OPTIMUM POPULATION TRUST
JOURNAL OCTOBER 2004

Vol. 4, No 2, compiled by Andrew Ferguson

Page

2 Introduction

3 *Climate Change and Sea Level in Relation to Population*, John Nunn.

9 *Hydrogen as an Energy Carrier*, Andrew Ferguson

15 *Vexponential Growth in the 21st Century*, Andrew Ferguson

18 *Comparing WROG Periods*, Andrew Ferguson

21 *Population Growth in The United States and Canada: A Role For Scientists*, Peter Salonius

22 *Capacity Factors — a simple analogy*, Andrew Ferguson

23 *The Relative Cost of PV and Wind Power*, Andrew Ferguson

28 *A Rule of Thumb for PV Annual Capacity Factors*, Andrew Ferguson

32 *Strangely Like War: The Global Assault on Forests*, Derrick Jensen and George Draffan

---

> One goal of my 1997 book, *The Heat is On*, was to impress on readers the fact that climate change is not a remote, theoretical future risk. Another was to highlight an extraordinarily effective campaign of deception and disinformation by the fossil fuel lobby. Both of those themes recur in this book, but virtually all the developments chronicled here have taken place since 1998.
>
> Sadly, while the particular developments about our changing climate are new, the larger trends are continuing unabated — and, at least in the United States, essentially unacknowledged.
>
> Ross Gelbspan, *Boiling Point*, 2004, (p. xi)

The Optimum Population Trust (UK): Manchester

<www.members.aol.com/optjournal> & <www.optimumpopulation.org>

INTRODUCTION

I am grateful to John Nunn, a doctor of medicine with a special interest in ancient Egyptian medicine, and a fellow of the Geological Society, for the impressive paper on sea levels which opens this issue. It includes a unique diagram — a noteworthy achievement in itself — showing the changes in sea level, temperature, and atmospheric carbon dioxide over the last 450,000 years. The lowest segment of the diagram includes a pointer for CO_2 concentration in 2002 AD. Within the context of the diagram, a glance at that pointer leaves no room to doubt that the human race is engaged in an unprecedented experiment with the earth's climate (as previously described in *Ice Age, Glacial and Interglacial*, OPTJ 2/1 pp. 24-26).

Pages 9-14, *Hydrogen as an Energy Carrier*, provide a commentary on a presentation made by *SFA Pacific*, Inc. The essence of our conclusion is that no paper or presentation is much use unless it addresses the main question, which is where to find the energy to produce the hydrogen. Incidentally, if space had allowed it, *Hydrogen as an Energy Carrier* would have gone into the April 2004 OPT Journal (OPTJ 4/1), as it contained two papers relating to aspects of hydrogen — *Hydrogen and Intermittent Energy Sources* and *Hydrogen Fantasies*. Note that OPTJ 4/1 is now available on the OPT Journal website.

Pages 15-20 include two related pieces. The first, *Vexponential Growth in the 21st Century*, arises because mathematicians sometimes insist that the word 'exponential' can only 'properly' be used when growth rate is constant. The piece reiterates that population growth remains of the compound interest type even if the rate is declining. This paper also sets the scene for the next piece, *Comparing WROG periods*, which applies the concept of vexponential growth to the 'Weak Restraints on Growth' idea introduced by William Stanton in his recent book, *The Rapid Growth of Human Populations 1750-2000*.

On page 21, Canadian scientist Peter Salonius gives a timely warning that North American legislators must be made aware that, "as a result of their present-centered, expansionist agendas, they are continuing to set their naive constituents on a course toward a dismal and crowded future brought about by massive immigration."

Pages 22-31 contain three pieces related either to 'capacity factors' or to comparing the cost of photovoltaics and wind turbines. As OPTJ 4/1 contained an eight page paper on *The Meaning and Implications of Capacity Factors*, this may seem to be overkill, but the papers came into being as a result of discussing these matters with people intimately concerned with developing renewable energy, and there still seemed to be a need to bring home, as clearly as possible, the fact that both PV and wind — two 'dream solutions' of environmentalists to energy provision — have an intractable problem on account of their intermittency. Let's look at these three pieces in a bit more detail.

It was difficult to decide what order to put them in. *Capacity Factors — a simple analogy* shows that improvement in module efficiency, in other words technical improvements, will not improve the capacity factor of PV. That piece is thus obviously related to the later one, *A Rule of Thumb for Annual Capacity Factors*, but it also relates to the paper which actually follows it, *The Relative Cost of PV and Wind Power*. The last mentioned paper shows that the capital cost of PV is about 9 times as much as wind, after taking capacity factors into account.

Page 32 provides some extracts from Derrick Jensen and George Draffan's worthwhile book, *Strangely Like War: The Global Assault on Forests*, the title of which speaks for itself.

As usual, I have received invaluable assistance in the preparation of the papers for which I am responsible. Most of them passed through David Pimentel's hands, and in addition to the stimulating material he sent me, he gave me much useful advice. Special thanks too to Harry Cripps, David Gosden (with whose help I struggled to make *Vexponential Growth* comprehensible), Albert Bartlett, Edmund Davey, and the ever-helpful Yvette Willey.

CLIMATE CHANGE AND SEA LEVEL IN RELATION TO OVERPOPULATION

by John F. Nunn

It would be hard to overestimate the significance of the amount of ecologically productive land that a country has in relation to its population. It is now becoming clear that the area of certain countries may be substantially reduced by rising sea levels in the foreseeable future. This will affect not only the most heavily populated regions, but also the most ecologically productive land. Approximately 100 million people live within 1 vertical metre of mean sea level{1} and 1,880 million people within 100 metres in 1997.{2} The Pacific island of Tuvalu has recently found its agricultural basis threatened by sea level rise, and is seeking to evacuate the entire island.

Sea level has been rising at about 18 cm per century since 1850,{3} with the probability that this will increase. The problem may be addressed at three levels: global warming, the effect of this on melting of polar ice and lastly the resultant effect on sea level. Although there is serious concern about all three, there are major difficulties in formulating precise quantitative predictions for changes beyond the immediate future. Nevertheless, there can be no doubt that sea level will rise. The uncertainties are the magnitude of the change and its time course.

Is global warming a reality?

Recent years have seen an explosion of new knowledge of bygone temperatures. Many technologies have been used, mostly giving gratifyingly similar results. The most dramatic have been measurements of the proportion of the heavy stable isotopes of hydrogen (^{2}H, deuterium) and oxygen (^{18}O) in ice cores. In Antarctica, samples go back 420 kyr, and are limited by fear of the drill breaking through into Lake Vostok. In Greenland they go back 140 kyr and are limited by reaching bedrock. The technique may also be applied to the shells of foraminifera found in cores drilled from ocean beds and data go back at least 67 Myr. Other approaches to the measurement of ancient temperatures include dimensions of tree rings (northern hemisphere data now available back to 14.3 kyr), pollen (extending back several million years), corals (extending back to 130 kyr), the geological record of past glaciations, and the relative abundance of fossil species known to be sensitive to temperature. It must, however, be stressed that the temperature change between the last glacial maximum and the present differs greatly between Greenland (20°C), Antarctica (8°C), and mean global temperature (6-8°C) (Severinghaus, personal communication).

The record of past temperatures from Antarctic ice cores{4} is shown in the diagram, and accords well with pre-existing data from ocean bed cores. Clearly shown are four glacial periods, interspersed by comparatively brief interglacial periods with temperatures not greatly dissimilar from today. Temperature changes have followed a saw-toothed pattern, with prolonged and progressive cooling into a glacial period, followed by rapid warming immediately before the next interglacial. This seemingly regular pattern correlates remarkably well with changes in the mid-June solar radiation (insolation) received from the sun at latitude 65° north, which has varied within the range 440 to 545 watts per square metre during the last 200 kyr.{5} These variations are due to cyclical astronomical factors, the most important being the ellipticity of the earth's orbit (periodicity approximately 100$\pm$25 kyr), the tilt of the earth's axis (periodicity 42 kyr) and the precession of the equinoxes (periodicity 21 kyr in relation to perihelion), generally known as Milankovitch cycles. These cycles are discernible in the temperature record in the diagram, although the frequencies show some variation due to modulation by other cycles (frequency-modulation). The 100 kyr cycle is the weakest as regards changes in insolation, but nevertheless seems to have been the main pacemaker of the major glacial/interglacial cycles. Changes in insolation have received powerful positive feedback from the greenhouse gases carbon dioxide and methane, the former averaging 180 ppmv at glacial maxima and 280 during interglacials. Carbon dioxide levels have risen dramatically since the onset of the industrial revolution and the burning of fossil fuels on a massive scale (see diagram).

The apparently repetitive pattern of temperature in the diagram, and the fact that the present interglacial has lasted for 10,000 years, suggested very strongly that the onset of the next glacial period was already overdue. In fact, many felt thankful for the current anthropogenic increase in carbon dioxide, since it was felt that the greenhouse effect might offset an impending ice age. However, this view was shattered by forward projections of the integrated insolation due to Milankovitch cycles for the next 130,000 years.{5} It now appears that the 100 kyr ellipticity cycle causing the major glacial and interglacial periods during the last 420 kyr is in temporary abeyance, since we now face 50 kyr when the earth's orbit will be almost circular. During this period, insolation is predicted to remain within the range 475 - 505 W/m^2, which is less that a third of the range during the last 420,000 years. So the next ice age is not imminent and greenhouse gases seem likely to play a dominant role in the foreseeable future. It is possible that we might eventually progress to a protracted "water age," with no ice at either pole, and a sea level 69 m higher than today. This was the situation from about 270 Myr ago until as recently as 35 Myr ago, when the ice sheets began to reform in Antarctica. The amplitude of cyclical (Milankovitch) changes in insolation are not predicted to return to the level of the last glacial/interglacial cycle (462 - 525 W/m^2) for at least 100 kyr.{5}

The most important greenhouse gas is water vapour (approximately 60%), followed by carbon dioxide (25%), ozone (8%) and the remainder due to methane, nitrous oxide (both increasing rapidly) and other trace gases.{6} Water vapour will tend to increase with rising temperature, providing positive feed back. After the last glacial termination about 10,000 years ago, the atmospheric carbon dioxide concentration remained relatively constant at 280 ppmv until the start of the industrial revolution in AD 1750. Since then, the CO_2 concentration has risen to 372.9 ppmv in 2002. However the increase has not been uniform. Over a period of about 20 years, the changes approximate to an exponential function (constant percentage rate of increase each year, as with a fixed compound interest account). However, over a longer term it becomes clear that the percentage rate of increase is itself increasing as another exponential function: for example there was a mean rate of increase of 0.385% per year for 1960-80 and a mean rate of 0.44% for 1980-2000 (as with a compound interest rate being progressively increased). On this basis, extrapolation of trends from 1750 to the present suggests that the concentration should reach at least 1000 ppmv by the year 2100, rather than the 450 ppmv which was previously expected. The increased estimate is similar to the latest computed predictions based on analysis of the many primary factors governing atmospheric CO_2 concentrations.{7,8} Thus we may expect to reach the highest

