ¢6 per kWh to cover the cost of having standby power, distribution facilities and maintenance — the cost comes to ¢17 per kWh rather than ¢9 per kWh.

Edmund Yes, I can see there is a problem with experts! And I note that your estimates are for sunny Spain. How would things be in England?

Andrew Average annual insolation was measured at a place in southern England, and the result was 108 W/m^2. That is 54% of the 200 W/m^2 figure for Toledo; so, taking the inverse of 54%, one could expect all the capital costs to increase by 85%.

Edmund Then PV is definitely out for England, but wouldn't the sunniest parts of the United States do far better than Toledo?

Andrew The very hottest region of the United States, the southwest, receives average annual insolation of 240 W/m^2, which is 1.2 times that of Toledo. So taking the inverse of that, on the face of it, one might expect the capital costs to be 83% of those for Toledo. However that estimate is dubious, because PV panels can get overheated and then do not perform so well. I have no data for areas with such intense sunshine.

Edmund There seems almost no hope for large scale PV. Do the annual reports in *Vital Signs* — a source of such a wealth of information on so many subjects — give any hint of the low capacity factor of PV systems, for that seems to be at the root of many of the problems we have been discussing?

Andrew You are absolutely right, a major problem is low capacity factors, and incidentally we are not including, as we really should, a 5% deterioration in module output over the life time of the modules. The answer to your question is no. The reports from *Vital Signs* are of the kind that one might expect from a salesman. For instance, in Christopher Flavin's report in *Vital Signs 2000*, there is no mention at all of achieved outputs; only installed capacity. Here is an example of the technique of the superior salesman, taken from that report: "European PV production grew from 33.5 megawatts in 1998 to 40.0 megawatts in 1999, propelled by solar home programs in countries such as Germany, Norway, and Switzerland."

It sounds as though solar power is a roaring success in the countries mentioned. The reality of the matter is that, delivered to the grid, the capacity factor for PV panels operating in Europe would be about 10% of rated power, so the 40 MW, installed in 1999, would have an output of 4000 kW. In the U.K, each domestic consumer uses, as an annual average, at home, about 0.5 kW of electricity, so this would satisfy 8000 customers. At our hoped for $5 per watt, the cost of the 40 MW would be $200 million, which works out at about $25,000 per 'satisfied' customer. And the cost of electricity would be about ¢32 per kWh, based on a rough calculation that for Europe as a whole the capacity factor would be around 10%.

Edmund I see that you are thinking of the UK importing the electricity, but how do you know that the average capacity factor in Europe would be about 10%?

Andrew There are few facts to go on, but at the University of Northumbria there was a good study, reported by BP Solar. The results there showed a 9.1% capacity factor. There was another trial at Zurich, which achieved 9.0%, but that result was distorted because the panels were horizontal. Most importantly, insolation charts indicate *average* insolation in Europe to be around 140 W/m^2. That is 70% of Toledo, which reduces Toledo's 14% capacity factor to 10%.

Edmund I wonder if Duncan McClaren, and his co-authors in the *Friends of the Earth* book, *Tomorrow's World*, are simply deluded by optimism, when they say, on page 103, that to suppose that the UK could be producing 80 terawatt hours a year from PV by 2050 would be a "conservative" estimate.

Andrew You could not have picked a better example of unbridled optimism! 80 TWh/yr, at the likely capacity factor of 9% in Britain, would require 888 TWh/yr of capacity, which works out at $888 \times 10^{12} / (24 \times 365) = 101$ billion watts of capacity. At $5 per watt, that would cost $505 billion. Enron, when it was the darling of the stockmarket, would have been a better investment! For there would be little hope of finding enough customers willing to pay the required ¢32 per kWh.

Edmund The *Worldwatch Institute*, and *Friends of the Earth*, are secondary sources, mainly reporting the work of others. What do the primary sources have to say?

Andrew *Global Energy Perspectives* was published by Cambridge Press in 1998. It had three editors, 13 contributing authors, with a steering group of 9, and it involved a "two-phase, five-year research effort," so I suppose we might categorize it as a primary source. This is what they had to say in the concluding chapter (p. 246): "A robust hedging strategy focuses on generic technologies at the interface between energy supply and end use, including gas turbines, fuel cells, and photovoltaics. These could become as important as today's gasoline engines, electric motors, and microchips."

You may, like me, have difficulty in knowing precisely what they are driving at, but there *are* useful comments which could be made about the things that they mention: (1) There is some scope for improving the efficiency of energy use with gas turbines, though not nearly fast enough to match expanding demand for energy; (2) Fuel cells, like gas turbines, are not an energy source, but rather a method of energy conversion. They are efficient, but at present about five times as expensive as current methods of converting energy; (3) Photovoltaic cells are different in kind from the other two, since they are an actual energy source; they capture current sunlight. However, since the cost of replacing 8% of U.S. primary energy use with photovoltaics would be $3200 billion, even supposing the price of modules could be reduced by two-thirds, thereby reducing fully installed cost to $5 per watt, photovoltaics cannot be considered as a viable large scale energy source.

Edmund And even the 8% output is not a true picture, because a proportion of the energy would go into the production. Can you explain why the experts appear to make every endeavour to obscure the most important facts?

Andrew I can only surmise that some people have a strong drive to be optimistic, and are willing to ignore everything which runs contrary to the view they wish to espouse. Bjorn Lomborg, a Danish Professor of statistics, is a current example, with his recent book titled, *The Skeptical Environmentalist*. It has been selling like hot cakes, but misleads by selection of the evidence. The situation is similar with PV. If one mentions only the expansion in PV production, and emphasizes the possibilities of cost reduction in the modules, while failing to mention the nearly irreducible costs of elements other than the modules, or the low capacity factors achieved, or the need for alternative power to cope with intermittency, and one forgets about the window cleaners, it is possible to conceal the reality of the situation, at least until someone like you comes along and asks pertinent questions.

Edmund I would like to know how BP Solar, the Worldwatch Institute, and Friends of the Earth respond to the points you have raised about low capacity factors.

Andrew What I plan to do is to send them a copy of this October 2002 *OPT Journal*, and invite them to write a page or so in response, but with the proviso that they will need to either show that there are flaws of logic or errors of data in what I am saying here, or to present new evidence — not projections — of what is actually being achieved in the field, by quoting capacity factors against ambient insolation levels.

Edmund What do you think the response is likely to be?

Andrew I think they will either decide that the safest thing is to keep their heads below the parapet, and not reply, or they will try to avoid the question, and instead put a good spin on some related matter. Thus it may take time to get any relevant responses. I will allow a year to see if I extract anything useful.

Edmund In that case, I shall especially look forward to the October 2003 issue of the Journal!

The coup de grâce for large scale PV, for solving future energy problems, was the amount of energy input needed to create the system. It reduced the *useful* output, from the whole 3200 billion dollar investment, to an amount that would cope with only 6 years of growth in U.S. demand. 25% was the *input* figure I think you suggested as being required, as a proportion of the *output*, with Toledo's 200 W/m^2 insolation. How secure is that estimate?

Andrew Not very secure, but it is probably in the right ball park. Hagedorn, in 1989, estimated that over the next 5 years it should be possible to reduce current inputs per peak kW by 60%, getting down to 9000 kWh/kW_p. His estimate was useful, because it included grid connections. I have spent a long time looking at other highly detailed analyses, but there are always omissions and areas of uncertainty, like whether air conditioning for the offices and factories has been included. Moreover, the other studies do not include grid connection. I came to the conclusion that, at least for mono-crystalline silicon panels, Hagedorn's estimate was probably in the ball park. Thus, with insolation of 200 W/m^2, over 30 years a peak kilowatt would deliver, 30 x 0.14 x 24 x 365 = 36,800 kWh, so an input of 9000 kWh would amount to 25% of the output.

