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In fact, deliberate disinterest in population change is a very recent phenomenon. Jack Parsons (1993) points out that one of the oldest known documents, a Babylonian tablet of baked clay, "is a cri de coeur for population control." Egyptians, Greeks, Romans, Chinese and Indians all wrote of the damaging effects of population pressure on ancient societies and their environments, and the need to control exponential population growth. So, Parsons continues, did philosophers and scientists in the second millennium AD, including Thomas Aquinas, Machiavelli, Francis Bacon, Benjamin Franklin and Rousseau, all pre-dating Malthus.

William Stanton, *The Rapid Growth of Human Populations 1750 -2000* (p. 127)

The Optimum Population Trust (UK): Manchester

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

INTRODUCTION

Roger Martin took up the challenge that I offered him of making a comparison between Clive Ponting's, *A Green History of the World* and William Stanton's, *The Rapid Growth of Human Populations 1750-2000*. His overview of the two books, with his insightful comparison of styles, makes interesting reading; that is where we start, pages 3-5, finishing with a quotation from *Green History*. To give a further briefing on Stanton's book, pages 6 and 7 provide a detailed resumé extracted mainly from the publisher's introduction and the book itself.

Pages 7-11 focus on another Clive Ponting book, published in 2000, *World History: a New Perspective*. In it, he continues to make use of his *Green History* idea — that the human narrative can be told in terms of human interaction with the environment — but this book is about twice the length of *Green History*, and also covers the political history of the world. Perhaps two major themes emerge. First, that western Europe has until recently only been a minor figure in world civilization's ten thousand year tapestry. Second, that while history does need to deal with the incessant struggle for power between states, and between the élites within those states, there has nearly always been another important struggle going on, namely that of the élites determined to maintain their superior status.

The latter conclusion was manifest in Barbara Tuchman's, *A Distant Mirror: the Calamitous Fourteenth Century*. Even more apposite to William Stanton's book is her 1984 book, *The March of Folly: from Troy to Vietnam*. The folly of which she speaks is an amalgam of ignorance, greed, and that pervasive tendency which humans have to believe what they feel comfortable believing, rather than assess the evidence. All three ingredients contribute to the mistaken view currently held by most economists, pundits and politicians, that renewable energy is likely to be able to substantially replace fossil fuels. That takes us to the next four items.

Pages 14-17 are devoted to the *Limits to Windpower*. The severe limitations of wind power have already been covered in OPT Journal 3/1 (*Wind/biomass Energy Capture: an Update*, pp. 3-10). In *Limits to Windpower* James Duguid and John Dyson contribute empirical evidence to support the theory.

That leads on to an exposition of *The Meaning and Implications of Capacity Factors*, pages 18-25, and to *Hydrogen and Intermittent Energy Sources*, pages 26-29. The latter shows that hydrogen is no solution to the problem of intermittency — a problem which afflicts most renewable energy sources.

Pages 30-32 present the paper *Hydrogen Fantasies*, as promised in the last issue, but space has prevented me from fulfilling another promise given there, namely to include *Hydrogen as an Energy Carrier*. In fact I have had to omit several papers that I would have liked to include, in order to keep to my self-imposed limit of thirty-two pages. The papers will be held over to the next issue. There I hope to include a page of extracts from a book sent to me by Gard Norberg, *Strangely Like War: the Global Assault on Forests*, by Derrick Jensen and George Draffen. Gard is in his eighties, like Jim Duguid, but both are still tireless in their efforts to save the human race from the nearly inevitable consequence of its folly!

Once again I would like to say that although my name appears frequently as the author, I am greatly indebted to many others beside the contributors, most particularly to David Pimentel, and also to Harry Cripps, Edmund Davey, Jim Duguid, David Gosden, Rosamund McDougall, Willie Stanton, Val Stevens, and Yvette Willey. Without the information with which they provided me, and without their valuable suggestions and criticisms, this journal would be a pale shadow of itself.

"A GREEN HISTORY OF THE WORLD" CLIVE PONTING; & "THE RAPID GROWTH OF HUMAN POPULATIONS 1750-2000" WILLIAM STANTON

a review by Roger Martin

These are two very different books, published 12 years apart, with very different scopes and styles, but the same grim message for the 21st century.