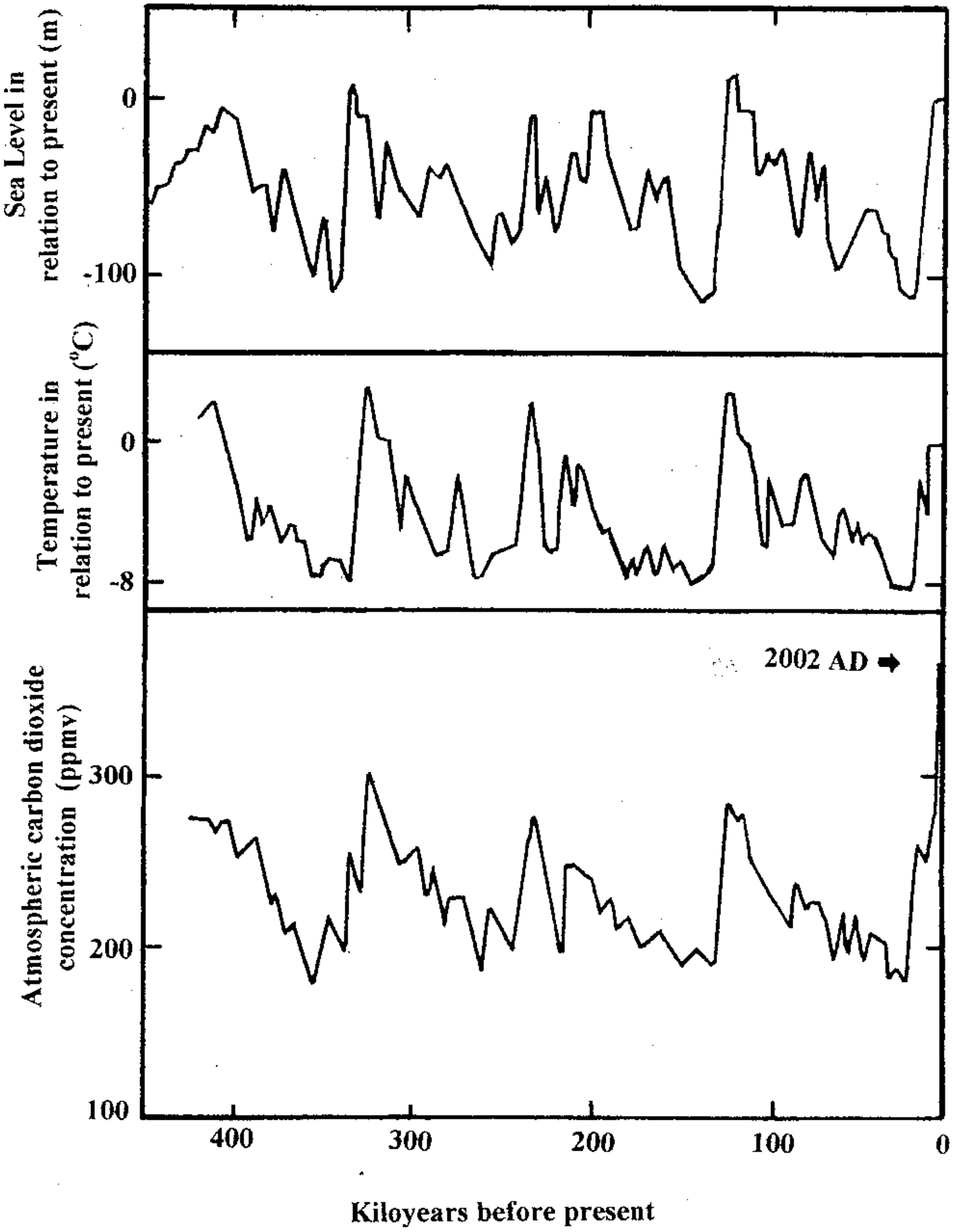

Figure 1. The diagram shows the broad trends in changes of sea level, temperature and atmospheric carbon dioxide concentration during the last 420 kyr. Sea level data are from sediments in the Red Sea (Siddall, M et al,. 2003, *Nature* **423** 853): other data are from Antarctica (Petit, JR et al. 1999 *Nature* **399** 429).

concentration that has existed since the formation of the present polar ice sheets. Whether the rate of change continues to accelerate is critically dependent on the continued efficiency of the global carbon sinks,{7} and attempts to control emissions with all its current political uncertainty.{9} The only certain limitation on emissions would seem to be exhaustion of the world's fossil fuels.

The resultant change in temperature is very difficult to predict. Apart from the inevitable increase in the greenhouse effect, future temperature increase is subject to many other uncertainties. These include the inevitable time lag between changes in carbon dioxide and resultant temperature, reflection of solar radiation by atmospheric aerosols and certain types of cloud, trapping of reflected heat by other types of cloud, and also decreased albedo (reflection of solar radiation) resulting from melting of ice sheets and enhanced forestation,{6, 7} the latter factors providing positive feedback. The range of uncertainty is reflected in forecasts of a mean global temperature increase between +1.5 and +4.5°C by AD 2100, but the Intergovernmental Panel on Climate Change has already confirmed a mean global warming of 0.6 (± 0.2) °C during the 20th century, most of which has occurred since 1950.

However, Milankovitch cycles and greenhouse gases are far from being the only factors governing our future temperature. A host of other possibilities include a major meteor strike or a massive volcanic eruption. Of special significance to the UK is the danger of melting ice from the Greenland icecap diverting the North Atlantic ocean conveyor (including the Gulf Stream), which brings to Northern Europe about 30% as much heat as that received directly from the sun. Northern Europe might then revert rapidly to the climate of Alaska, which is at the same latitude, a scenario known as "shivering in the greenhouse," which featured in the epic film *The Day after Tomorrow*.

Effect of temperature rise on polar ice sheets and resultant change in sea level

It is most important to distinguish between the effect of floating and grounded ice. Melting of the former does not affect sea level, while melting of the latter raises sea level by approximately 2.56 m for each million cubic kilometres of grounded ice (eustatic rise, due to change of mass of water). In addition, there is thermal expansion of the oceans (steric rise) now considered to make a relatively minor contribution to sea level.{3} Another (local) factor is the rebound of the earth's crust where it was depressed by the weight of grounded ice at the time of the last glacial maximum. Aberdeen, for example, has a lower gauge rise of sea level than the global mean.{3} This factor, together with tectonic changes, results in substantial regional variations in the rate of rise (or fall!) of sea level. There are fossil corals near the summit of Everest.

At the last glacial maximum (around 20,000 years ago), it is estimated that the total grounded ice volume was about 74 million km^3. Of this, approximately 47 million km^3 has already melted, resulting in a rise in sea level of 120 m which, amongst other geographical changes, has resulted in the separation of the United Kingdom from Europe. Sea level is still some 6m below the level during the previous interglacial, although atmospheric carbon dioxide concentration is now far higher than at that time. There now remain approximately 27 million km^3 of grounded ice in Antarctica, Greenland and Alaska, with lesser amounts in smaller ice caps and glaciers elsewhere. Ice cores from Antarctica and Greenland provide a continuous record, indicating that the Eastern Antarctic Ice Sheet has survived intact through the last four major deglaciations, and Greenland at least the last deglaciation. If all remaining ice were to melt, sea level would rise by a further 69 metres. As we enter the present period of unprecedented anthropogenic greenhouse effect, it is important to know if and when we can expect melting of these residual polar ice sheets.

The largest ice reservoir is the East Antarctic Ice Sheet (approx 20 million km^3). Total melting would raise sea level by about 51 m, but fortunately there is, at present, no convincing evidence of net loss of ice.{10} The combination of high latitude and mean altitude of 2,300 m, results in a mean winter temperature of -60°C, and -30°C on a good summer day. Much more warming is therefore needed before melting becomes an immediate threat. The South Pole is cooling slightly at present. Furthermore, rising mean global temperature increases atmospheric water vapour concentration, with the hope that increased snowfall at high latitudes may sequester some water, at least temporarily.

The West Antarctic Ice Sheet (WAIS) contains 3.8 million km^3 of ice, partly grounded above sea level, partly grounded below sea level and partly floating, with a mean annual temperature of -15 to -25°C.{11} Changes in mean temperatures are very variable across the area, and the Antarctic Peninsula in particular has recently warmed within the range 0.02 - 0.11°C per year.{12} There have been recent major disruptions of seven floating ice shelves, including the Larsen Ice Shelves. Although this does not itself raise sea level, there is evidence that grounded glaciers feeding these ice shelves are now moving more rapidly towards the sea. The estimated current net ice loss from the WAIS is only about 48 km^3/year,{10} but this could increase, and the forward projection is that it could contribute 19 cm to the estimated total increases in sea level for the 21st century, for which estimates range from 13 to 94 cm. Complete melting of the WAIS would raise sea level by 4 - 6 m.{11}

The third major ice reservoir is Greenland which contains 10% of the world's ice (2.73 million km^3) mostly grounded and this, if all melted, would raise sea level by about 7 m. As in most of the northern hemisphere, low lying glaciers are in retreat, but the grounded ice sheet of the interior (surface altitude 1500 - 2500 m) has shown very little reduction of surface elevation between 1954 and 1995.{13} However, longer term predictions are less reassuring. It has been estimated that a temperature rise of only 2.7°C would be sufficient to initiate the loss of most of the ice cap.{14} This would probably be a gradual process, taking hundreds of years. However, once the ice cap was lost, the decreased altitude and albedo might well cause the loss of the Greenland ice cap to be permanent, with tundra replacing the ice. It is to be hoped that an outpouring of melt water from the Davis Strait will be gradual, because it could deflect the North Atlantic ocean conveyor from northern Europe (see above). Fortunately, there is no evidence of immediate cause for concern (Severinghaus, personal communication). However, one is ever mindful of the Younger Dryas episode 11.6 - 12.8 kyr before present (radio-carbon date, corrected by tree-ring ages) when a sudden and massive outflow of glacier-dammed fresh water from Lake Agassiz entered the North Atlantic, stopped the conveyor, and hill-top (cirque) glaciers returned to North Wales.

Alaska carries a volume of ice many orders of magnitude smaller than those mentioned above. Due to rapid retreat of glaciers at low level, it is currently making a disproportionately large contribution to rising sea level, although it can only make a very small contribution to the ultimate increase in sea level.{1}

Summary

There are substantial uncertainties in almost every factor concerned with increase in sea level as a result of global warming due to the increase in anthropogenic greenhouse gases. The mean rate of rise is currently about 18 cm per century and has been almost constant since 1850. However, atmospheric carbon dioxide concentration is increasing at a rate about 170 times greater than at any of the glacial terminations in the last 420 thousand years, and the rate of change is currently increasing. It appears highly likely that this will result in a large increase in global temperature, which must inevitably increase sea level as a result of accretion of melt water from polar ice sheets and also oceanic thermal expansion. This will inevitably flood low lying areas, including all sea ports and extensive heavily populated and ecologically productive areas. Only the time scale and the ultimate magnitude of the changes remain in doubt.

Acknowledgements:

I am indebted to Jeff Severinghaus (Associate Professor of Geosciences, Scripps Institution of Oceanography, University of California, San Diego), Richard Betts (Manager, Ecosystems and Climate Impact, Hadley Centre, Met Office, Exeter) and Joel E Cohen (Rockefeller University, Columbia Earth Institute and School of International Public Affairs, New York) for invaluable assistance and advice.

References

1. Meier, MF & Dyurgerov, MB. 2002 *Science* **297** 350
2. Cohen, JE & Small, C. 1988 *Proc Natl. Acad Sci.* USA **95** 14009
3. Douglas, BC, Kearney, MS & Leatherman, SP. 2001. *Sea Level Rise*. Academic Press.
4. Petit, JR et al. 1999 *Nature* **399** 429
5. Loutre, MF & Berger, A. 2000 *Climatic Change* **46** 61
6. Karl, TR & Trenberth, KE. 2003 *Science* **302** 1719
7. Cox, PM et al. 2000 *Nature* **408** 184
8. Hasselmann, K et al. 2003 *Science* **302** 1923
9. Watson, RT. 2003 *Science* **302** 1925
10. Rignot, E & Thomas, RH. 2002 *Science* **297** 1502
11. Openheimer, M. 1998 *Nature* **393** 325
12. Vaughan, DG et al. 2001 *Science* **293** 1777
13. Paterson , WSB & Reeh N. 2001 *Nature* **414** 60
14. Gregory, JM et al. 2004 *Nature* **428** 616

HYDROGEN AS AN ENERGY CARRIER

by Andrew R.B. Ferguson

This paper lacks an Abstract, but those wishing to save time will lose little of importance by going straight to the pithy conclusion at the end.

My paper, *Verdict on the Hydrogen Experiment: an Update*, was published in the October 2003 edition of this journal (OPTJ 3/2). For brevity, that paper will be referred to as 'VHEU'. After perusing and advising on VHEU and also *Hydrogen Fantasies* (OPTJ 4/1), David Pimentel of Cornell University kindly sent me photocopies of forty overheads from a presentation to the "National Academies' Committee on Alternatives and Strategies for Future Hydrogen Production and Use." The presentation was delivered on 23rd January, 2003, by Dale Simbeck and Elaine Chang of *SFA Pacific*, Inc. The presentation — and indiscriminately its authors — will be referred to as 'SFAP'.

The purpose of overheads is to facilitate a presentation, so my interpretation of the brief 'bullet points' extracted from their overheads may be somewhat suspect, however, I invited SFAP to respond to my comments and, rather to my surprise I must say, they simply indicated that they endorsed them. It will be readily apparent that I quote their text at the start of each of the nine sections. It should be said that I have not attempted to comment on everything of possible interest, but instead I focus on points which are generally relevant to using hydrogen for *transportation*.

1. "■ Electrolysis H_2 is 50 kWh/kg H_2 just power cost + high capital costs.
"■ Liquid H_2 is 10 kWh/kg H_2 just power costs + high capital costs." (SFAP)

COMMENT: Since 1 kg of liquid hydrogen occupies 1 / 0.070 [kg/liter] = 14.3 liters, each liter requires (50 + 10) / 14.3 = 4.2 kWh_e to produce it. This corroborates the calculations in VHEU, which estimate that it requires 4.0 kWh_e to produce a liter of liquid hydrogen (see next section for more details). The slightly higher figure given by SFAP is not surprising, since the amount of electricity needed is dependent upon the scale of the production process. My VHEU analyses were based on very large scale production.