Edmund Assessing inputs must be difficult. I suppose that really one should measure the amount of diesel fuel that was used in the manufacturing process, and then calculate how much of the electrical output would be needed to make liquid hydrogen to replace it.

Andrew You are quite right, but I have not seen any analyses mention that. Perhaps there is a general awareness that to produce hydrogen from PV electricity would be economic suicide.

Edmund A lot seems to rest on that capacity factor figure of 14%, down near the bottom right hand corner of the Toledo spreadsheets. Is it easy to show that the figure is right?

Andrew I commend your policy of doubting everything! Yes it could not be more simple. The report stated that 1200 MWh was the average annual output, over several years of operation, from the 980 kW system. Thus the capacity factor was (1.2 x 10^6 [kWh] / (24 x 365)) / 980 = 14.0%. As you see, the spreadsheet shows other figures alongside for each of three separate arrays. Note that in the spreadsheets, the rows (l) to (p) cover the whole four and half year period. The data at the top of the first and second spreadsheet refer to the years 1997 and 1998 respectively.

Acknowledgements

My thanks go to David Pimentel, of Cornell University, and F.E. (Ted) Trainer, of the University of N.S.W. Australia, for checking that I am not laying before our 'Plain Man' anything but the unvarnished truth. Both have made a significant contribution to the study of photovoltaics in their books and papers, and I am indebted to them for their thoughts on the subject and their data.

Analysis of PV data from Toledo, Spain, taken from http://www.toledopv.com/ingles/masesp.htm on 25/04/2000

	Repeat of data for 1997as appears on web				
		Nukem	Fixed BP	Tracking BP	TOTAL
	Reference yield	5.14	4.97	5.68	N/A
	Array yield	3.82	3.66	3.75	3.74
	Final yield	3.62	3.44	3.39	3.52
	All these figures are referred to the Plants's installed power peak pursuance to CIEMAT readings expressed in kWh/day/kWp.				

	Analysis of data, with explanations				
(a)	Reference yield (this is stated to be "radiation received" in each field. However the figures make no sense interpreted as kWh/day/kWp, and the assumption is that they refer to kWh/day/m2. (kW/m2)	0.214	0.207	0.237	
(b)	Yield from array in terms of DC power generated (kW / kWp %)	15.9%	15.3%	15.6%	15.6%
(c)	Final yield from array in terms of AC power generated (kW / kWp %)	15.1%	14.3%	14.1%	14.7%
(d)	Module efficiency (note these figures are given just as "efficiency"; however it seems obvious they are for module efficiency, because the cell efficiency of the BP cells is 17% (kW/kW%)	10.6%	14.3%	14.3%	
(e)	So module area required to provide 1 kWp (m2)	9.43	6.99	6.99	
(f)	Insolation on module area of (e) at insolation of (a) (kW)	2.02	1.45	1.66	
(g)	Ratio of energy captured as DC to insolations on panels	7.9%	10.5%	9.4%	
(h)	Ratio of energy captured as AC to insolations on panels	7.5%	9.9%	8.5%	
(i)	Insolation that would fall on a horizontal plate of the same area as (e). Note this is partly because the figures at (a) are somewhat suspect as to meaning, and partly because the output in relation to the insolation in the area is more useful. However precise insolation for Toledo is not known. 200 W/m2 is estimated from an insolation chart. (kW)	1.89	1.40	1.40	
(j)	Ratio of energy captured as DC to insolation on `flat' surface of same area	8.4%	10.9%	11.2%	
(k)	Ratio of energy captured as AC to insolation on `flat' surface of same area	8.0%	10.2%	10.1%	
	Overview is that total energy flowing to the grid while plant operating in automatic mode uniterruptedly between July 94 and February 98 (the official trial period) from the three fields totalled 4165 MWh, thus over 3.5 years = 1190 MWh/yr. By 31 December 1998, the total power came to 5244, thus over 4.42 = 1187 MWh/yr. Neither of these are quite full years and in the text the figure is given as 1200 MWh/yr, which is used here for the total.				
					Total
(l)	Rated power of three arrays (kW)	456	423	101	980
(m)	Energy delivered to the grid over the course of an average year (kWh)	547,143	515,143	127,714	1.20E+06
(n)	Ratio of energy delivered to the grid to rated power (kW / kWp %)	13.70%	13.90%	14.43%	14.0%
(o)	Module surface area (m2)	4309	2942	703	7954
(p)	Ratio of energy delivered to the grid to insolation on `flat' surface of same area	7.2%	10.0%	10.4%	8.6%

These are summaries of the most important data based on at least three years operation.
Exactly the same summary data are shown under the 1998 data overleaf.
Rows (n) and (p) are the most important.
The values of row (n) are only true for the actual level of insolation at Toledo, Spain (about 200 W/m2 on a horizontal surface).
Row (p) is approximately true for any insolation. Results are somewhat variable because it depends on how tightly the cells are packed into the module. For a specified insolation and module, a vaue for (n) can be calculated from (p), e.g. for the Nukem column, with its modules of 10.6% efficiency, and with the 200 W/m2 insolation at this site:
kW/kWp = 0.0725 x 200 x (1 / 0.106) / 1000 = 13.7%; and for insolation of 100 W/m2:
kW/kWp = 0.0725 x 100 x (1 / 0.106) / 1000 = 6.8%

Analysis of PV data from Toledo, Spain, taken from http://www.toledopv.com/ingles/masesp.htm on 25/04/2000

	Repeat of data for 1998 as appears on web	Nukem	Fixed BP	Tracking BP	TOTAL
	Reference yield	5.39	5.35	5.67	N/A
	Array yield	4.21	3.91	3.78	4.03
	Final yield	4.01	3.71	3.55	3.83
	All these figures are referred to the Plants's installed power peak pursuance to CIEMAT readings expressed in kWh/day/kWp.				

	Analysis of data, with explanations	Nukem	Fixed BP	Tracking BP	Total
(a)	Reference yield (this is stated to be "radiation received" in each field. However the figures make no sense interpreted as kWh/day/kWp, and the assumption is that they refer to kWh/day/m2. (kW/m2)	0.225	0.223	0.236	
(b)	Yield from array in terms of DC power generated (kW / kWp %)	17.5%	16.3%	15.8%	16.8%
(c)	Final yield from array in terms of AC power generated (kW / kWp %)	16.7%	15.5%	14.8%	16.0%
(d)	Module efficiency (note these figures are given just as "efficiency"; however it seems obvious they are for module efficiency, because the cell efficiency of the BP cells is 17%. (kW/kW%)	10.6%	14.3%	14.3%	
(e)	So module area required to provide 1 kWp (m2)	9.43	6.99	6.99	
(f)	Insolation on module area of (e) at insolation of (a) (kW)	2.12	1.56	1.65	
(g)	Ratio of energy captured as DC to insolations on panels	8.3%	10.5%	9.5%	
(h)	Ratio of energy captured as AC to insolations on panels	7.9%	9.9%	9.0%	
(i)	Insolation that would fall on a horizontal plate of the same area as (e). Note this is partly because the figures at (a) are somewhat suspect as to meaning, and partly because the output in relation to the insolation in the area is more useful. However precise insolation for Toledo is not known. 200 W/m2 is estimated from an insolation chart. (kW)	1.89	1.40	1.40	
(j)	Ratio of energy captured as DC to insolation on `flat' surface of same area	9.3%	11.6%	11.3%	
(k)	Ratio of energy captured as AC to insolation on `flat' surface of same area	8.9%	11.1%	10.6%	
	Overview is that total energy flowing to the grid while plant operating in automatic mode uniterruptedly between July 94 and February 98 (the official trial period) from the three fields totalled 4165 MWh, thus over 3.5 years = 1190 MWh/yr. By 31 December 1998, the total power came to 5244, thus over 4.42 = 1187 MWh/yr. Neither of these are quite full years and in the text the figure is given as 1200 MWh/yr, which is used here for the total.				
					Total
(l)	Rated power of three arrays (kW)	456	423	101	980
(m)	Energy delivered to the grid over the course of an average year (kWh)	547,143	515,143	127,714	1.20E+06
(n)	Ratio of energy delivered to the grid to rated power (kW / kWp %)	13.70%	13.90%	14.43%	14.0%
(o)	Module surface area (m2)	4309	2942	703	7954
(p)	Ratio of energy delivered to the grid to insolation on `flat' surface of same area	7.2%	10.0%	10.4%	8.6%