Ponting's book, with its eloquent sub-title "The Environment and the Collapse of Great Civilisations," was published by Penguin in 1991. It is an under-appreciated scholarly classic, containing a vast compendium of secondary research, largely of course historical. It opens with the now familiar "The Lessons of Easter Island;" but then takes us through basic ecology, and "Ninety-nine per cent of Human History" (i.e. the hunter-gatherer phase), before broaching the transition to agriculture (and hence the dawn of civilisation, and of history proper) in Chapter 4. From this point on, relentless population growth, and its Malthusian consequences, is a leitmotif of almost every chapter, notably in "The Long Struggle," of all agricultural societies to feed themselves. This lasted until about 1850, when the richest nations first achieved enough food for all, through imports of food and fertiliser, and the safety valve of emigration. Later chapters with more weight on environmental degradation include: "Ways of Thought" about man's relationship with nature, from Genesis, via Christianity and Marxism, to modern consumer economics; "The Rape of the World," from wildlife destruction, via fishing and alien species, to the idea of conservation; "Creating the Third World" by colonialism; the effects of fossil fuel energy; "The Rise of the City;" "The Affluent Society;" and pollution; and an oddly tentative glance at the future — "...too soon to judge whether modern societies are ecologically sustainable..." — when he has conclusively shown that they are not.

Stanton, in contrast, as his title indicates, has a far narrower focus on the period since the industrial revolution, the role of population growth alone in compounding most of our problems, and no inhibitions over interpreting recent history in terms of demographic pressure, nor in drawing conclusions about the future. He also provides some original research in a comprehensive set of demographic graphs, based on the best evidence available (often the Statesman's Yearbooks), for virtually every country in the world; with population density (persons/sq. km.); natural and total change (% per year); percentage change between 1900-2000; main population groups; a short historical summary of facts considered germane; and the occasional personal comment on the future. Of Ethiopia, for instance, (currently in the news since the BBC's Michael Buerk returned 20 years after his famous famine report to find more hungry people now than then, and attribute it to Malthusian factors) Stanton says: "Now, even when harvests are good, 5 million Ethiopians need food aid. Unless it can escape from the combination of droughts, famines, destructive wars and rapid population growth, a poverty-stricken future is assured."

These country-specific sections occupy the top half of each page. The bottom half contains the continuous text of the book proper, comprising chapters on: "two centuries of surging populations" by region; "natural controls on population growth;" "myth and reality in the population debate;" "some consequences of population pressure;" "globalisation and multi-culturalism;" population sense and sentimentality;" and "the future." In this, he introduces and refers frequently to four interesting and useful new concepts (or terms) to illuminate interpretation of recent history.

The WROG period (*Weak Restraints on Growth*) covers roughly the 19th and 20th centuries, and is now drawing to a close. It was caused by industrialisation, rapid economic growth and improved welfare in the developed countries, based on fossil fuels and the technology to spend long-term natural capital at increasing rates; and very recently in the developing countries, by modern medicine, improved water supplies, food and other aid, extensive suppression of warfare, etc, temporarily immunising societies from the harsh disciplines of natural ecological balance. With the WROG comes a demographic **DC Surge** (a period of rising population resulting from improved *Death Control* unaccompanied by birth control) globally explosive in the 20th century, mostly in the second half. Unless widespread birth control is rapidly adopted, however, the **Micawberish Rule** will ensure that countries remain poor: "The West's economy has grown faster than its population, result: wealth. In most of the developing world, population growth has outpaced economic growth, result: poverty." Eventually, failure to grasp this obvious relationship, between the size of the economic cake and the number of people each wanting a slice of it, leads inevitably to **VCL** (*Violent Cutback Level*), as groups fight for survival.

The logic is unassailable; and indeed Ponting lists a number of ancient civilisations, from Sumeria, via Meso-America to Easter Island, which collapsed into internal conflict or conquest by neighbours as populations outgrew food supplies. It is a weakness of Stanton's book, however, that he interprets a number of modern conflicts as examples of VCL in action, such as Rwanda, Palestine, Cyprus, Kosovo or Iraq, where population pressure and resource competition may well have exacerbated other causes of violence, but are clearly not the sole or even prime cause. (Indeed Iraq looks like the first of the 21st century's resource wars, for oil, but for reasons of greed rather than survival). Stanton seems equally clearly right, however, in maintaining that homogeneous societies under pressure can defer VCL for longer than diverse societies comprising large, distinct and potentially competing groups.

While the content of the two books is fully convergent, the styles of the two authors could hardly be more contrasting; and unfortunately, neither is very reader-friendly. Ponting (briefly famous as the MoD's "Belgrano" whistle-blower) remains the dispassionate civil-servant-turned-academic. His long, dense paragraphs teem with thousands of facts and statistics, strengthening his case but tending to numb the brain with overload. His opinions about the global catastrophe he describes may be inferred, but are never stated. There is a serious need for someone to compress it into a much shorter version, illustrated in colour, and suitable for, say, GCSE students as well as the general public. Conversely Stanton makes no attempt to conceal his total exasperation at the sheer imbecility of much that he sees around him. Objects of his scorn include political correctness (especially), globalisation, multi-culturalism, sentimentality, the litigious society, the blame culture, the Catholic church (obviously), Islamic suppression of women (hence high breeding rates), the nanny state, health and safety, the permissive society, immigration, and a massive aid/development lobby that exacerbates the problems it purports to solve by offering ever more Death Control without tackling birth control and promoting a belief in the impossible idea that all nations will be able to follow the European path of "demographic transition."