It is also worthy of note that since 1 kg of hydrogen has a calorific value of 120 [MJ] / 3.6 x 10^6 = 33.3 kWh (LHV), only 33.3 [kWh] / (50 + 10) [kWh_e] = 56% of the energy put in as electricity is captured as liquid hydrogen. Moreover, in terms of primary energy input (i.e. assuming the electricity is generated from fossil fuels) the proportion of energy captured would be 33.3 / (60 / 0.33) = 18%. For comparison (using rather old data from 1953), we may note that producing "1 t of gasoline requires 3.65 t coal, including the coal needed to carry out the conversion process" (Durrant, 1953, p. 309), and therefore synthetic gasoline production captures 43.7 [GJ/t] / (3.65 x 30 [GJ/t]) = 40% of the energy in the coal. It would be fairer to hydrogen to say that, since it transforms to motive energy 75% more efficiently than gasoline (see section 5), the above 18% should be revised to an effective 30%, but that still leaves synthetic gasoline as the energy carrier of choice.

It might be thought that no one would contemplate using fossil-fuel-derived electricity to produce hydrogen. Better, it might seem, would be to extract hydrogen directly from coal. But two points contradict that thought: (a) Only electrolysis easily produces sufficiently pure hydrogen to use in fuel cells; (b) SFAP *do* consider producing hydrogen by electrolysis, locally — at the forecourt — in order to overcome hydrogen's distribution problems. So let us look further at this option.

SFAP give a cost estimate of “electrolysis onsite.” Their graph shows a cost of $12.2 per U.S. gallon of gasoline equivalent. As is explained in section 8 below, we can factor this by 0.6, to account for the greater efficiency of transforming hydrogen in a fuel cell. That makes the cost $7.3 for an amount of hydrogen that will take a vehicle as far as one U.S. gallon of gasoline. We can see, therefore, that although on-site electrolysis may be worthy of consideration, this method of producing the energy carrier hydrogen is likely to be ruled out on the basis of cost, and is more certainly ruled out because producing synthetic gasoline from coal is more energy efficient.

2. “**H_2 compressors are very expensive**

   “■ Generally water cooled positive displacement compressors at only 3 compression ratios per stage (high pressure H_2 requires 3-5 stages). Thereby, high capital of $2,000 - 4,000/kW unit costs & high O&M.” (SFAP)

   “**Sensitivities of ultra-high pressure H_2 (720 - 875 atm)**

   “■ H_2 compressors - both higher kWh operating power & $/kWh capital.

   “■ H_2 storage - higher $/kg H_2 capital.” (SFAP)

COMMENT: To achieve high (for present purposes above about 200 atmospheres or 3000 psi) pressures, it appears likely that it is going to be cheaper, in terms of energy and perhaps cost, to accomplish this by liquefying the hydrogen first, although this requires lowering the temperature to below the critical temperature of -240°C, the liquid then being allowed to heat up to achieve the desired pressure. It appears that by this method, the pressurised gas could be obtained at less energetic cost than using brute force to compress it. The evidence for this is not in the quotations from SFAP above, although it might be said they tend to support such a view. Rather it is in a draft paper, currently in circulation, by Baldur Eliasson and Ulf Bossel, *The Future of the Hydrogen Economy: Bright or Bleak?* (I must thank Ted Trainer, of New South Wales University for discovering this valuable study and sending it as a PDF file).

These authors state that the electrical power needed to produce 34,000 kg of hydrogen per day (compressed to 200 bars or 197 atmospheres) is 81 MW. From this, it can easily be calculated that it requires 4.0 kWh_e to produce 70 g of hydrogen (70 g = 1 liter of liquid hydrogen). 4.0 kWh_e/liter of liquid hydrogen is the figure I reached in VHEU (see endnote {T3} therein), when making the full electrolysis calculation, which of course included allowing the usual 30% of the energy contained in the hydrogen for the liquefaction process (it may be noted, too, that the theoretical calculation was confirmed empirically, based on Icelandic data). The equality of result, at 4.0 kWh_e/70 g, implies that compression to 200 bars requires the same energy as liquefaction (incidentally, at 200 bars the volume would be about 4 times that of liquid hydrogen; for volume problems see section 6 below).

3. “However, H_2 from fossil fuels is cheaper until the fossil fuel age peaks in 50-100 years making the fossil fuels increasingly more expensive.” (SFAP).

COMMENT: The time premise is false, for the following reasons. Most petroleum geologists think the oil peak will be about 2010, although some extend that to 2025 (see also OPTJ 2/2, pp. 7-8, and Colin Campbell’s *The Coming Oil Crisis*). Natural gas does not follow the Hubbert supply curve, but tends to hold steady at a peak, and then drop off a precipice. All the signs are that, in the U.S., the plateau phase of natural gas production has been reached (with 15% of consumption being imported from Canada, where gas also shows signs of reaching the plateau). There are indications that it will not be possible to increase the U.S. gas supply to satisfy the 180,000 MW of gas-fired power plants scheduled to be built during 2000 - 2005 (also see endnote 3, page 15, OPTJ 3/1). The UK energy minister forecasts that Britain will be importing 80% of its gas by 2020. Coal also presents a problem, as mentioned on page 27 of OPTJ 3/1. There I summed up the overall situation in the following words: “Most petroleum geologists believe that shortly after the middle of this century our supplies of oil and gas will be about half what they are today, and although coal will still be available, the energy profit ratio, that is the ratio between the energy extracted and the energy needed to extract the coal, will be falling rapidly. It is estimated that the energy profit ratio for U.S. coal, at the mine-mouth, fell from 80:1 in the 1940s to 30:1 in the 1970s.”

Thus it is apparent that there is what might be called an ‘oil problem’, a ‘natural gas problem’ and a ‘coal problem’. SFAP’s failure to take this into account constitutes a lacuna in their thinking.

Thus the statement quoted at the start of this section should perhaps be revised to read: “Producing hydrogen from fossil fuels as an energy carrier, *to substitute for liquid fuels*, is not a viable project because of the imminent ‘oil problem’, ‘natural gas problem’, and ‘coal problem’.” Incidentally, if the reader’s time is short, this is an appropriate point to jump to the conclusion!

4. “Over 65 kg container weight per 1 kg gaseous or hydrate hydrogen.” (SFAP)

COMMENT: This container weight seems plausible, but more detail is needed to establish the fact, especially since the weight is far in excess of the figure quoted in Pimentel and Pimentel (1996), page 211: “Storing 25 kg of gasoline requires a tank with a mass of 17 kg, whereas storage of 9.5 kg of hydrogen require 55 kg (Peschka, 1987).” That works out at 55 / 9.5 = 6 kg of container weight per 1 kg of liquid hydrogen. 6 is an order of magnitude different from 65. The SFAP reference is to gaseous or hydrate hydrogen, rather than liquid hydrogen. The totally different figures need explanation. Perhaps Peschka’s figures rely on keeping the liquid hydrogen below its boiling point, of -253°C, and the tank that is referred to is designed to allow the hydrogen to boil off if the cooling mechanism fails. Anyhow, SFAP’s different figure highlights the need to give precise detail when talking about container weights.

5. “H_2 use is inefficient due to the large water formation & energy loss in the flue gas — LHV/HHV is 84.6% or 15.4% losses.” (SFAP)

   “1 kg of hydrogen contains the same useful energy content as 1 U.S. gallon of gasoline: 113,800 Btu or 33.3 kWh_t (LHV).” (SFAP)

COMMENT: The second quotation gives a Lower Heating Value for hydrogen of 33.3 [kWh] x 3.6 x 10^6 = 120 MJ/kg. This accords with the figure given in the McGraw Hill encyclopedia. The statement that the LHV/HHV ratio is 0.846 indicates a High Heating Value of 120 / 0.846 = 142 MJ/kg. But it seems illogical to state that hydrogen use is inefficient on this count. What is surely a more relevant criterion is the difference in motive energy (the capacity to move a vehicle), between what can be achieved with a specified amount of heat contained in hydrogen (LHV), compared to the usefulness of the same amount of heat contained in gasoline (LHV):

When burnt in an internal combustion engine, 3 liters of liquid hydrogen provide the same motive power as 1 liter of gasoline (VHEU). Thus 3 x 8.4 [MJ/liter] = 25.2 MJ of hydrogen provide the same motive power, in an internal combustion engine, as a liter of gasoline, which contains about 33.3 MJ/liter. Thus hydrogen burns 33.3 / 25.20 = 1.32 times as efficiently as gasoline, or in round numbers, 30% more efficiently.

When transformed in a fuel cell, 2.3 liters of liquid hydrogen provide the same motive power as 1 liter of gasoline (VHEU). Thus 2.3 x 8.4 = 19.3 MJ of hydrogen provide the same motive power, transformed in a fuel cell, as a liter of gasoline, which contains about 33.3 MJ/liter. Thus hydrogen burns 33.3 / 19.2 = 1.73 times as efficiently as gasoline, or in round numbers, 75% more efficiently.

While these improved efficiencies, relative to gasoline, of 'burning' and 'transforming' hydrogen, may not outweigh other disadvantages, they should not be overlooked.

6. "One fuel cell vehicle at 12,000 miles/yr & 55 mpg gasoline equivalent require only 218 kg/yr H_2 or $0.83kW_t$ or 1 fill-up per week of 4.2 kg H_2." (SFAP)

COMMENT: This does not seem to be a very useful way of bringing out the essence of the matter. A fairly small car, of the *Ford Focus Fuel Cell Vehicle*, or *Honda FCX*, or *Hydrogen 3* variety (see VHEU), which one might expect to achieve 40 mpg if fitted with a gasoline engine, would, when fitted with a 4.2 kg tank of *liquid* hydrogen, have to use a fuel tank occupying at least 4.2 / 0.070 [kg/liter] = 60 liters, or 16 gallons, of the available space. As noted in VHEU, the fuel consumption of such a vehicle is about 14 km per 2.3 liters of liquid hydrogen (160 g), so the 'tanks dry' range is 365 km, or 227 miles. In practice, one would probably want to keep 20%, say, of the fuel in reserve, so 180 miles is a more realistic range. This of course would be lower for a larger car designed to allow the same free space in the trunk as in a gasoline powered car — that is after the large hydrogen tank had been accommodated. The conclusion is surely that with liquid hydrogen, volume is a slight problem, but not so serious as to vitiate the idea of using liquid hydrogen as an energy carrier. However, gaseous and hydrate hydrogen need further assessment, especially since, according to the figures given in 4 above, the tank weight would be 4.2 x 65 = 270 kg. Moreover, at 200 bars the volume would be 64 gallons. This volume is so great that it suggests that higher pressures would be used in practice. This is confirmed by a mention of 270 atmospheres, for buses, in the Icelandic report referred to in VHEU, while a program by General Motors to design a tank to hold 10,000 psi, or 680 atmospheres, has been reported. If tanks of sufficient strength can be designed, the latter pressure makes sense, as if the route to obtaining them is liquefaction, the limit of energy needed would be that required for liquefaction.

7. "**High Pressure H_2 Tube Trailers for Small H_2 Demands**.

"■ only net 250 kg per tube trailer due to 133 kg of container per kg H_2." (SFAP)

COMMENT: Note that this figure of 133 kg per kg of H_2 exceeds even the container weight of 65 kg per kg of H_2 given under 4 above. Were a solution to be found to the principal problem, namely that of finding energy to produce the hydrogen, then more details of the assumptions which underlie these container weights would be needed. However, we should note that unless a solution to the principal problem — of finding an energy source — can be found, then not only the observations in this section, but most of the rest of these notes become redundant!

8. "**Hydrogen Economics for Fuel Cell Vehicles**" (SFAP)

COMMENT: The graph on this page affords food for thought, as it equates 1 kg of hydrogen to 1 gallon of gasoline, i.e. 120 MJ of hydrogen are being equated with 33.3 [MJ/liter] x 3.785 = 126 MJ of gasoline. As pointed out in 5 above, when transformed in a fuel cell, 2.3 liters, or 160 g, of liquid hydrogen, provide the same motive energy, that is capacity to drive a vehicle, as 1 liter of gasoline. Thus 160 x 3.785 = 606 g of hydrogen are equivalent to 1 gallon of gasoline, which means that the cost figures given in the diagram, if they are to be understood as the cost of providing the amount of hydrogen that affords the same motive energy as 1 U.S. gallon of gasoline, need to be reduced by multiplying by the factor 0.6. Note that this is just another way of demonstrating that since hydrogen transforms in a fuel cell 1.75 times as efficiently as gasoline burns, then, when considering fuel cell vehicles, figures which ignore this greater efficiency need correcting by a factor of 1 / 1.75 = 0.6.