These are summaries of the most important data based on at least three years operation.
Exactly the same summary data are shown under the 1997 data overleaf.
Rows (n) and (p) are the most important.
The values of row (n) are only true for the actual level of insolation at Toledo, Spain (about 200 W/m2 on a horizontal surface).
Row (p) is approximately true for any insolation. Results are somewhat variable because it depends on how tightly the cells are packed into the module. For a specified insolation and module, a vaue for (n) can be calculated from (p), e.g. for the Nukem column, with its modules of 10.6% efficiency, and with the 200 W/m2 insolation at this site:
kW/kWp = 0.0725 x 200 x (1 / 0.106) / 1000 = 13.7%; and for insolation of 100 W/m2:
kW/kWp = 0.0725 x 100 x (1 / 0.106) / 1000 = 6.8%

THE COST OF 'STAND ALONE' PV ELECTRICITY

By Andrew Ferguson, based on data from two Australians: F.E. (Ted) Trainer of N.S.W. University, and Jill Curnow of Sustainable Population Australia. Thanks to them both.

Gleaned from twenty years of operation, Ted Trainer gave the following data from his home PV system. The site location in New South Wales is at latitude 34° South. Annual insolation (as assessed by inspecting an insolation chart) is 200 watts per square metre (W/m^2). As far as one can discern from the insolation charts, this is the same as in Toledo, Spain, where trials were carried out with three large arrays, over 4½ years.

Trainer's solar collector consists of 3 panels, each with a rated capacity of 60W, i.e. 180W altogether, of 11% rated efficiency. The BP Solar panels in Toledo were rated at 14.3% efficiency, but this does not affect the capacity factor (measured in kW/kW_p), only the area of panel needed. Trainer's panels track the sun in *both* the vertical and horizontal axes. He tells me that, theoretically, this should improve their performance by 30%. But his results fail to confirm this, because, relative to their rated capacity, his panels produced the same output (in direct current) as was delivered to the grid by the fixed array at Toledo, 13.9% kW/kW_p. As an annual average, Ted's three panels together produce 600 Wh/day (0.6 kWh/day). Thus the output is the ratio (600 / 24) / 180 = 13.9% of rated capacity. *If* the insolation was the same in the two places, the dual axis tracker produced no benefit. But equality of insolation cannot be guaranteed; a far better check occurs when arrays are adjacent. This occurred at Toledo, but with a *single* axis tracker array. This raised output to the grid to 14.4%, compared to the aforementioned 13.9% of the fixed array (nearby, and similar in all other respects).

Capacity factor (the amount of actual output compared to rated capacity) is likely to be within the range of 9% to 17% of rated capacity, depending on how sunny the location is. As we shall see, the 13.9% for Trainer's home system is not a realistic indication of what is *usefully* available from a stand alone system. First, though, let us look at some costs.

The 3 panels together cost about US$855 (all prices will be translated to US dollars at A$1 = US$ 0.57, although the purchases were in Australian dollars). The balance of system costs (panel support system, inverters and regulators) are usually assumed to be about as much as the panels, but, for present purposes, so as not to overstate the case, let us estimate these at only *a third* of the panel cost, making the total $1140. Note that this works out at $1140 / 180 = $6.33 per peak watt. In the *2nd Footprint forum*, page 18, it was estimated that prices for installed capacity might drop as low as $5 per watt. However, the investigators at Toledo were not alone in stressing that low prices could only be achieved when operating at a large scale, so in the medium term, for 'stand alone' systems, $6.33 is a probable realistic lower limit for fully installed modules, without batteries, even though we will later consider the possibility of greater reductions, for further into the future.

With a stand alone system, batteries are essential. Three 220Ah batteries were used, costing about $170 each. Batteries are problematic. Although lifetime should be about 8 years, mistakes and faults of various kinds can often shorten their lifetime. A reasonable assumption would be 4 sets in a 30 year plant lifetime, i.e. a cost of $170 x 3 x 4 = $2040. Thus the total system cost would be $2040 + 1140 = $3180. Note that this cost is based on a lower limit 'balance of system' cost, but with a panel cost which, as we will consider later, may possibly reduce. The cost per peak watt, including batteries, has now risen to $3180 / 180 = $18. As we know that there were cost problems at a price of $5 a watt, we should now brace ourselves for some unwelcome results.

The total power generated over 30 years, at 0.6 kWh a day, would be 0.6 x 365 x 30 = 6570 kWh. On the face of it, that might appear to make the cost of the electricity $3180 /

6570 = ¢48 per kWh. However, some of the power generated has to be dumped because the batteries are full. For this reason, the energy that Trainer finds he can actually use is not 0.600 kWh a day, but 0.380 kWh, thus over 30 years the useful electricity is 0.38 x 365 x 30 = 4161 kWh. This figure puts the cost of the electricity at $3180 / 4161 = ¢76 per kWh (compared to a fossil fuel price of about ¢6 per kWh). Note, too, that the *'useful* capacity factor' is thus 4161 / (0.180 x 24 x 365 x 30) = 8.8%, to compare with 14.0% delivered to the grid at Toledo (although to make a fair comparison the latter should be reduced to about 13.3%, to take account of panel deterioration over time).

Looking into the future: We have set a lower limit price for the balance of system costs, including installation, but it is possible to imagine cost improvements in the production of PV panels. Perhaps it is even possible that the cost of the PV panels will, in time, reduce by two-thirds. This would bring the total installed cost of this three panel system to $(855 / 3) + (855 x 0.33) = $567. This would reduce the cost of electricity to $(2040+ 567) / 4161 = ¢63 per kWh.

It is clear that even with large improvements, stand alone electricity is going to remain an expensive option, and we should remember, too, that as fossil fuels become scarce, and the price of energy rises, the cost of PV electricity will rise commensurately, since a large element of the cost in PV panels is the energy needed to make them.

Ted Trainer's figures are corroborated by data from Jill Curnow, also from New South Wales. She gave details of her system, purchased in 1996, with a rated output of 680 watts. In relation to the output, she paid 50% more for battery capacity. This reduced the wastage of electricity to an estimated 25%, compared to Trainer's 37%.

Although Curnow did not provide an actual output figure, it can be estimated accurately on the basis of the 13.9% capacity factor of Trainer and the Toledo study (with a *fixed* array of *high efficiency* modules, Curnow's output would have been similar, 13.9 kW/kW_p). With her slightly lower wastage, the cost of electricity works out at US ¢95/kWh (using the same assumptions about battery life as were used for Trainer).