As observed in 5 above, while these improved efficiencies of transforming hydrogen may not outweigh its other disadvantages, they should not be overlooked. There is a further consideration to bear in mind: it must be doubted that the improvement in efficiency of a fuel cell — compared to burning hydrogen in an internal combustion engine — namely an improvement of 1 - (2.3 / 3.0) = 23%, is sufficient to justify the increased cost of a fuel cell compared to an internal combustion engine, especially as fuel cells require hydrogen of a high degree of purity.

Let us compare the figures given in the SFAP graph with the *very* rough cost estimates of VHEU. For large scale electrolysis and conversion to liquid hydrogen, the graph shows a cost for production, delivery and dispensing of $7.5 per gallon. That, as explained above, needs correcting to $7.5 x 0.6 =$4.50, for providing the same motive energy as a gallon of gasoline. In VHEU, the very cheap electricity of Iceland (2¢ per kWh) was used as the basis of calculation. Changing this to a more realistic U.S. price, of 6¢ per kWh$_e$ (wholesale), the calculation would be, (9.1 x $0.06) x 3.785 = $2.07 for electricity supply, plus (9.1 x $0.05) x 3.785 = $1.72 to cover everything else, for a total cost of $3.79 — again to provide the same motive energy as a gallon of gasoline. Since the 5¢ per liter cost used to cover all costs other than the electricity was only an ill-supported guesstimate, the degree of agreement between the figures is reassuring. The SFAP figure leaves the broad conclusion of VHEU unchanged. It was noted in VHEU that when the cost of oil rose to $32 per barrel, the cost of gasoline in the UK rose to $4.54 per U.S. gallon, thus the costs calculated above are just bearable. But more importantly, as was concluded there:

> *However, outside Iceland, costs are only of background interest; what is more significant than cost is whether the electricity can be made available, and if so at what environmental cost.*

The SFAP graph, under consideration, shows many alternatives to producing hydrogen from electricity, but, as observed in 3 above, the other alternatives suffer from the ‘oil problem’, the ‘natural gas problem’ and the ‘coal problem’.

The SFAP graph also shows liquid hydrogen being produced directly from biomass. The cost is shown as $5 x 0.6 = $3.00 to provide the same motive energy as a gallon of gasoline. The cost is again acceptable, but with the production of any liquid fuel from biomass, we run into the insuperable problems of low net energy-capture (amount of useful energy captured per hectare), as has been explained with reference to ethanol in the *Implications of the USDA 2002 Update on Ethanol from Corn*, (OPTJ 3/1). This is a problem which is inherent in biomass, because only about one thousandth part of insolation is captured as biomass energy even on agricultural land, rising to 0.5% in special cases such as corn and sugarcane (Pimentel and Pimentel, 1996, p. 14). The latter crops require large inputs and are associated with soil erosion (OPTJ 3/1, p. 13). Also there is inevitably *very substantial* further attenuation of the net energy usefully captured due to the energy costs of collecting the biomass and converting it into a useful form of ‘liquid’ energy.

9. " 'Green power' is generally 25-50% higher price than generic power."

COMMENT: It would be interesting to see what data SFAP could produce to substantiate this assertion, and whether they take into account the fact that most renewable forms of energy require back-up. The 25%-50% figure does not seem to apply to wind turbines, as recorded in the *Daily Telegraph*, on 3rd February 2003:

> The attractiveness of wind power is mostly thanks to the Government's decision to award valuable certificates to providers of green energy. Wind farms are entitled to a Renewable Obligation Certificate (ROC). This allows them to sell electricity to suppliers for the market price plus a standard £30 per megawatt hour fee [¢4.7 per kWh]. Suppliers, meanwhile have to buy 3 pc of their power from renewable sources, or pay fines which are distributed among those holding ROC's.

This tells us the price at which wind farms are happy to sell, but not the price at which suppliers would be willing to buy, which, because of variability, may be close to zero.

As to photovoltaics, in Germany it was reported, in *Vital Signs 2001/2002* (p. 46), that their program to encourage photovoltaic installation "includes a 10-year, interest-free loan from the German Federal Bank plus a guaranteed purchase price of 50¢ per kilowatt hour." Admittedly Germany is not as sunny as California, and average annual insolation in Germany may be as low as 140 W/m^2, while California's may be as high as 220 W/m^2, but that improved yield suggests a guaranteed selling price of ¢50 x 140 / 220 = ¢32 per kWh would be required to encourage a voluntary expansion of photovoltaics in California. Overall it is hard to reconcile these figures with the mooted 25-50% increase in price of 'green' power compared to 'generic' power.

Conclusion

Most people who write about hydrogen slip in a brief sentence stating that hydrogen is not an energy source, but then they proceed to ignore the importance of that fact. SFAP is no exception. They assert that, "Hydrogen Has Some Inherent Problems as it is Not a Fuel Source, Merely an Energy Carrier." However, although SFAP states the truth of the matter baldly, their statement does not lead to a realization that the quintessence of the problem with hydrogen is finding an energy source to produce it. Only after that aspect has been thoroughly and satisfactorily addressed, does it make much sense to consider the multiple problems associated with using hydrogen as an energy carrier. However, since SFAP went to the trouble of producing 40 overheads, it would seem churlish not to address some of the points they raise, which explains why this paper is significantly longer than this concluding paragraph.

References

Campbell, C.J. 1997. *The Coming Oil Crisis*. Essex, U.K.: Multi-Science Publishing Company & Petroconsultants S.A. 210 pp.

Durrant, P.J. 1953. *General and Inorganic Chemistry*. London, UK and New York: Longmans, Green and Co Ltd.

OPTJ 2/2. 2002. *Optimum Population Trust Journal*, Vol. 2, No 2, October 2002.

OPTJ 3/1. 2003. *Optimum Population Trust Journal*, Vol. 3, No 1, April 2003.

OPTJ 3/2. 2003. *Optimum Population Trust Journal*, Vol. 3, No 2, October 2003.

OPTJ 4/1. 2004. *Optimum Population Trust Journal*, Vol. 4, No 1, April 2004.

Peschka, W. 1987. The status of storage and handling techniques for liquid hydrogen in motor vehicles, *International Journal of Hydrogen Energy* 12: 753-764

Pimentel, D. and M. Pimentel. 1996. *Food, Energy, and Society*. Revised edition. Niwot Co., University Press of Colorado. 363 pp.

Vital Signs 2001-2002. 2002. Worldwatch Institute. London: Earthscan.

VEXPONENTIAL GROWTH IN THE 21ST CENTURY

by Andrew R.B. Ferguson

Abstract: Populations grow according to a principle which might be described as ‘compound interest growth at varying rates’. This cumbersome description is here termed ‘vexponential growth’. Even in academic circles, the fallacy seems to persist that a falling ‘vexponential growth rate’ indicates that the annual increase in numbers is falling. The danger of that fallacy is exposed by the fact that despite a projected halving of the ‘vexponential growth rate’ in the 21st century, compared to the 20th century, the population during the twenty-first century is likely to grow by 4800 million, exceeding even the astonishing 4400 million growth of the preceding century.

Over two hundred years ago, Thomas Malthus used the term “geometric” to describe the type of growth which applies to populations. In those days, a “ratio” was called a “geometrical ratio,” and since a “ratio” refers to a proportion between two things, “geometric” was an appropriate word to describe the type of growth which occurs. However language changes, and the word “exponential” has become the adjective most commonly used. The meaning of that word appears to give trouble, because John R. Bermingham and Albert A. Bartlett filled thirty-six pages of the academic journal *Population and Environment* trying to thrash out the subject. {1,2,3} Let us see if we can deal with the matter in briefer compass, while drawing attention to the present plight of the world.

First, we may draw a distinction between ‘exponential’ and ‘linear’ growth by considering the amount of water in a newly completed reservoir. Suppose that water is diverted from a river to fill the reservoir, with the amount of water flowing into it being controlled by sluice gates. If the same amount is allowed in each year, then the increase in volume would be the same each year. That is appropriately called a linear type of growth, because the volume, plotted on a graph, would produce a straight line.

Now let us look at a very curious circumstance, in which those responsible for operating the sluice gates — controlling the water flow into this idealised reservoir — decide to introduce a rule regarding the amount of water that is to be allowed in, namely that the amount allowed in will be equal to 10% of the amount of water that is already in the reservoir. That is what is today called an exponential function. Were the rule to be followed, the effect would be that by the time the reservoir was full, twice as much water would have been allowed in during the final year as had been allowed in when the reservoir was half full. Of course this is a ridiculous rule for filling reservoirs, but it serves to show why exponential growth is dramatically different from linear growth.

It is unlikely to have escaped the reader’s notice that the type of growth we have just described is virtually the same as that which occurs with money invested at compound interest. Thus we may, at least for the present, refer to it as ‘compound interest growth’.

Let us now consider something for which compound interest growth is natural. If a farmer has 12 cows and five years later the number has increased by 6, then it would be reasonable to expect the ratio to be approximately maintained, so that over another five years the increase would be around 9. For cows and human beings, compound interest growth (not at a constant rate) is what happens naturally without any rules being imposed.

Indeed in nature the ratio will never remain precisely constant over any considerable period of time. Thus we can note two things. First, that in matters of population, the growth, whether it be cows or human beings, is naturally of the compound interest type. Second, that it would be absurd to expect the ratio to be exactly maintained, in the way that we imagined it to be by the people operating the mooted sluice gates. In fact the ratio will vary almost continuously. Thus to be more precise, the type of growth we are referring to is 'compound interest growth at varying rates'. Since that is rather long-winded, and since compound interest tends to be associated with money, let us employ a new term for applying to population growth, namely "vexponential growth."

With that definition, the word 'exponential' becomes a rare case of 'vexponential' growth: a case which is likely never to be encountered, except for very brief periods of time, or in imaginary situations such as we dreamt up with regard to the controlling of sluice gates to fill a reservoir. Nevertheless, and as we are about to see, it is useful to summarize a period of vexponential growth by calculating a 'vexponential growth rate', the meaning of which we will define after giving an example.

Irrespective of how variable the growth rate happens to be in vexponential growth, the rate can be described in terms of the exponential growth which would arrive at the same arithmetical result. Let us illustrate that by looking at some actual data. In the year 2000, world population was about 6000 million. A century earlier it was about 1650 million — an increase of about 4400 million. An exponential growth rate which arithmetically describes this change is $(6000 / 1650)^{1/100} -1 = 1.3\%$ per year. We should observe, too, that the growth in numbers could be described merely in terms of a series of figures of how many people were added each year, but because population growth is naturally of the vexponential type, it is most appropriate to describe the growth in vexponential terms rather than as a series of numbers, leaving the reader with the task of discerning their significance.

The example shows the meaning that we are ascribing to 'vexponential growth rate'. It can be defined as the rate of exponential growth which would, over a specified period of time, produce the same result as the varying rates of growth which actually occur (or which we anticipate will occur) over that period .

Of course we do not yet know what vexponential growth rate will best describe the twenty-first century, but at present the Population Bureau and the United Nations would place their bets on a population of 10,800 million by 2100, an increase over the century of 4,800 million.{4} We can calculate the vexponential growth rate which best describes the actual rates of growth expected during the 21st century as $(10{,}800 / 6000)^{1/100} -1 = 0.6\%$ per year.

Note that this vexponential growth rate is less that half of what we calculated for the twentieth century, yet we have seen that the population would, according to this projection, increase during the twenty-first century by 4800 million rather than the 4400 million of the twentieth century. One could hardly have a better illustration of the power of vexponential growth: the vexponential growth rate halves, but the total number of people added to the world population increases.

With a clear understanding of the meaning of vexponential and exponential growth, we can judge who is right in the dialogue between Bartlett and Bermingham. Bartlett argues that we should stand in awe of the power of exponential growth, and educators should do all they can to get people to be aware of its extraordinary power. In no uncertain measure, the above figures confirm his assertion.

Bermingham tries to defend himself against Bartlett by saying:

> Though a small number of countries in Africa and west Asia continue to experience very rapid growth, there is not a single country in the world for which demographers are projecting population growth that is exponential. Too many members of the public and lay writers either are unaware of this remarkable demographic shift or else they enjoy embellishing their arguments with hyperbole.{3}

We need not be concerned to dissect the exact arguments by which Bermingham reaches his conclusion; what we can see is that his conclusion is misleading to the extent that it induces people to suppose that because the vexponential growth rate in the twenty-first century is likely to be half that of the twentieth century, we are any considerable way along the road to solving the world's population problem.

The point to keep in mind is that populations always either grow vexponentially or go into vexponential decline. That is simply the nature of the way in which populations grow and decline.

Bermingham's charge that people use the word 'exponential' to embellish their arguments with hyperbole cannot be accepted. For while it may be true that people's terminology is loose, it would be close to impossible to exaggerate the enormity of the problem enshrined in the figures of a population growth of 4400 million in the twentieth century followed by a projected growth of 4800 million in the twenty-first century.

The horror of the increase in numbers is a challenge to describe adequately, and when the numbers are put in the context of the constraints which operate, then words might fail even Shakespeare. The first of those constraints is that if the world continues to emit carbon from burning fossil fuels at the same per capita rate as obtains today, then world population needs to be about 2100 million in order to have a chance of stabilizing the concentration of carbon in the atmosphere (for stabilization we need to reduce emissions from 6.3 GtC per year to 2.5 GtC per year).

The second constraint is that, according to the most eminent petroleum geologists,{5} within the next two decades the world will have consumed half its endowment of oil and gas, and from that point in time there will be increasing scarcity. Furthermore, although there is plenty of coal underground, the energy needed to extract it is increasing. Moreover we are just beginning to appreciate that every method of extracting energy in 'real time' — instead of using energy collected over millions of years — is so limited that we can only expect a small fraction of the present energy to be available to us in the future (that is once we have effectively exhausted fossil fuel supplies). Taking this into account, we are again looking at a sustainable world population of around 2000 million.

When the projected twenty-first century growth of 4800 million is put in the context of these constraints, anyone might struggle in vain to introduce hyperbole in attempting to describe the nature of the problem that is going to be brought upon the world by the vexponential growth we may expect during the present century, which in sheer numbers of people is more than five times as great as occurred throughout the 100,000 years of human history, up to the year 1800.

Endnotes

1. John R. Bermingham. 2003. Exponential Population Growth and Doubling Times: Are they Dead or Merely Quiescent? *Population & Environment*, 24, 313-327.
2. Albert A. Bartlett. 2003. On Exponential Growth and Half-Lives: A Comment on Bermingham. *Population & Environment*, 25, 61-69.
3. John R. Bermingham. 2003. On Exponential Growth and Mathematical Purity: A Reply to Bartlett. *Population & Environment*, 25, 71-73.
4. Population Bulletin, Vol. 58, No.4, December 2003, p. 33, by J.A. McFalls Jr.
5. Colin J. Campbell stands in the company of such giants as M. King Hubbert, Walter Youngquist, L.F. Ivanhoe, Kenneth Deffeyes. Campbell's recent singular contributions are his 1997 book, *The Coming Oil Crisis*. Essex, U.K.: Multi-Science Publishing Company & Petroconsultants S.A. 210 pp; and, in 2003, *The Essence of Oil and Gas Depletion*, Brentwood, Essex, England: Multi-Science Publishing Co. 348 pp, $48, paperback.

COMPARING WROG PERIODS

by Andrew R.B. Ferguson

William Stanton, in his book *The Rapid Growth Of Human Populations 1750-2000,*{1} coined the acronym WROG to describe periods during which human populations have experienced Weak Restraints On Growth. As Clive Ponting tells us in his book *World History: A New Perspective,*{2} there was a WROG period during the first millenium BC, or BCE to use Ponting's preferred acronym (Before the Common Era). This is how Ponting describes that period as he starts Chapter 12:

> By 1000 CE the Eurasian world had begun to change significantly in many respects from the conditions found under the early agricultural empires which had existed across the continent for about the previous three millennia. The pace of change had been very slow but overall the world's population had risen from about 30 million in 2000 BCE to 50 million a thousand years later. The boom brought about by the introduction of iron tools and the ability to cultivate more land had doubled the population by 500 BCE and doubled it again to about 200 million by the first century CE. Then a long period of relative stagnation set in — little more land could be cultivated, technology was largely static and the spread of disease brought about by the linking together of the Eurasian continent severely restricted population growth. By 1000 CE the world's population had only grown to about 250 million.

So we see that during the first WROG period — the first millennium BCE — population rose from 50 to 200 million. The vexponential{3} growth rate was 1390 people per million per year. Let us compare that with the present WROG period. William Stanton describes the whole period, 1750 to 2000, as a WROG period, but let us choose one part of that period, the twentieth century. Population grew from about 1650 million to 6000 million. The vexponential growth rate was therefore 13,000 people per million per year. That is 13,000 / 1390 = 9 times as fast as during the first WROG period (the first millennium BCE).

With regard to actual increase in numbers, another factor is supremely important, namely the base from which growth starts. Comparing the start of the two WROG periods under consideration, the population base increased by the factor 1650 / 50 = 33 times.

As the human race moved into the twenty-first century, it advanced into an even more perilous situation, because the base from which growth started was 6000 / 50 = 120 times as great as at the start of the first WROG period. Furthermore we are still in a WROG period (despite what pundits, politicians and the media may say), as we can easily see by looking at the figures. If forced to make a forecast, the Population Reference Bureau would probably come up with a figure of 10,800 million for the population at the end of this century (anyhow that is how they drew one illustrative graph). That works out at a vexponential growth rate of 5900 people per million per year, and that is 5900 / 1390 = 4 times as fast as the first WROG period.

The factors which will bring this WROG period to an end will not be so very different from those which ended the first WROG period. Many aspects of strain are already apparent. The facts were summarized in *Perceiving the Population Bomb.*{4} The main points mentioned there were extracted from a 1999 paper by David Pimentel, et al., *Will Limits of the Earth's Resources Control Human Numbers?*{5} The points enumerated in the first mentioned paper (which quotes from the second) are worth repeating.

> (a) "3 billion humans malnourished worldwide;" (b) "40,000 children die each day due to malnutrition and other diseases;" (c) "Globally, the annual loss of land to urbanization and highways ranges from 10 to 35 million hectares per year, with half of this lost land coming from cropland;" (d) "Worldwide, more than 10 million hectares of productive arable land are severely degraded and abandoned each year" (about 7% of the total per decade); (e) "Water demands already far exceed supplies in nearly 80 nations of the world;" (f) Since 1960, "nearly one-third of the world's arable land has been lost due to urbanization, highways, soil erosion, salinization, and water logging of the soil;" (g) "grain production per capita started declining in 1984 and continues to decline;" (h) "irrigation per capita started declining in 1978 and continues;" (i) "food production per capita started declining in 1980 and continues;" (j) "fertilizer supplies essential for food production started declining in 1989 and continues to do so."

Not only will the present WROG period come to an end as those factors grow more grave, but the decline will be precipitous for a more dramatic reason, namely that the very thing which has removed most restraints to population growth, namely cheap energy from fossil fuel, is likely to start entering the phase of scarcity within the next few decades. Exactly what happens as fossil fuels become scarce is mainly dependent upon two things. First, whether we will find another source of energy, such as fusion. That is not impossible, but on the evidence available at present it can be listed as no more than a possibility. The second thing is the extent to which it will be possible for the human race to sustain itself without abundant cheap energy. Various people are beginning to ask that question. Yvette Willey noted that there was a discussion of a closely related matter in the *Daily Mail*. We, in OPT, decided to concoct a reply; this is what was published in the paper.

> **How many people could the world support with organic farming?**
>
> In special cases, organic farming can do even better than conventional farming, but one would surely be wise to be guided by Sir H. Charles Pereira, FRS, a doctor in soil physics, with immense international experience, when he tells us that to grow the world's supply of crops without added fertiliser would require the cultivation of 2.5 hectares for every 1 hectare now in production. Furthermore, the doyen of energy experts, Professor Vaclav Smil, has pointed in much the same direction in emphasizing the extent to which our present population is reliant on our ability to produce synthetic nitrogen fertilizers (something which requires a lot of energy).
>
> A substantial fraction of the present world population is suffering hunger, so it would seem appropriate to inflate Pereira's 2.5 hectares to say 3 hectares. Since virtually all land which can be cropped is being cropped, that means that, with organic farming, about a third of the present population could be supported, that is about 2000 million.
>
> Perhaps it is worth pointing out that if there were only 2000 million people emitting carbon dioxide from burning fossil fuels, then the emissions would be such that there would be a chance of stabilizing atmospheric carbon and thus halting climate change. Furthermore, the discipline of ecological footprinting indicates that for everyone to live a modest European lifestyle (except using only about two-fifths of present energy) would also require a population of 2000 million.

Clive Ponting, in *A Green History of the Earth*,{6} gave some figures which suggest a somewhat similar result. He said (page 291):

> In the twenty years after 1952 energy inputs into industrialised agriculture rose by 70 per cent but food production only increased by 30 per cent. In the United States the production of corn shows an even worse situation. There energy inputs rose 400 per cent between 1945 and 1970 but this only increased yields by 138 per cent.

It seems probable that most of this improvement in yield has been achieved by increasing the energy inputs, so we can deduce that without the 70 per cent additional energy input, we would — as a first cut at the problem — return to 1952 yield levels of 77% of current production; with respect to corn production in the USA, we could anticipate returning to the 1945 level of 42% of current production. However, that is far from the end of the likely reduction for two reasons: (a) we are unlikely to always have as much energy available to us as we had in 1952 and 1945 respectively; (b) there are other ways, as well as agriculture, in which cheap energy increases the availability of food, such as reducing wastage by, for example, refrigerating and delivering food where it is needed.

Thus Ponting's figures broadly confirm Pereira's. We should note, too, that the food shortage problem will be exacerbated when there is also an urgent need for using biomass for providing energy. People may prefer to go hungry (and let others starve) rather than die of cold.

We can surely conclude that the end to the current WROG period will be far more difficult than the end of the first WROG period, especially in countries like Britain and the Netherlands, where population exceeds the existing ecological capacity by a factor of two or three. Currently it looks as though the problem could be almost as bad in the USA, because rapid population growth there seems likely to mean that the population will soon be able to feed only itself, and yet, because of its cold climate, the need to keep warm will require large areas of ecologically productive land to be used for producing biomass, so as not to freeze to death in winter. This is not totally to discount the possibility of appropriate action being taken without delay, but if we consider *Extraordinary Delusions and the Madness of Crowds* (Charles Mackay, 1841), The *Comforts of Unreason* (Rupert Crawshay-Williams, 1947) and *The March of Folly: from Troy to Vietnam* (Barbara Tuchman, 1984), it surely seems that suitable action is a possibility rather than a probability.

Endnotes

{1} Multi-Science Publishing Company Ltd, ISBN 0 906522 21 8; published in UK, September 2003, 230 pp., £25; in the USA, April 2004; $40, from bookstores or direct from IPG, , Tel: 1-800 888 4741.

{2} Ponting, C. 2000. *World History: a New Perspective*. London: Chatto and Windus. 925 pp.

{3} Population growth is inherently of the compound interest type with the rate of 'interest' varying almost continuously. There are two reason for coining the word 'vexponential' to use, in the context of populations, for describing compound interest growth: (a) compound interest explicitly refers to *money* not *people*; (b) mathematicians prefer to keep the word 'exponential' to describe growth by compound interest *when the rate of interest remains constant* (although in practice, they do not seem to hold too accurately to that usage). Thus vexponential growth is growth of the compound interest type; the vexponential growth rate is specifically the constant rate of compounding that will cause a growing quantity to grow from an initial size to a final size in a stated period.

{4} *Perceiving the Population Bomb* was first published in the July/August 2001 edition of *World-Watch*, and the paper is archived on the web at www.members.aol.com/optjournal2/optj1.doc

{5} Pimentel, D., Bailey, O., Kim, P., Mullaney, E., Calabrese, J., Walman, L., Nelson, F. and Yao, X. 1999. Will Limits of the Earth's Resources Control Human Numbers? *Environment, Development and Sustainability* 1: 19-39, 1999. Archived on the web at www.dieoff.org/page174.htm

{6} Clive Ponting. 1991. *A Green History of the World*. First published in New York, by St Martin's Press, then by Penguin, in 1992, 432 pp.

`The following deserves a place in these pages on various counts. First, it highlights another scientist (one of a very few) who continues to struggle against all the odds — the commercial world, the media, economists and politicians. Second, perhaps other nations might emulate Canada, in that there is apparently a possibility of attaching a ballot to a general election. However it is hard to imagine that happening in the UK, for politicians cling tenaciously to their 'right' to thwart the wishes of the electorate, for instance over voluntary euthanasia, globalization, immigration, and going to war.

POPULATION GROWTH IN THE UNITED STATES AND CANADA: A ROLE FOR SCIENTISTS (excerpts from *Conservation Biology* 13: 1518-1519, 1999)

by Peter Salonius. Natural Resources Canada, Canadian Forest Service, P.O. Box 4000, Fredericton, New Brunswick, E3B 5P7, Canada <psaloniu@nrcan.gc.ca>.