Curnow's costs provide corroborative evidence for some of our earlier assumptions. First, her installed cost per watt of module, without batteries, was US$9.14, confirming the earlier statement that $6.33 is a probable realistic lower limit for the fully installed modules (without batteries). Second, the *additional* costs (excluding batteries), in the initial purchase, added 42% to the module cost. These items comprised an inverter, battery charger, regulator, DC/AC switchboard and solar mounting arrays. Especially as the necessary generator to run the battery charger has not been included, these figures confirm our earlier assumption that 'balance of system' cost is unlikely to be less than one third of present module cost.

Despite the high cost of this electricity, stand alone PV is not necessarily a bad bargain over a 30 year period. If the price of connection to the grid is about US$20,000 (as was indicated by the Australian electricity authorities), then the total price of the PV system and the electricity consumed over 30 years is about 15% less than it would have been with connection to the grid, paying ¢6 per kWh (this is true whether or not interest is taken into account).

That assessment of cost conceals the extent of lifestyle change involved in living with a relatively small amount of PV electricity. The Curnow family, despite having spent about US$9,100 on their complete system, has to make do with only about 9% of the electricity used by an average New South Wales household. Neither should one underestimate the nuisance of trying to carry out activities, that require electricity, to coincide with times when there is a healthy solar input.

Secretary of the Optimum Population Trust (UK), Edmund Davey, continues in his role of the 'Plain Man', asking questions of interest to himself and other members of OPT.

A PLAIN MAN'S QUESTIONS CONCERNING PV, PART II

Asked by Edmund Davey; answers provided by Andrew Ferguson

Edmund From our previous discussion, I know that the idea of large scale PV is dead, deceased, passed over, with less life in it than Monty Python's parrot, but, at least until the price of fossil fuel rises massively, and everything becomes too expensive, some people may be able to use 'stand alone' PV, so would you mind clearing up a few queries I have about that?

Andrew I think your judgement about large-scale PV is sound. The plain fact is that no one will want to make expensive PV electricity until fossil fuels prices have risen four or five-fold, and that will send the cost of PV electricity off the clock. As to any other questions. Fire away!

Edmund You have mentioned a peak kilowatt. Can you tell me exactly what that is.

Andrew First, let me explain that the peak output of a module, which is also called the 'rated output', is a measurement of the proportion of the incoming radiation that an array of cells would produce, as electricity, when subjected to irradiation of 1 kilowatt per square metre. A typical figure would be say 11%. The same module out in the field would not perform quite as efficiently, in fact it would probably achieve something like 75% of that. But the more important fact is that the module in the field would not get 1000 W/m^2 irradiation. For instance, in a sunny clime like Toledo, Spain, the average annual insolation is 200 W/m^2, so that you would expect the module to produce only 200 / 1000 = 20% of its rated output. Moreover, as it performs in the field only about 75% as efficiently as it would under laboratory conditions, you would expect it to produce only 0.75 x 20 = 15% of the rated output. The actual figure, as measured over all three arrays at Toledo, over several years, was 14% of rated output. That figure is assessed in terms of the electricity delivered to the grid; there is some loss in inverting to AC and delivering to the grid. That is all background information, before telling you that a peak kilowatt is the amount of panel that would produce 1 kilowatt, when experiencing 1000 W/m^2 irradiation, under laboratory conditions.

Edmund OK, I get the idea, but can you tell me what a peak kilowatt of module would look like, sitting on a roof?

Andrew Certainly! For example take the 14.3% efficiency modules made by BP Solar. Incidentally they are made up with cells of 17% efficiency, but of course some space is taken up by the frame, which reduces the overall efficiency. One would need to stick 1 / 0.143 = 7 square metres of module on the roof to have a peak kilowatt of capacity. You really need to think of a peak kilowatt as something with two personalities. The first is what it manages to do under the lovely conditions of the laboratory, and the second is what it can manage out in the field, enduring the vissicitudes of life there. Under irradiation of 1000 W/m^2 in the laboratory, it will produce 1 kW of electricity.

Edmund So how about the second personality, what will those 7 square meters of module do on someone's roof?

Andrew As mentioned, in sunny Spain, where the insolation is 200 W/m^2, you would get 14% of the rated output of 1000 watts, namely 140 watts. Perhaps it is a bit confusing that the achieved output measured as a percentage of the rated output — you will have noted that a good name for this is the *capacity factor* — is often about the same figure as the rated efficiency of the modules, but there is only an indirect connection between them; there is no particular reason for the numbers to be even close. For instance, in a place where insolation was half that of Toledo, the capacity factor would, *with the same panels*, be about half as much as at Toledo.

Edmund 7 m^2 seems a lot of panel to stick on my roof to get only 140 watts. Can you just take me through a standard cost calculation as a cross-check.

Andrew 140 watts over 30 years would yield 0.140 x 30 x 24 x 365 = 36,792 kWh of electricity. At the reduced cost we used for large scale PV, the peak kilowatt, when installed, would cost $5000, so the cost per kWh would be $5000 / 36,792 = ¢14; that of course is only the capital cost with no interest or other things taken into account..

Edmund O.K., that number rings a bell. To get back to capacity factors, I read recently that the average capacity factor of wind turbines in the U.K. was 25%, so what you are saying is that the average capacity factor of photovoltaics is much lower, namely 14%.

Andrew It would not even be 14% in the U.K.; more like 9%.

Edmund How do you know that?

Andrew Insolation was measured at Reading, west of London, over the period 1978-87; the average annual figure was 108 W/m^2, so you might expect the capacity factor to be 108 / 200 = 0.54 of the 14% figure in Spain. However, there are figures available from BP Solar of a study at Northumbria University, and the outcome there was a 9.1% capacity factor.

Edmund That 108 W/m^2 insolation at Reading is presumably an average for the whole year. What was the average insolation there over the 8 winter months of September to April?

Andrew It was only 71 W/m^2, so you see capacity factors can vary considerably, but in terms of annual averages we are mainly talking in terms of 9% to 14%. Possibly in very sunny regions the capacity factor may go up to 17%, but that is an extrapolation. I have no good data on that, and the figure may be optimistic, because in very hot conditions PV cells do not perform so well.

Edmund Getting back to the sunny Spain figure of 200 W/m^2, you said that we would get 140 watts for 7 m^2, which is 20 watts for each square metre. I'm still having problems, because that does not seem much for a square metre of panel.

Andrew Well, looking on the bright side, it is 20 / 200 = 10% of the insolation. You will note that the equivalent figure, down at the bottom right hand corner of the Toledo spreadsheet, is 8.6%. The exact figure varies with the type of module, although indications are that the percentage figure stays fairly constant at different levels of insolation. Also note that the percentage of insolation captured would be slightly lower were we to assess it against the insolation that actually falls on the panels, since more insolation falls on the raised panels than it does on a horizontal surface. But those are points which are not really relevant to the fact that the normal range is between 7% and 10% of insolation, and that is an impressive achievement compared to plants, which capture only 0.1% to 0.5% of insolation.

Edmund That comparison is not really fair, because plants store their energy in a semi-permanent form, whereas electricity is evanescent.

Andrew You have a good point there Edmund. Were one to store the electricity as liquid hydrogen, overall the efficiency of capturing insolation would be half as much. While that is still better than plants, we have laid on another two layers of cost, electrolysis and liquefaction.

Edmund You have previously shown that producing liquid hydrogen from wind power electricity is not viable in most places, so people who suggest that liquid hydrogen could be produced from PV electricity would be off their rockers!

There is another thing that puzzles me. Why is it that your friend Ted Trainer reported an average annual output of 600 watt hours per day, rather than dividing by 24 and reporting instead an average 600 / 24 = 25 watts, because then it would have been so much more obvious that, with his panel rating of 180 watts, the achieved capacity factor was 25 / 180 = 13.9% of the rated power.

Andrew I do agree with you. Only if Ted's panels were rated as 180 x 24 = 4320 watt hours per day, would it be logical to report the achieved output as 600 watt hours per day. I believe PV manufacturers have always preferred to report the achieved output in different units from the rated output, in order to disguise the low actual outputs. I did write to BP Solar, and made the same point as you are making; perhaps it is no coincidence that our correspondence dried up at that juncture! Purveyors of optimism, like the Worldwatch Institute, go along with the scheme, by never mentioning what capacity factors are being achieved with PV installations. I did think of changing Ted's 600 watt hours a day into 25 watts, without giving his figure of 600 watt hours a day, but somehow felt I should present the exact data that he had reported.

Edmund You mentioned the low winter insolation in the United Kingdom. How much of a problem is the variation between winter and summer insolation for the United States?

Andrew David Pimentel sent me some figures, published by Reifsnyder and Lull in 1965. The figures were marvellously detailed, giving month by month insolation for the five areas of the United States: Northeast, Southeast, Midwest, Northwest and Southwest. Combining all these areas, the average insolation in the four winter months of November, December, January and February was 38% of that in the four summer months of May, June, July, and August; the actual figures being 104 W/m^2 and 276 W/m^2.

Edmund I should think those variations are fairly similar to Ted's site. I do admire the way that Ted kept such detailed records of his system, but I still wonder whether he would have done better to buy himself more batteries, so that he was able to store up all the electricity available during a long sunny spell.

Andrew No, that's not right. Ted judged things very well. What matters is the capital cost for the useful output. You will remember that, after I had made some optimistic assumptions about the balance of system cost, and after I had taken into account that a proportion of the electricity was being lost through lack of battery capacity, I arrived at a cost of $3180 / 4161 = ¢76 per kWh. Now suppose that Ted had bought twice as many batteries, and suppose, too — although it is exceedingly optimistic — that he then never wasted any electricity. The cost of his set-up would have risen to $4080 + 1140 = $5220. The benefit he would have gained is that over the 30 year lifetime of the system he would have received the full 6570 kWh instead of 4161 kWh. The cost per kWh would work out at $5220 / 6570 = ¢79 per kWh. So despite a greater investment, he would have been paying ¢3 more per kWh for his electricity. Also he would have the worry of more batteries to look after.

Edmund Why are batteries a problem to look after?

Andrew It is quite easy, during a long spell of cloudy weather, to allow them to run down, and that can ruin them. Also, according to Ted, you find yourself carrying batteries off to a local garage to get them recharged, or buying a generator at a cost of about $1200, or having to add another room to your house to store more batteries!

Edmund You just mentioned the optimistic assumptions you made about the cost of installation and the 'balance of system' costs. For this 'stand alone' study you assumed that these would only amount to a third of the module cost, but you did not make exactly the same assumptions for the large scale calculations, and just assumed that overall costs would not fall below $5 per watt. Why was that?

Andrew Such reductions in the balance of system and installation cost for stand alone systems seem possible. Other costs are so high for a 'stand alone' system that assuming such a reduction made little difference, so I did it for simplicity. For the grid scale study, where batteries were not needed, it was necessary to attempt to put a realistic lower level on costs.

In a BP Solar booklet, produced in 2000, prices were given for various claddings of buildings. The range of $560-800 m^2$ was given for glass walls. A typical square metre of high performance panel, in the 200 W/m^2 insolation of Toledo, is rated at 143 watts, so even with a zero cost for the PV cells, installed cost, based on the cost of glass panels, would be around $4.75 per watt. If you add to that the cost of the inverters and power conditioners $5 per watt would appear to be a lowest possible price, even assuming a zero cost for the PV cells. However, there are complicating ideas which float around. One argument, which is put forward in the BP Solar booklet, is that: "solar photovoltaics can be incorporated into new constructions at relatively little cost." Their argument is based on the fact that the PV cells could replace the glass wall cladding systems. I tried to get an architect friend to do some costing, but it turned out that every case would be different, depending, for instance, on how high the building was, and its location. Until there are examples, with costings, of buildings which have actually been constructed using PV panel cladding instead of glass wall systems, I think our $5 per watt remains a realistic lower limit.

Edmund I have to agree, and I note too that simple wall cladding would not orient the panels ideally. I have come across references to making PV roof tiles. I suppose the efficiency may not be as good as for standard PV panels. Do you know what capacity factor is being achieved with these systems?

Andrew No, that is something, or so it seems to me, that the manufacturers are keeping under their hats!

Edmund Another thing I noted from the Toledo spreadsheets was that output was reported both as DC and as AC, with a significant difference between the two. Was the average 600 watts per day output that Ted reported, AC output at the usual voltage that is used for household equipment?

Andrew Ted tells me that he has a DC system and has to purchase equipment that runs on DC. There would be about a 9% power loss in making the conversion to AC.

Edmund Let me just recapitulate on what I have learnt. The capital cost of large-scale PV, without allowing for interest charges, could be brought down to a rock bottom overall installed cost of $5 per watt. However, for a 'stand alone' system, after taking into account the batteries, that figure becomes $18 per watt of capacity. That high cost is made worse by the fact that, after allowing for the wasted electricity, the capacity factor is 8.8%. The combined effect of this is to make the cost of electricity — even in a fairly sunny place — 76 U.S. cents per kilowatt hour.

Andrew By Jove Edmund, you are an apt student! Together with your opening observation, that large scale PV has less life in it than Monty Python's parrot, you have summed up how things look with PV very neatly.

Edmund But to argue against myself for a moment, surely we need to take into account that as human affairs reach the straightened circumstances that seem inevitable, people will pay more or less whatever it takes to ensure that they get their electricity.

Andrew You are looking at things from the perspective of someone living in the rich world in a peculiar epoch in history — the petroleum interval — and forgetting that our wealth is founded on cheap energy. As can been seen from the *Living Planet Report 2002*, the 900 million people living in the 'high income' countries consume about six times as much energy as the mean for the rest of the world. When fossil fuels become scarce, there will be very few people who are in a position to pay whatever it takes.

Edmund I see. We need to think ahead. Taking a wider view of the renewable energy situation, it seems that if America invested about 18 billion dollars each year in wind turbines, for 20 years, they would have fully exploited their wind resource, and yet replaced only about 6% of their energy consumption, and we have seen that photovoltaics are unlikely to make a useful contribution due to their cost, so perhaps you were being unduly optimistic in estimating an energy/land ratio of 3 kW/ha for eco-footprinting.

Andrew You will remember that I covered myself by suggesting the need for some relaxation in the ideal of relying on renewables. There is a lot of coal in the ground, the difficulty is getting it out. One simple back-of-the-envelope calculation is that with a global population of 2 billion, each person could have the use of 1.5 kW of power from coal (for comparison each European now uses a total of about 5 kW), without the Earth exceeding the climate change emission limit of 9 billion tonnes of carbon dioxide per year. Actually, even a population of 2 billion would not enjoy that amount of useful energy, because a considerable proportion of the energy would need to take the form of synthetic gasoline, and it takes about 3.65 t of coal to make 1 t of synthetic gasoline. Basically, though, you are absolutely right that the predominant form of truly renewable energy will come in the form of energy captured from biomass, and by time a proportion of that energy has been converted into liquid form, net energy-capture will be low, somewhere in the region of 1.5 kW/ha.

Edmund Thus the world is in a race against time to reduce its population to about 2 billion — the sort of level of population which could be supported without fossil fuels — before it reaches the point when it takes more energy to get fossil fuels out of the ground than they contain, or, what will probably happen long before that, they become prohibitively expensive.