The annual rate [of population growth] in Canada is 1.2% (Keating 1997). The rate of population growth in the United States is also over 1% annually (Kolankiewicz 1998). Because these North American population growth rates are driven largely by immigration (Keating 1997; Kolankiewicz 1998), reducing them requires stemming the immigration tide. Since 1985, Canadian immigration policy has sought to increase population growth; since 1993 Canada has had an immigration target of up to 1% of the total population annually (Trempe et al. 1997). . . .

Because economists are generally wedded to the continuing increase of the gross domestic product . . . the possibility of ending human expansion is viewed with consternation. . . .

Cooperrider (1996) implicates academic fragmentation as one reason for the lack of progress in solving broad societal problems such as population growth and excess consumption. Each discipline concentrates on its own specific area of interest, while issues of a more holistic nature are left unaddressed.

In reaction to federally orchestrated expansionism and apparent indifference to the consequences of exponential growth, the concept of a plebiscite or referendum on the desirability of immigration-driven population growth was presented to the Canadian government (Salonius 1998). If approved, the question would be attached to a future federal general election ballot, as has been done previously for constitutional questions. . . .

Concerted efforts should be launched by conservation biologists . . . North American legislators must be made aware that, as a result of their present-centered, expansionist agendas, they are continuing to set their naive constituents on a course toward a dismal and crowded future brought about by massive immigration.

References

Cooperrider, A. 1996. Science as a model for ecosystem management: panacea or problem? *Ecological Applications* **6**: 736-737

Keating, M. 1997. Canada and the state of the planet: the social economic and environmental trends that are shaping our lives. Canadian global change program. Oxford University Press, Don Mills, Ontario.

Kolankiewicz, L. 1998. Is immigration an environmental issue? Carrying Capacity Network, Washington, DC.

Salonius, P. 1998. Response to the legislative review advisory group report entitled, "Not just numbers: a Canadian framework for future immigration." Mimeographed document. Durham Bridge, New Brunswick, Canada.

Trempe, R., Davis, S., Kunin, R. 1997. Not just numbers: a Canadian framework for future immigration. Legislative Review advisory group report. Minister of Public Works and Government Services Canada.

CAPACITY FACTORS — A SIMPLE ANALOGY

by Andrew R.B. Ferguson

There is a general rule of thumb for establishing the capacity factor that a PV module will achieve in any specified insolation. For example, at 200 watts per square metre, the capacity factor will be 14% (at 100 watts per square metre it would be 7%). However, it is not immediately obvious either why capacity factors are more or less fixed — to the extent that cells of double the present efficiency would not affect the capacity factor — or what the implications are. Here is a simple explanation using an analogy.

Let us start by taking note of the fact that a yacht, capable of say 30 knots in ideal conditions, will not sail around the world at a steady 30 knots. Its actual speed around the world would be a fraction of 30 knots. Were we to use the same terminology as is used for renewable energy, we would call the 30 knots speed the "rated capacity" of the yacht, and the fraction of 30 knots at which it sailed around the world its "capacity factor." With that introduction, we can follow the analogy in more detail.

Suppose that one yacht has a top speed of 30 knots, and another a top speed of 10 knots. In a round-the-world race they might achieve the following results:

Fast yacht (30 knots "rated capacity"): 100 days, average speed 9 knots (= 30% "capacity factor").

Slow yacht (10 knots "rated capacity"): 300 days, average speed 3 knots (= 30% "capacity factor").

Were one to point out to the fast yachtsman that his "capacity factor" was no improvement on the slow yacht, I expect he would reply, "What the hell; that's not the name of the game."

He would be right of course, but when it comes to photovoltaics (also wind, and other variable but non-flexible energy sources), capacity factor is indeed the "name of the game," for two reasons:

1) The capital cost of PV is normally given in terms of cost per unit of rated capacity. To work out the capital cost of electricity delivered to the customer, one has to divide by the capacity factor (for more detail see the next paper).
2) Once peaks in demand have been satisfied, then the task of an electricity supplier is to provide a constant power supply. We can more simply envisage the situation for the whole of the USA by considering a single citizen, who, on average, uses 1.4 kilowatts (kW) of electricity (this includes indirect use). Let us, for simplicity, make the rough assumption that the 0.4 kW is a variable demand, leaving the 1 kW as a constant demand. For simplicity again, we can set aside the 0.4 kW, which may possibly be fairly efficiently satisfied by PV (to the extent that there is a coincidence of peak demands and high PV output), and focus on the 1 kW of steady demand. If we try to use PV for that, then we would install 1 kW of PV capacity, which would do the job nicely during the middle of the day in summer. However, if the capacity factor were to be 14%, then PV would supply only 0.14 x 1 x 24 x 365 = 1214 kWh during the year. However the citizen would require 1 x 24 x 365 = 8760 kWh of steady supply, so PV would satisfy only 14% of that requirement.

In the next paper, *The Relative Cost of PV and Wind Power*, we will consider the cost implications of the fact that the capacity factor of PV, even in a sunny location, is considerably lower than that of wind, at an average site.

THE RELATIVE COST OF PV AND WIND POWER

by Andrew R.B. Ferguson

Abstract: In a European Green Paper, photovoltaic electricity was estimated to be about nine times as expensive as electricity from wind turbines. Very broadly, we confirm that estimate. So long as fossil fuels are available, this confines PV electricity to niche use. When fossil fuels become scarce, it seems inevitable that costs will escalate, and purchasing power fall, so one must conclude that photovoltaics, at least with the current generation of technology, will never play a significant part in renewable energy supplies.

In *Hydrogen and Intermittent Energy Sources* (OPTJ 4/1, p. 27), we noted, in passing, the high figure of US77¢ per kWhe for the cost of photovoltaic (PV) electricity given by the authors of the Green Paper, *Towards a European Strategy for the Security of Energy Supply, 2000.* That is nine times as high as the same paper gave for wind, 8.3¢. Perhaps I should remind readers that PV has already been covered in considerable detail in the October 2002 issue of the *OPT Journal*, pp. 23-37 (OPTJ 2/2, 2002). Those pages used a minimum cost of $5 per watt of installed capacity, and arrived at a minimum cost for PV electricity of 25¢ per kWh (for 200 W/m^2 insolation). It is likely to remain arguable whether the *absolute* cost of electricity from PV is any particular figure. Especially because, as we shall see, there are many indeterminates in attempting to pin down absolute cost. Thus there seems a need to explore the *relative* cost of PV compared to electricity from wind; while noting the effect of the 'capacity factor'.

The main cost of both PV and wind electricity is capital cost. Although wind power does have a substantial element of maintenance cost, comparison of the capital cost paints the most important part of the picture. Making that comparison is easy. It can be expressed in a formula as the ratios between the cost per unit of *actual output* of each system, i.e.:

cost per watt of rated capacity of PV / (*1 watt x capacity factor of PV*) compared to,

cost per watt of rated capacity of wind / (*1 watt x capacity factor of wind*)

Somewhat pre-empting the discussion below, we can say that works out thus:

$5 / (1 x 0.14) compared to $1 / (1 x 0.28) = 35.7 to 3.57 = 10 to 1.

Expressed in words, the capital cost of PV is 10 times that of wind for the same output.

The thought of how to make the comparison in a more striking and thus hopefully memorable manner occurred when I was sent a copy of Bernard Gilland's paper, *Energy for the 21st century: an engineer's view* (Endeavour, Vol. 14, No. 2, 1990). The general principle of the comparison is that a wind turbine sweeps out a certain area, and each square metre of that area captures a certain amount of power from the wind. Were that swept area to be filled with PV cells, suitably supported and inclined to the sun of course, then there would be two aspects of comparison: first, the difference in cost; second, the difference in output. Since power from PV and wind is substantially capital cost, we would expect the relative cost of the electricity to be contained within these two aspects of performance. In the process of analysis, it will become apparent to what extent the total expense has arisen because of the cost of covering an area with something which has a capacity to capture the sun's energy (wind is an indirect form of the sun's energy), and to what extent the problem lies in a low rate of energy capture. Gilland states, page 83:

> Rotors with 100 m hub height produce approximately 1300 kWhe/yr/m^2 rotor-swept area at offshore and coastal locations, which corresponds to an average power of 0.15 kWe/m$^{2.}$

A wind turbine with a 100 m hub height is likely to have a rotor of 80 m diameter. That calculates as a swept area of 5026 m^2, or say 5000 m^2 after allowing for a dead area near the hub. At the said power capture of 0.15 kWe/m^2 (150 We/m^2), this swept area would yield a mean power of 750,000 watts. At a 30% capacity factor, appropriate to an offshore installation, this indicates Gilland is describing a 750,000 / 0.30 = 2.5 MWe capacity turbine. The fully installed cost of a wind turbine is about US$1 per watt of capacity, indicating a cost of $2.5 million. Being located offshore, the cost might be more, but that figure is in the ball park.

Now let us consider the cost of replacing the swept area, of 5000 m^2, with PV modules. The fully installed cost of PV cells may come down to about $5 per watt of capacity, equal to about $700 per m^2 (1 m^2 of module has a rated capacity of around 140 watts). So 5000 m^2 of module would cost $3.5 million. So for the same area of energy capture, the PV would be 40% more expensive than the 2.5 MW wind turbine that we are considering. Note that we are ignoring the difference in output only for the present.

Using cells of 17% efficiency, packed into modules so as to achieve 14% efficiency, we can expect modules to capture 10% of the insolation which falls on them. Thus in a sunny place like Toledo, Spain, with an insolation of about 200 W/m^2, the energy captured is at the rate of 20 W/m^2. We could calculate the total energy captured by the 5000 m^2 of PV module area and compare it with the total energy captured by the 5000 m^2 swept area of the wind turbine, but as we are concerned only with relative costs, it is easier to simply note that the rate of capture of the wind turbine (150 W/m^2) is 7.5 times as much as the rate of energy capture of the PV modules (20 W/m^2).

Combining these two aspects, we can say that because the 2.5 MW wind turbine captures 7.5 times as much energy, we would expect the PV electricity to be 7.5 times as expensive were the capital cost to be the same. Adjusting for the 40% difference in capital cost, we would expect the expense ratio to be 7.5 x (3.5 / 2.5) = 10.5. While maintenance costs are likely to be higher for wind turbines than for PV, this 10.5 factor of cost for unit of output lends considerable plausibility to the cost factor of 9 given in the EU Green Paper.

Perhaps a more striking way of creating a clear picture in one's mind as to the meaning of those conclusions is to imagine a PV salesman offering you a 'special model of windmill', which is 40% more expensive yet produces only one seventh as much electricity. Put that way, there would be few buyers! Whatever way the facts are presented, it is apparent that the magnitude of the capital expenditure problem has been overlooked by some people. For example, Gilland says, page 83, "The developable potential of solar power in the post-fossil era is therefore approximately equal to the hydropower potential of the tropics — 700 GWe."

Let us take a look at that 700 GWe to see why such a figure is implausible. At the aforementioned 20 watts per square metre, 700 GWe would require 700 x 10^9 / 20 = 35 billion m^2. At $700 per square metre, that would cost $24 trillion ($24 x 10^{12}). It is hard to imagine a sum of that size, so let's break it down to an annual investment of $100 billion a year. It would take 240 years to complete the investment, except that after 30 years, with 13% of the investment complete, the PV modules installed in the first year would require replacing, so a continuing expenditure of $100 billion a year would merely maintain the status quo. Our achievement would be to have built a PV system which would achieve a mean power output of 88 GWe, 13% of the target 700 GWe, after which there would be no further progress because from then on the $100 billion a year would all be spent replacing the PV modules installed 30 years earlier.

Bernard Gilland is by no means alone in being carried away on tides of optimism about PV. Even the sainted (to my mind at least) David Pimentel, in his paper, *Renewable Energy: Current and Potential Issues* (2002), was caught up in the tide of misinformation. He quoted a cost for PV electricity of 12¢ to 20¢ per kWhe and on that basis — no doubt anticipating improvements too — projected a renewable energy scenario for 2050, in the US, with an output of 3200 billion kWht from PV. The electrical equivalent is about 1060 billion kWhe, or 120 billion GWe. 120 GWe is 17% of Gilland's proposed 700 GWe, and therefore equates to a cost of $4.2 trillion ($4.2 x 10^{12}).

We are considering the US now, so let us choose a more moderate investment rate of $15 billion a year (a choice that we will seek to explain later). The investment would take 280 years to complete, except that after 30 years we once again get into the situation of 'running in order to stand still'. After 30 years, the total investment (of $450 billion) will provide a total PV output of (30 / 280) x 120 GWe = 13 billion GWe (11% of the 120 GWe planned).