Andrew Edmund you are a genius! You have put the whole situation in a nutshell.

Postscript

For the sake of veracity, I thought it best not to spare Edmund's blushes, but rather record the dialogue verbatim.

WIND/BIOMASS ENERGY CAPTURE

by Andrew Ferguson

Wind energy can have only a tiny effect on raising mean net energy-capture to the figure of 3 kW/ha, which is assumed for eco-footprinting, from the mean of 1.5 kW/ha available from biomass. Most hydropower has already been developed, leaving wind as the only remaining renewable energy source that is likely to be a *significant* contributor to improving the net energy-capture beyond that which applies to biomass alone. The importance of a realistic assessment of net energy-capture is apparent from the fact that biomass alone could support only a fraction of the present population.

The present issue of this journal (pp.33-37) shows that photovoltaics cannot play a significant part in the quest for renewable energy. The previous issue showed that the problem with wind power is that it is limited in scope (April 2002, pp. 11-13). However, one aspect of wind power requires further investigation, namely the implications of the variability of wind strength.

Some clues came from an article by science editor, Peter Bunyard, in *The Ecologist*, April 2002, pages 51-53. He told us that, in 2001, the UK energy department produced a new energy trading arrangement (NETA). This demands that the wind power generator should predict, four and a half hours in advance, the exact amount of electricity that is to be produced. Financial penalties apply for getting the figure wrong.

Wind power generators have two possible responses for dealing with the uncertainty surrounding their output over the next four and a half hours. The first is to incorporate a margin to account for variability, marketing less than they expect to generate. Apparently some of them did this, because output to the distributors fell by 14% as a direct consequence of NETA.

The alternative action is for generators to have their own reserves of time-independent generating capacity, which they can bring on line should the hoped for output from the turbines fail to materialize. Apparently some generators have taken this course of action, but obviously there is a carefully balanced judgement to be made, whether the cost of having the reserve capacity standing by is going to exceed the cost of allowing the unpredictable portion of the wind output to go to waste.

What is important about NETA is that it throws a first shaft of light on the problems of an unpredictable supply. It is far from being a spotlight, because this arrangement still leaves the distributors with difficulties when several wind generators say they can guarantee only a negligible proportion of their usual output: the distributors then have the problem of finding a generator with spare capacity.

The only way to get a clear insight into the underlying realities of the situation would be to get wind generators to predict to what extent they could fulfil the requirements of the distributor, not just for four and a half hours, but for the next twelve months. That would more or less certainly require generators to purchase spare capacity themselves, in order to sell nearly all their wind-generated supply, despite its variability. The 14% drop, related to a four and a half hour prediction requirement, gives some basis on which to judge the amount of electricity that wind generators would have to take from a time-independent source in order to guarantee an output for the year ahead (perhaps not a constant amount, but one which would be agreeable to the distributor, e.g. fifty per cent more in December as compared to July). Anyhow, it adds a further clue to what can be gleaned by looking at the variability of achieved capacity factors, e.g., for Sweden: 13% in July, 11% in August, 17% in September, but that is just one year. In such circumstances, a reasonable guesstimate for the amount of electricity that would need to be generated from a time-independent sources is probably 15% of the whole; at least that estimate is unlikely to be excessive.

Perhaps the 15% datum will require some revision, nevertheless it is good enough to make it possible to work out a useful energy-capture figure combining wind and a time-independent source. The time-independent source — in the field of renewable energy — can be taken to be electricity generated from biomass, grown in a sustainable manner. Present indications are that a sustainable yield of biomass, over large areas, averages 3 t/ha/yr, which approximates to 60 GJ/ha/yr, or 2 kW/ha.

Because wind turbines, including the required access roads, actually occupy only a small area (about 2-5% of the area over which the turbines are deployed), their energy capture is high. In terms of primary energy equivalent, 1100 kW_{th}/ha is a sound estimate. Additionally, a proportion of the wind turbines would be situated off-shore, or on land that was not biologically productive. Thus — accurately enough for our purposes — we may put the energy-capture of wind turbines as high as 3000 kW_{th}/ha of productive land required.

We can now do the arithmetic on a representative sample of total supply, say 1000 kW of electricity, or 1000 / 0.33 = 3030 kW of primary energy equivalent. 850 kW_e would come from the wind turbines. This has a primary energy equivalent of 850 / 0.33 = 2576 kW_{th}. It would thus require 2576 / 3000 = 0.86 ha. The remaining 150 kW of electricity, from time-independent sources, would require 150 / 0.33 = 455 kW of thermal energy in order to generate the 150 kW_e. The area needed would be 455 / 2 = 227 ha. Thus the composite wind/biomass energy-capture is 3030 / 227.86 = 13.30 kW_{th}/ha. It is now evident why we did not need to be too careful with our estimate of the energy-capture of wind by itself: had we guesstimated 4000 kW_{th}/ha, instead of 3000, the result would be very similar, namely 13.31 kW_e/ha. That is also the reason that is not worth bothering about *net* energy-capture, — subtracting the inputs — the difference is not important. Also the inputs which apply to sustainably harvested biomass are small in proportion to the output.

It will be recalled that the chief limitation on wind power in the U.S. was that if the full potential were to be exploited, producing 777 billion kWh/yr, this would still only replace 8% of U.S. primary energy demand (or more like 6.5% if allowance is made for inputs). To that picture, we can now add land demand. 777 billion kWh_e/yr = 88.7 million kW_e. This is equivalent to 88.7 / 0.33 = 269 million kW_{th} of primary energy. That would need 269 / 13.3 = 20 million hectares of biologically productive land.[1]

The 20 Mha is not by itself a cause for much alarm, since the U.S. has 500 - 740 Mha of biologically productive land, depending on definition. What is of more concern is that the composite energy-capture of wind/biomass is only going to contribute 8%, at best, to the whole. Moreover there is little else, amongst renewables, of sufficient magnitude and with a high enough energy-capture, to make a significant contribution. As has already been observed (page17), the mean energy-capture that can be achieved to provide heat and liquid fuels is unlikely to exceed 1.5 kWh. Now we can take a representative sample of the whole energy supply, this time of say 1000 kW_{th}. Of this, 8%, 80 kW_{th}, would come from wind/biomass and require 80 / 13.3 = 6 ha, while the remaining 92%, 920 kW, would require 920 / 1.5 = 613 ha. Thus, overall, energy-capture would be 1000 / 619 = 1.6 kW/ha. In other words wind energy would have improved the mean energy-capture figure by only 0.1 kW/ha.

This result makes it clear why, in order to reach eco-footprinting's energy/land ratio of 3 kW/ha, it will probably be necessary to assume some input from fossil fuels — probably coal for the most part, and perhaps some contribution from tar sands and shale. It is only on that basis that the 3 kW/ha figure can be honestly defended as falling within the scope of not being excessively optimistic.

A lesson from a wind project in northern Britain.

Peter Bunyard mentioned plans for the "world's largest wind farm, with a capacity of 600 MW, on the Isle of Lewis," adding that this "one project alone would meet nearly 0.5 per cent of the UK's electricity needs." The figure seems encouraging, perhaps suggesting the thought that were this project to be repeated 40 times, it would provide 20% of the UK's electricity needs. However, from our previous considerations, the total area of biologically productive land needed to produce that amount, as a steady supply, based on wind resources, would be 1.5 million hectares.[2] That constitutes 8% of the UK's biologically productive area, and is of course ludicrous in the context of the UK's present population and its wood production. Although the UK is gradually increasing the amount of timber grown at home, a peak is expected around 2025. By that time the UK will be producing a *third* to a *half* of its present consumption; and of course UK citizens are not presently burning much wood for heating — they are merely using it for products of various kinds.