Americans consume about 3.7 trillion kWh per year, which is a mean 422 GWe. Thus if $15 billion a year is a ceiling on PV investment, then the ultimate PV contribution towards satisfying US electrical demand is the fraction 13 / 422 = 3.1%

The inveterate believer in a photovoltaic future may not give up yet. He may argue that far more than $15 billion a year could be spent if necessary. But that is unlikely to be true. A problem with PV is the significantly large energy inputs needed to produce the cells, modules, the supporting structure, and control equipment. Higher estimates are also plausible, but we are likely to be in the right ball park if we say that a quarter of the total output of PV modules will be used in the construction and installation of the panels, etc. (OPTJ 2/2, p. 8, and see below).

It has become apparent by now that to achieve any specific objective as a final output, we need to accomplish the entire investment over 30 years (otherwise the available expenditure is consumed in replacing those built thirty years earlier). One thirtieth of the aforementioned $4.2 trillion is $140 billion a year. That would be the required annual investment. The lifetime (30 year) yield from the first year's installation would be 1060 billion kWhe. As mentioned, a quarter of this, 265 billion kWhe, is likely to be required as input. Thus spending $140 billion a year on PV installations is initially going to *increase the electricity demand* by about $265 \times 10^9 / 3.7 \times 10^{12}$ = 7% (diminished by the small output of the first year of PV operation). Since large scale PV building is unlikely to take place while we are flush with fossil fuel energy, the prospect of such huge investments taking place when energy is scarce is almost non-existent.

Moreover, one must always bear in mind the two factors frequently mentioned in these pages, namely that it is now fairly well established that the world will have used about half of the total store of oil and gas supplies before the second decade of this century is out (Campbell, 1997), so we will soon be entering the age of scarcity of fossil fuels. This will make *everything* more costly, so estimations of possibly acceptable cost need to take account not only of the increased price of PV modules, supporting structures, transmission lines, inverters and maintenance, but also anticipate lower purchasing power for nearly everyone.

The tide of optimism

Perhaps a few words of explanation should be inserted about the tide of optimism which held sway a few years ago regarding PV. It was hoped, at that time, that thin film PV could reduce to a tiny fraction of current cost both the energy and dollar cost of PV cells. Since then, doubts have arisen in the industry about whether thin film can be made to survive conditions in the outside world, and BP solar have abandoned development. There remain intrepid researchers working in the field, but even if they are successful with the thin film, they have a second problem to solve: how to get down the cost of the 50 square metres of support structure needed (in 200 W/m^2 insolation) to deliver (in the usual erratic fashion) 1 kW of electricity. A few years ago, less attention may have been paid to the energy cost of PV, because it was often imagined that natural gas would remain in plentiful supply. In fact energy inputs are an enormous problem; that is obvious when one bears in mind the fact that even in a sunny place like Toledo, Spain, with 200 W/m^2 insolation, each square metre of module only yields 20 watts. Over a thirty year life time that is 20 x 24 x 365 x 30 / 1000 = 5260 kWhe. In pure heat terms that is three barrels of oil; and making PV cells is a high energy process; also required are glass, plastics, supporting structure, inverters and 30 years of maintenance.

The Green Paper's 77¢ per kWh cost

Respectable sources have given the cost of PV electricity as being well below the Green Paper's 77¢. David Pimentel kindly told me of other cost estimates per kWh: 20-20¢ from the University of Wisconsin, 20¢ from the Energy Center Wisconsin, and 25-30¢ from the Alliance to Save Energy. How can those costs differ so much from the EU Green Paper? A part of the answer would be higher levels of insolation in the US. That might reduce US costs to about 70% of European costs. Other factors which are highly relevant to any estimate of cost, but which are extremely difficult to put useful figures on, are: (a) the cost of capital with the loan only fully extinguished after 30 years; (b) the cost of providing back-up, to deal with the intermittent supply from PV; (c) the extent to which it will be possible to actually use all the electricity generated from PV, for it is likely to suddenly increase or decrease in an unpredictable manner. What can be said is that were I to adjust my figures for an additional 4% interest to cover inflation, this would put up the cost — based on $5 per watt of rated capacity and 200 W/m^2 insolation — to 40¢ per kWhe. Moreover, a formula presently being circulated in the industry for this same calculation would put the cost as high as 54¢ /kWhe (showing the difficulties of estimating absolute cost).

The figures in the 20-30¢ per kWh range probably ignored some or all of the factors of the previous paragraph. Almost no data appear to be available on the price at which PV generators are willing to sell their electricity, and under what terms electrical distributors would willingly buy it. There is one clue as to a realistic price of PV electricity. It comes from page 46 of *Vital Signs* 2001-2002:

> PV production reached 61 megawatts in 2000, an increase of 52 percent over 1999. The European solar industry is being led by Germany, which launched its own 100,000 rooftop program in late 1998. That program — which includes a 10-year, interest-free loan from the German Federal Bank plus a guaranteed purchase price of 50¢ per kilowatt-hour — resulted in 45 megawatts of new installations in 2000.

Thus the PV generators — the general public in this case — are willing to sell their electricity at 50¢ per kilowatt-hour provided they are given a ten year interest-free loan to purchase the equipment. There is a further problem regarding the willingness of distributors to buy the electricity. When a requirement was introduced into the UK that wind generators must specify, four and a half hours ahead, the amount of wind power they would be able to provide, the sales of wind energy dropped by 14% (OPTJ 2/1, p. 5). Similar issues would apply to PV. Without being able to quantify everything, we can see that the price of 77¢ per kWh may not be unreasonable.

A point worth noting about the above quotation is that it is in one respect typical of the media, because it quotes the *rated capacity* of the installation without giving any information about the *capacity factor*. From an insolation map, it appears likely that insolation in Germany is around 120 W/m^2, so the capacity factor of 14% achieved in Toledo, Spain, would be reduced to 14 x (120 / 200) = 8.4%. If that is the case, then the last mentioned 45 megawatts of new installations will provide 3.8 megawatts of output (33 million kWh/yr). Perhaps those who have to pay out for the 50¢ per kWh are glad it is not any larger!

The collection area

It is wise to never altogether forget the collection area. While it is true that the collection area is not of much concern with either wind or PV, one needs to retain an appreciation of the efficacy with which the energy from the sun is being captured. It is hard to put a cost on growing and harvesting biomass, but for biomass, cost is not the essence of the problem. The problem with biomass is the low energy capture per square metre. We gave the figure 150 We/m^2 for wind and 20 We/m^2 for PV. For sustainable biomass it is about 0.2 Wt/m^2 — and note that is thermal energy. That amount of thermal capture would be sufficient to generate electrical energy at a rate of about 0.06 We/m^2. Of course that varies a bit depending on insolation, but it is near enough: it is generally true that biomass captures, as thermal energy, about one thousandth part of the sun's energy (Pimentel and Pimentel, 1996, p. 15). With a figure as low as 0.06 We/m^2, it need be no surprise that the area of land required to supply a city of 100,000 US citizens, with electricity from biomass, would require an area of 220,000 ha, that is 2200 km^2 (Pimentel and Pimentel, 1996, p. 206). That estimate, which broadly agrees with the figures that have been given here, does not take into account the fact that there would be energy costs in transport when collecting biomass from such an area, even if the city were surrounded by forest. In other words the *useful* energy captured would be significantly less that the energy output of the system.

In summary, the main problems of living off renewable energy are: (a) the cost when an intensive method (e.g. wind and PV) of collection is employed; (b) the intermittency of those intensive methods; (c) that biomass is almost the only time-independent renewable energy source, and the intensity of energy capture with biomass is very low even in gross terms, and even lower in net terms (i.e. after the inputs have been subtracted).

Acknowledgement

Harry Cripps, energy consultant and member of OPT, was immensely helpful in suggesting ways to improve the presentation in this paper.

References

Campbell C.J. 1997. *The Coming Oil Crisis*. Essex, U.K.: Multi-Science Publishing Company & Petroconsultants S.A. 210 pp.

OPTJ 2/1. 2001. *OPT Journal*, October 2002; arch. at www.members.aol.com/optjournal2/optj21.doc

OPTJ 2/2. 2002. *OPT Journal*, October 2002; arch. at www.members.aol.com/optjournal2/optj22.doc

OPTJ 4/1. 2004. *OPT Journal*, April 2004; arch. at www.members.aol.com/optjournal2/optj41.doc

Pimentel D, Pimentel M. 1996. *Food, Energy, and Society*. Revised edition. Niwot Co., University Press of Colorado. 363 pp. (£30).

Pimentel D., Herz M., Glickstein M., Zimmerman M., Allen R., Becker K., Evans J., Hussain B., Sarsfeld R., Grosfeld A., Seidel T. 2002. Renewable Energy: Current and Potential Issues. *BioScience* Vol. 52 No. 12, 1111-1120.

Vital Signs 2001-2002. 2002. Worldwatch Institute. London: Earthscan.

A RULE OF THUMB FOR PV ANNUAL CAPACITY FACTORS

a memorandum by Andrew R.B. Ferguson

It is necessary to have very precise knowledge of PV output in order to efficiently control PV arrays, as I have now learnt from Tom Hansen, but precise knowledge is not our concern here. That concern is to make a general assessment of the viability of PV. For that it is useful to be able to make an approximate prediction of the annual capacity factor likely to be achieved in various situations. I am now able to dwell on that more fully, as Tom Hansen has very kindly passed on to me further data regarding the seven performance indexes he supplied earlier, which covered 4 sites at Tucson, Arizona, and 3 sites at Springerville (SGSSS) 240 miles away. So as not to lose the essential simplicity of this analysis, many details he provided are confined to the notes.

The rule of thumb, which I had already tested for levels of insolation at 200 W/m^2 and below, is that by looking at an insolation map showing insolation on a horizontal plate, namely the world insolation map available from F. Kreith and J.F. Kreider, *Principles of Solar Engineering*, 1978, page 17, one can obtain an acceptably accurate estimate of the capacity factor likely to be achieved by PV modules. However, I was concerned that the rule might be upset by the known poor performance of modules at high temperatures. With Hansen's additional data, we can study that.

At Toledo, Spain, where a four year study was conducted, there was a difference between (1) the amount of electricity delivered as AC; and (2) the amount that was fed into the grid. Measure (1) gave a capacity factor of 14.7%, and (2) 14.0%. Hansen told me that the data he had supplied referred to output of type (2), so the 14% capacity factor is the relevant one. The insolation at Toledo — as taken from Kreith and Kreider's insolation map — looks to be about 200 W/m^2.

Assessed from Kreith and Kreider's insolation map, the insolation in the Springerville and Tucson area is 250 W/m^2. Thus, according to our rule of thumb, we would expect a capacity factor of 14.0 x 250 / 200 = 17.5% in that region.

In Case 1 to Case 7 respectively, Hansen's performance data showed these achieved capacity factors: 15.7, 15.4, 16.3, 18.2, 18.3, 19.0, 19.9% for an average capacity factor of 17.5%. The first four relate to Tucson, the last three to Springerville (SGSSS). While it may be coincidence, one surely has to admit that there is a surprisingly close match between the 17.5% predicted and the average result of 17.5%! To regard that as more than coincidence, we need to ask why there is such a spread in the individual figures.

Module temperature affects PV performance to a considerable effect. Outside of solar flux, the two chief factors which affect the temperature of the modules are ambient temperature and wind speed. Hansen told me that, "Tucson has an annual average temperature of about 71 degrees F and SGSSS is about 49 degrees F and much more windy." With that background, it is no surprise that the first three results, which are from Tucson, average 15.8%, and thus are 1.7% below our predicted 17.5%. The fourth result, 18.2%, seems high for the Tucson location, and is something of an anomaly,{N1} but including that puts the average at 16.4%, which is 1.1% below the 17.5% prediction. The last three results, all from Springerville, average 19.1%, which is 1.6% above the 17.5% prediction. Perhaps we can conclude that our rule of thumb does serve to put us in the right ball park when predicting the average capacity factor to be achieved, even at high insolation sites (which was the area of insolation regarding which doubt existed). For fine-tuning, to estimate capacity factors for specific installations, we could propose an additional rule of thumb, namely that at a high insolation site, when everything is unfavorable and the site is hot and balmy, one may need to knock off 2.5% from the predicted capacity factor, whereas if all things are favorable and the site is cool and windy, then one may need to add 2.5%.{N2}

The validity of a point that Hansen made is readily admitted. The point was that there are other factors as well as windiness and temperature which affect the capacity factor, namely, "inverter efficiency, wiring losses, module to inverter mismatch". But I am only suggesting a rule of thumb which may be applied when those factors can be assumed to be held constant, and also when wind and temperature are assumed to be *average* for that area of insolation, leaving the effect of insolation to become the controlling factor.