On page 103 of *Tomorrow's World*,[3] Duncan McLaren and his co-authors said that 190 billion kWh/yr was their "optimistic" estimate for electricity from wind power in the UK by 2050. Perhaps it would be wise to apply a reality check to that figure before considering the land implications in the context of a fossil free society.

The UK has a land area which is 2.6% of that of the United States. The American Wind Energy Association estimate a potential wind output of 675 billion kWh for onshore turbines. Thus on the basis of land area, one would think that the UK might get 18 billion kWh/yr. However the UK is far more built up, so perhaps half that would be a more plausible estimate, say 9 billion kWh/yr.

Off-shore is more difficult, but the UK has a coastline of roughly 2000 km compared to 6000 km for the US. On that basis the UK should, pro-rata, be able to get a third of the estimated offshore potential of 102 billion kWh/yr of the US. That makes a total of 43 billion. Thus 60 billion kWh/yr would seem a better figure, in order to keep optimism within bounds! So how much land would be needed to supply a regular 60 billion kWh/yr from wind/biomass? 60 billion kWh/yr is 20% of the UK's electrical supply, so the figure is still 1.5 Mha and, as mentioned, for Britain's present population it is clearly unrealistic to make that available.

Endnotes

1 A more long-winded, but more transparent way of doing the calculation would be to say that the 777 x 0.85 = 660.5 billion kWh_e, generated from wind, would use:
$(660.5 \times 10^9\ \ 24 / 365) / 0.33 / 3000 = 76{,}161$ ha.
And the 777 x 0.15 = 116.6 billion kWh_e which would be generated from biomass would use:
$(116.6 \times 10^9 / 24 / 365) / 0.33 / 2 = 20.2$ Mha, for a total of <u>20</u> Mha.

2 UK's electrical consumption is about 295 billion kWh/yr.
20% of this is 0.20 x 295 = 59 billion kWh/yr.
The primary energy equivalent is 59 / 0.33 = 179 billion kWh_{th}/yr = $179 \times 10^9 / (24 \times 365)$ = 20.4 million kW.
Thus at 13.3 kW/ha, the biologically productive land required = 20.4 million / 13.3 = 1.5 Mha.

3 McLaren, D., S. Bullock, Y. Nusrat. 1997. *Tomorrow's World*. London: Earthscan.

THE FOLLOWING PAGES DID NOT APPEAR IN THE PUBLISHED JOURNAL, BUT THEY MAY BE OF INTEREST. NOTE THAT ALTHOUGH THE REFERENCES ARE HIDDEN, THEY ARE ALWAYS PROCEEDED BY THE SYMBOL `{` SO THEY ARE EASY TO SEARCH FOR

1 The *Vital Signs* books come from the World Watch Institute. The two editions referred to herein are: Brown, L. R., Kane, H., Roodman, D. M., 1994, and Brown, L. R., Renner, M., Halweil, B., 2000.

2 McLaren, D., Bullock, S., Nusrat, Y. 1997. *Tomorrow's World*. London: Earthscan.

3 Nakicenovic, N., Grubler, A, McDonald, A. (Ed.). *Global Energy Perspectives*, 1998. Cambridge, UK: Cambridge University Press.

4 Hagedorn, G. 1989. Hidden Energy in Solar Cells and Photovoltaic Power Stations. Ninth European Photovoltaic Solar Energy Conference, 542 (1989).

Notes from OPT 22 not for publication in this version.

While these notes did not appear in the publication, they may be of interest, and the references can be located fairly easily since there is a hidden {symbol before the notes.

A PLAIN MAN'S QUESTIONS CONCERNING PV, PART I

Temporary {T?} notes to assist reviewers

{T1} The mean energy/land ratio used in *LPR 2002* can be calculated as follows:

The total energy figure used was incorrect because 9.5 EJ of hydro was not changed to its primary energy equivalent. Thus the correct figure is

360 - 7.5 + (7.5 /0.33) = 375 EJ/yr.:

Note all gha figures refer to LPR 2002 gha units.

Total energy FP - fuelwood FP = 1.06 gha/cap.

Therefore, the figure for the world is 1.06 x 5.98 x 10^9 = 6.34 x 10^9 gha.

So energy/land ratio = 375 x 10^{18} / 6.34 x 10^9 = 59.2 GJ/gha/yr.

Forest equivalence factor (p. 32) = 1.35.

So energy/land ratio = 59.2 x 1.35 = 80 GJ/ha/yr.

{T2} Present (*LPR 2002*) forest biocapacity is 0.86 gha/cap, and forest products footprint is 0.27 gha/cap, so area presently available for absorption is: (0.86 - 0.27) x 5.98 x 10^9 = 3.53 x 10^9 gha = 3.53 x 10^9 / 1.35 = 2.61 x 10^9 ha.

Cropland + grazing land + forest = 1.5 + 3.5 + 3.8 = 8.8 billion ha (*LPR 2002*).

20% expansion would give an extra 8.8 x 0.20 = 1.76 billion ha.

So total available for absorption = 2.61 + 1.76 = 4.37 billion ha.

Requirement

Carbon to be absorbed according to LPR = 65% of the total 6.3 Gt/yr fossil fuel emission = 0.65 x 6.3 x 10^9 = 4.10 GtC/yr.

At LPR's 0.95 tC/ha absorption rate, area needed = 4.10 / 0.95 = 4.32 Gha.

{T3} Methanol data from Foran and Mardon, p. 14 of Trainer's *Can solar sources* . . . paper:

Total input = 68.6 GJ, but this includes 2.2 t of feedstock.

2.2 t of feedstock at a standard 17.5 GJ/t = 38.5 GJ.

9.4 GJ of the methanol output is also assumed to be part of the input.

This reduces the net input (but including feedstock) to 68.6 - 9.4 = 59.2 GJ.

Assuming 3 dry t of biomass /ha/yr, at 18 GJ/t, i.e. 54 GJ/ha, this requires 59.2 / 54 = 1.10 ha.

After subtracting 9.4 GJ of methanol to use as input, Foran and Mardon assume that the net output of methanol is 13 GJ.

Thus *net* energy-capture = 13 / 1.10 = 11.8 GJ/ha/yr = 11.8 x 0.03171 = 0.37 kW/ha, say 0.4 kW/ha.

Assuming a yield of 10 dry t/ha/yr would increase this to 13 / 1.10 x 10 / 3 = 39.39 GJ/ha/yr = 39.39 x 0.03171 = 1.25 kW/ha, say 1.3 kW/ha.

Note it appears that the authors are only assuming 9.40 / (68.6 - 38.5) = 31% of the input has to be in the liquid form of methanol, which seems a reasonable guesstimate.

{T4} The basic calculations were shown on page 12 of the *OPT Journal*, April 2002. This is a brief exposition, making use of those data.

In an internal combustion engine, hydrogen burns 1.33 times as efficiently as gasoline.

The energy density of gasoline is about 33.5 MJ/litre.

So 33.5 / 1.33 = 25.19 MJ of hydrogen would provide the same motive power as 1 litre of gasoline.

To produce the 3 liters (210 gm) of liquid hydrogen, which have the same motive energy as 1 litre of gasoline, requires 12 kWh_e (43.2 MJ_e).

Thus the efficiency of producing *gasoline equivalent* is 33.5 / 43.20 = 77.5%.

Thus 20 GJ/ha/yr of electrical energy would produce 20 x 0.775 = 15.5 GJ/ha/yr (say 16 GJ/ha/yr)

<u>Cross-check</u>

43.2 MJ_e produce 33.5 MJ of gasoline equivalent (in the form of 3 liters of liquid hydrogen).

So 1 J_e produces 33.5 MJ / 43.2 MJ = 0.775 J of gasoline equivalent (as liquid hydrogen).

So 20 GJ_e would produce 20 x 10^9 x 0.775 = 15.5 GJ of gasoline equivalent (as liquid hydrogen).

{T5} The American Wind Energy Association estimates that there are land sites available in the U.S. sufficient to generate 675 billion kWh_e/yr of electricity, with a further 102 billion kWh_e/yr off-shore (AWEA, 2000; Pimentel, 2001), for a total of 777 billion kWh_e/yr.

A 25% capacity factor is assumed; it is unlikely to be better than this since *all* suitable wind sites would be used (i.e. not just the best). Thus 777 x 10^9 / 0.25 = 3.108 x 10^{12} kWh/yr = 3.108 x 10^{15} Wh/yr = 3.108 x 10^{15} / (24 x 365) = 355,000 x 10^6 W, i.e. 355,000 turbines of 1 MW capacity.

The cost of wind turbines is about $1 per rated watt, so the cost would be $355 billion.

That the output is about 8% of current U.S. total energy use is estimated as follows:

2000 U.S. energy use (estimated from 1995 data) = 93.97 [quads] x 1.0112^5 = 99 quads = 99 x 1.055 x 10^{18} = 104.8 x 10^{18} J, or 104.8 EJ.

Primary energy required to generate 777 x 10^9 kWh_e = (777 x 10^9 / 0.33) x 3.6 x 10^6 = 8.47 EJ.

So wind could replace 8.47 / 104.8 = 8.1% (say 8%) of the total energy use.

The DOE reported a nearly 40% increase in energy between 1970 and 2000, making an annual growth rate of 1.127%, say 1.12%.

Thus after six years, growth would be 1.0112^6 - 1 = 6.9%, i.e., greater than the mentioned 6.5%.

{T6} The nearly four and a half year experiment at Toledo, Spain recorded radiation at the panels of 210-220 W/m^2, thus insolation on horizontal plane would be of the order of 200 W/m^2, which is convenient as average insolation in the USA is about 190 W/m^2.

The report (www.toledopv.com/ingles/masesp.htm, 25/04/2000) as well as giving annual breakdowns for the three arrays states that the average output for the whole system, delivered to the grid, was 1200 MWh/yr. This came from three arrays with a total rated capacity of 980 kW. Thus the 'capacity factor' as delivered to the grid was 1.2 x 10^6 [kWh] / (980 x 24 x 365) = 14.0%

{T7} At the level of insolation at Toledo, Spain (about 200 W/m^2; roughly the same as the average in the U.S.A.), the 'capacity factor' of high efficiency panels is 14.0%. Thus the 777 x 10^9 kWh/yr, being studied for wind turbines, would require 777 x 10^9 / 0.14 = 5.55 x 10^{12} kWh/yr = 5.55 x 10^{12} / (24 x 365) = 633.5 x 10^6 kW.

At $5000 per kW the cost = $5000 x 633.5 x 10^6 = $ 3168 billion, say $3200 billion.

References for (T?} notes

AWEA. 2000. Wind energy and climate change. www.awea.org/bubs/factssheets/climate.pdf

Pimentel D. 2001. Offshore wind potential received by letter dated April 25, 2001.

Temporary notes to *The Cost of 'stand alone' PV electricity*

{H1} There is some contradiction between the apparent fact that Curnow's 12 batteries, have a capacity of 1100Ah x 24v = 26,400 Wh, which is only 26,400 / 680 = 38.8 Wh/W. Whereas Trainer has 220Ah x 3 x 24v= 15,840 Wh, which is 15,840 / 180 = 88 Wh/W. Thus it appears that Curnow has 38.8 / 88 = 44% of the battery capacity *in relation to the rated module output*.

On the other hand a different picture emerges from cost. Curnow paid A$5064 / 680 = A$7.45 for batteries, per watt of rated module output. Trainer paid A$(300 x 3) / 180 = A$5.00 per watt of rated module output. Thus Curnow paid 7.45 / 5.00 -1 = 49% more for batteries per watt of rated module output. It is of little consequence what the manufacturers claim for their batteries (there was some lack of clarity about Curnow's 1100Ah batteries), what matters is how much one has to pay as backup, in relation to the module output, and how well that capacity performs. Thus the important thing about Curnow's set-up is that she paid about 50% more for battery back-up, but still had to try to use power when it was available in midday, and have a standby generator to recharge the batteries in winter.

Trainer was able to use only 380 / 600 = 63% of the PV output, thus wasting 37%. Having paid 50% more for her batteries Curnow should do better than this. How much better would depend on how assiduous she is in using the power when available thus saving battery storage. From the general picture she has painted, it would seem reasonable to assume that without much diligence, in power use, she would have fared only a little better than Trainer, perhaps reducing his 37% loss to say 37 / 1.5 = 25% by virtue of having paid an extra 50% for battery capacity. Thus 75% useful output appears to be in the ball park for Curnow's set-up. Anyhow this seems a good enough estimate, since what we are really interested in is what the average user would achieve, rather than what Curnow's family managed to do!

{H2} Initial cost = A$15,969. Assuming that over 30 years, 3 additional sets of batteries are required, total cost = A$15,969 + (5064 x 3) = A$31,161 = A$31,161 x 0.57 = US$17,762. Perhaps it should be observed that battery life is the most difficult thing to assess (as Trainer intimated). Curnow said that she was told her batteries should last 8 years and may last twice as long. However, naturally I have stuck with the same assumption that Trainer made — a mean life of 7½ years.

Output over 30 years from the 8 panels, of 85 watt rated capacity (0.680 kW), with a 13.9% capacity factor = 0.680 x 0.139 x 30 x 24 x 365 = 24,840 kWh.

Assuming that 25% of this is wasted (see previous endnote), then useful electricity is 24,840 x 0.75 = 18,630 kWh.

So cost = US$17,762 / 18,630 = US$95/kWh.

{H3} It occurred to me to compare what Curnow would have paid for connection to the grid, which she said would have cost A$30,000 - A$40,000, plus paying for the electricity that we estimates she gets from the PV system. Taking the mean grid connection figure, and a price of grid electricity of A$0.10 per kWh, the cost would have been, over the 30 years, A$35,000 + (18,630 x 0.10) = A$36,863, so the A$31,161 which we calculated she would have to pay for PV if the batteries need replacing every 7½ years, would be cheaper than the grid option by 1 - (31,161 / 36,863) = 15%.

Adding interest charges obviously makes little difference, but we can do the calculation to be precise. Dealing in real terms (removing inflationary distortion), total interest for the PV system would be about

A$(31,161 / 2) x 0.025 x 30 = A$11,685. This makes the total cost of PV electricity A$31,161 + 11,685 = A$42,846.

For the grid system, interest charges would fall on connection to the grid. That makes the overall cost of grid electricity: A$35,000 + (35,000 / 2) x 0.025 x 30 + (18,630 x 0.10) = A$49,988. So PV electricity is still 1 - (42,846 / 49,988) = 14% cheaper.

{H4} The capacity factor would be about 14%, so Curnow's 680 watts of panel would deliver 0.14 x 0.680 = 0.0952 kW.

Wastage due to overloading the batteries is estimated at 25%, so useful power = 0.0952 x 0.75 = 0.0714 kW

A NSW household uses about 20 kWh a day = 20 / 24 = 0.8333 kW.

Thus Curnow's house obtains 0.0714 / 0.8333 = 8.6% of what an average NSW householder uses, from their PV system.

THE END