One factor which does not need to be held constant is the efficiency of the modules. We could equally well be considering modules of say 10% efficiency or of 20% efficiency. The factors which affect capacity factor, in addition to those mentioned in the previous paragraph, are (a) the amount of insolation received in proportion to the 1000 W/m^2 which is used for the standard assessment; (b) the degradation of performance due to the fact that the insolation is rarely hitting the modules at the optimum angle (and so may be reflected); (c) reduced efficiency at lower levels of irradiance than at 1000 W/m^2; (d) performance degraded by dust on the surface of the modules (this was a significant factor at Toledo, Spain); (e) the *average* degradation of performance due to overheating of the modules.

It may be a surprise to some people to realize that not only are none of those factors relevant to efficiency of the modules, but also that the efficiency of the modules does not affect the capacity factor. The latter point becomes immediately clear if you conceive of the extreme case, and consider the fanciful idea of the modules being 100% efficient. The 1000 W/m^2 at the laboratory would then produce 1000 watts/m^2 of electricity, but out in the field, with say 200 W/m^2 insolation, factors (a) to (e) would still operate to reduce the output proportionately, to 140 watts, a capacity factor of 14%. What changes with changing module efficiency is the area of module needed to achieve that output (with beneficial effects in reducing Balance of System costs). Perhaps it should be mentioned that capacity factor might vary between different types of module (e.g. thin film rather than mono-crystalline silicon), but only because items (a) to (e) may not have exactly the same effect on all types of module. Possibly item (b) could be improved with non-reflecting glass, and (e) with better module heat-conduction; however the differences appear likely to be minimal; and anyhow we need to wait to see a demonstration of those differences before attempting further refinement of the rule of thumb.{N3}

So we have arrived at a conclusion, but let me circumscribe my claim somewhat. I go no further than saying that the following rough rule of thumb currently appears to be supported by the evidence: **Considering an adequate (that is adequate to be representative) number of PV plants situated in a specified area, one can predict the average capacity factor that will be achieved, in terms of electricity delivered to the grid, because it will vary from 14.0% in direct proportion to the insolation shown by Kreith and Kreider, divided by 200 W/m^2.** An alternative presentation of the rule of thumb is to say that the aforesaid capacity factor will be 70% of that which would result from adjusting only for the insolation, e.g. at 200 W/m^2, capacity factor = (200 x 0.70) / 1000 = 14%.

Sensitivity of the rule of thumb

If we do not know what proportion of Arizona reflects Springerville conditions and what proportion reflects Tucson conditions, then there is an area of uncertainty as to where, within the 16.4% to 19.1% band, we can expect the capacity factor of PV to turn out when operating in the 250 W/m^2 insolation in Arizona. Let us see what difference it makes to assume either end of the capacity factor band by comparing the capital cost of PV to that of wind turbines, for which we will assume a cost of $1 per rated watt and a capacity factor of 28%. For the fully installed cost of PV, we will assume what appears to be close to the current cost for Utility Scale PV, namely $5.50 per fully installed peak watt.

With a capacity factor of 16.4%, relative cost is ($5.50 / 0.164) / ($1 / 0.28) = 9 times as much for PV. With a capacity factor of 19.1%, relative cost is ($5.50 / 0.191) / ($1 / 0.28) = 8 times as much for PV.

The difference between 9 and 8 is surely not of great importance. Anyhow, it could be argued that a more important assessment would be the relative capital cost for the average insolation of the whole of the U.S., which I normally take to be 200 W/m^2 (although 190 W/m^2 is probably a truer average). We already know from Toledo, Spain, that the capacity factor at 200 W/m^2 is 14.0%, so relative capital cost for PV in the U.S., at current PV fully installed costs, is: ($5.50 / 0.14) / ($1 / 0.28) = 11 times as much for PV. We should not forget that it is probably not fair to PV to compare only the capital cost, as the maintenance cost of wind turbines is likely to be considerably higher. Note, too, that wind turbine capacity factor is not 28% everywhere. Assessed over two years, the mean capacity factor for Sweden, Denmark, the Netherlands and Germany was 22% (OPTJ 3/1, p. 4). In the USA, during 1998, it was 23.5% (Hayden, 2001, p. 21).

Notes

Tom Hansen claims only to be “gaining field experience” in PV, but he is certainly far more of an expert on the subject than I am. These notes, taken from the information he kindly passed on to me, are often close to verbatim, even when not in quotes.

N1. The capacity factor, of 18.2%, in Case 4, surprisingly high for Tucson, is echoed to some extent by a high capacity factor, of 19.9% in Case 7, which is high even for Springerville. Hansen explains. “Case 4 in Tucson is data from a single 30 kW, a couple of 108 kW and three 22 kW PV systems which all use exactly the same crystalline PV modules as the 135 kW system size Case 7 in Springerville. The anomaly exists to the rule of thumb because both Cases are systems larger than 20 kW, and take advantage of the efficiencies inherent in large scale PV systems, and the much better maximum power point tracking and DC to AC conversion efficiencies found in large inverters. And, all Case 4 and Case 7 systems are monitored on a daily basis to ensure proper operation. These systems are also all ground mount, south facing, fixed latitude tilt systems with plenty of room behind and in front for air flow for cooling, and there is no shading at any time of year, other than from inter row shading. Also, the 30 kW Case 4 system is in southern Arizona, but about 80 miles from Tucson and one 22 kW Case 4 system is actually located at Springerville, but we lump it in with the data for the other 22 kW systems since it represents about 7% of the capacity of the Case 4 group.”

N2. The data only suggest as much variation as 2.5% if we consider particular installations. Hansen points out **“**that different combinations of climate, inverter size used, PV module material technology and mounting style will produce annual capacity factor variance of as much as + or - 2.5% from the Rule of Thumb.” He amplifies that assessment as follows: “I would estimate that a large (20 kW and up) ground mount PV system with high quality inverter using crystalline modules in a cool windy climate will have a capacity factor of up to 2.5% higher than the average rule of thumb number and a small (6 kW and less) roof mount PV system with an average small scale inverter using crystalline modules in a hot climate will produce at down to 2.5% below the rule of thumb capacity factor. Amorphous silicon will have a different range of variation around the rule of thumb, since its performance drops off in both cold and hot temperatures, and CdTe and CIGS variance factors in field conditions are still under review.”

N3. Hansen also provided this information which may be useful to those following up the subject in more detail. In addition to the points in the previous note, he says that large inverter size and open mounting style will improve capacity factors, and “PV material technology, while having an effect on annual capacity factor, will have an effect that will vary depending on the other factors and the inherent temperature characteristics of the material. An effect I am still trying to quantify for the different material technologies.”

It may be useful to pass on the specifics of each Case (capacity factor in brackets):

Case 1 (15.7%): Less than 5kW. Almost all typical roof mount, many with nearby shading sources. South facing, fixed latitude tilt. All a-si PV material. Only BP Solarex MST-50 modules

Case 2 (15.4%): Less than 5kW. Almost all typical roof mount, many with nearby shading sources. South facing, fixed latitude tilt. All crystalline silicon material, except also includes all of the Case 1 a-si systems. A wide variety of modules.

Case 3 (16.3%): Less than 5kW. Almost all ground mount, with no shading sources. South facing, fixed latitude tilt. Primarily crystalline silicon, with a couple of amorphous silicon systems, a single crystalline/amorphous high efficiency system and a single CIGS system.

Case 4 (18.2%): Close to perfect conditions as per Note N1, except the 30 kW system is roof mount. Only ASE DG300/50 modules.

Case 5 (18.3%): Close to perfect conditions as per Note N1. Only BP Solarex MST-43 modules.

Case 6 (19.0%): Close to perfect conditions as per Note N1. Only First Solar FS-50 modules.

Case 7 (19.9%): Close to perfect conditions as per Note N1. Only ASE DG300/50 modules.

References

Hayden, H.C. 2001. *The Solar Fraud: Why Solar Energy Won’t Run the World*. Pueblo West, Colorado: Vales Lake Publishing, LLC.

OPTJ 3/1. 2003. *OPT Journal*, Vol 3, No 1 (Apr), Manchester, UK: Optimum Population Trust. 32 pp. Archived at www.members.aol.com/optjournal2/optj31.doc

Gard Norberg kindly sent to me a review copy of Jensen and Draffan's book named below. The extracts which follow could be left to speak for themselves, but perhaps the reader's attention should be drawn to one point: If we substitute the word "Earth" for the word "Republic," in the Abraham Lincoln quotation below, then Lincoln is expressing the points listed as items 1 and 2 in *The Social and Ecological Consequences of Globalization*" (OPTJ 3/1, p. 23). While *Strangely Like War* is mainly about forests, it provides within its own smaller scope a stinging critique of globalization, adding weight to the aforementioned piece.

The figures given in the book, on paper consumption, illustrate a point to which we frequently return in these pages: *Strangely Like War* makes it clear that over-use of paper is already a desperate problem, yet to bring the non-industrialized world up to the level of paper use in Europe and Japan (let alone the United States) would involve a 330 / 12 = 27-fold increase, by that largest part of the world which falls into the non-industrialized category. Environmental organizations and suchlike, who reject any realities which may be uncomfortable to their supporters, need to face up to the fact that the sovereign remedy which they promote for controlling population, education of women, is going to be hard to achieve without increasing the consumption of paper to a level which will destroy the world's remaining forests, and most likely pollute its fresh water sources beyond redemption.

STRANGELY LIKE WAR: THE GLOBAL ASSAULT ON FORESTS{1}

by Derrick Jensen and George Draffan

p. 60. If we had to describe the pathology of our culture in a nutshell, that might be it: our economic system rewards destructive behavior.

p. 85. [A quotation from President Abraham Lincoln] I see in the near future a crisis approaching that unnerves me and causes me to tremble for the safety of my country. . . . Corporations have been enthroned and an era of corruption in high places will follow, and the money power of the country will endeavor to prolong its reign by working upon the prejudices of the people until all wealth is aggregated in a few hands and the Republic is destroyed.

p. 85. The consuming elites (that is, the middle and upper classes of the United States, Europe, and Japan, and to some degree the upper classes in every other country) have an insatiable demand for luxury goods, commodities, and consumer products, including wood and paper products. I am sure you can see the problem with infinite demands on a finite planet.

p. 120. What we said earlier, about how corporations need never stop growing, is not precisely true. They will not stop growing until they have consumed the world. Surely they will stop then. And so will the forests. And so will we.

p. 122. We mentioned before that annual world paper consumption increased from 15 million tons in 1910 to 463 million tons in 1996. . . . The average person in America consumes almost 700 pounds of paper per year; the average in Great Britain and Japan is 330 pounds [150 kg] per year; the average in the nonindustrialized world is 12 pounds per year.

p. 135. Adam Smith's invisible hand of the market only worked when the market was local, face to face, voluntary, transparent, low-tech, and based on ethical, mutual relationships. It's been a long time since that was the case.

{1} 2003. Chelsea Green Publishing Company, VT 05001, USA. 160 pp. $15. ISBN 1-931498-45-8
www.chelseagreen.com/2004/items/strangelylikewar

John Nunn:

<u>Legend for Diagram.</u>

The diagram shows the broad trends in changes of sea level, temperature and atmospheric carbon dioxide concentration during the last 420 kyr. Sea level data are from sediments in the Red Sea (Siddall, M et al,. 2003, *Nature* **423** 853): other data are from Antarctica (Petit, JR et al. 1999 *Nature* **399** 429).

Above as originally sent

Figure 1. The diagram shows the broad trends in changes of sea level, temperature and atmospheric carbon dioxide concentration during the last 420 kyr. Sea level data are from sediments in the Red Sea (Siddall, M et al,. 2003, *Nature* **423** 853): other data are from Antarctica (Petit, JR et al. 1999 *Nature* **399** 429).

Figure 1. The diagram shows the broad trends in changes of sea level, temperature and atmospheric carbon dioxide concentration during the last 420 kyr. Sea level data are from sediments in the Red Sea (Siddall, M et al,. 2003, *Nature* **423** 853): other data are from Antarctica (Petit, JR et al. 1999 *Nature* **399** 429).

Figure 1. The diagram shows the broad trends in changes of sea level, temperature and atmospheric carbon dioxide concentration during the last 420 kyr. Sea level data are from sediments in the Red Sea (Siddall, M et al,. 2003, *Nature* **423** 853): other data are from Antarctica (Petit, JR et al. 1999 *Nature* **399** 429).