Both writers acknowledge, albeit with different weight, that unsustainable over-consumption by the rich 20%, consuming 90% of the earth's resources, is a major problem alongside unsustainable breeding by the poor. Despite Ponting's caution, however, it is hard to believe he does not also broadly share Stanton's view that the Earth is probably unable to sustain its present numbers, let alone the additional growth forecast by UN demographers, let alone to sustain it at anything resembling a decent standard of living; and that therefore the coming century is likely to see a significant drop in human numbers.

Stanton's apocalyptic vision is of the Malthusian crunch coming with the forthcoming oil shortage in the 2020s, and consequent structural global food shortage, since modern agriculture consists essentially of turning oil into food. (Ponting sets out its huge energy-inefficiencies, e.g. the energy output of South-East Asian rice paddy is fifty times the input, while all food production and processing in the industrialised world consumes more energy than it produces, twenty times more in the case of frozen fish! Nor will irrigation fill the gap; thanks to water-logging and salination, schemes are now being abandoned as fast as new ones are introduced). Thenceforth, Stanton's future is nakedly Darwinian until, with luck, a much smaller population (that of the pre-industrial revolution?) has stabilised, is intelligent enough to keep its numbers stable, and can build a decent, and for the first time a *sustainable*, society.

This is a bleak vision, that many readers will share, with heavy hearts. The Penguin edition of *Green History* quoted from a review in *The Observer*: "If there is a single book on the subject to engage the enthusiast, silence the cynic and enlighten the ignoramus, this is it." A fair summary I think, and Stanton's book is an important successor. But the power of denial remains huge; and it is hard to believe that any of the cornucopian, indefinite growth fantasists who rule our world will read either of these books.

From *Green History*, Chapter 13, *The Second Great Transition*

If individual items of energy producing and using equipment are not always efficient, is modern industrialised society energy efficient as a whole? In the past it was possible to make some fairly crude calculations about energy use — for example, people could set the cost of feeding animals against the savings in time and effort to be gained from using them for agricultural tasks — but now it is possible to do sophisticated calculations about energy use. But even when the facts are known societies have found it very difficult to make the necessary adjustments to achieve more efficient use. An example of poor energy use is found in modern industrialised agriculture. The most energy efficient agriculture in the world is the production of rice in paddy fields in China and south east Asia, where the output of energy is about fifty times greater than the input. Other so-called primitive agricultural systems are also highly energy efficient, producing about twenty times as much energy as they use. At best, modern industrialised cereal farming produces only about twice as much energy as it consumes in the form of fertilisers, pesticides and machinery. Modern agriculture is, moreover, becoming steadily less energy efficient. 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. Overall the energy efficiency of American corn production has fallen by half since 1915.

Penguin edition, page 291, *A Green History of the World*, Clive Ponting.

As an introduction to William Stanton's important book, published in September 2003, it would be hard to improve on the publisher's description, so keeping (well almost!) to my resolve not to review the book myself, I here reproduce material from the publisher's introductory leaflet.

THE RAPID GROWTH OF HUMAN POPULATIONS 1750-2000{1}

by William Stanton — the publisher's introduction

The human population explosion is demographic fact, starkly illustrated in Stanton's graphs of every nation's recorded population history. It began in the mid-18th century, as the Industrial Revolution introduced technologies that vastly expanded food production and began to control disease. By the mid-20th century the explosion was affecting the whole world.

Stanton draws on his graphic evidence to argue that the explosion marks a fundamental shift from a Darwinian world of ruthless competition, in which one population could only grow at the expense of another, to a gentler world of weak restraints on growth *(WROG)*. Populations could now increase side by side. Tolerance and compassion for other people became possible. Environmental concerns, and the concept of 'human rights', were born. To most of us, today, *WROG* conditions seem natural and normal.

But *WROG* conditions are self-destructive, because the hugely expanded world population is rapidly devouring the finite resources, especially the fossil fuels, that make *WROG* possible. We get glimpses of future resource wars in overpopulated regions such as Palestine and Rwanda, where Darwinian rivalry has resurfaced. Superficially, these are religious or tribal conflicts, but the deeper cause is competition within dense and divided populations for a limited resource: productive land. Such conflicts will become so common, as populations grow and resources shrink, that peacekeepers and compassionate aid will be ineffective. The resource wars will run their courses, and populations will crash.

The journey back to 'natural' levels of world population will not be a joyous one. Have policy-makers begun to grasp the scale of the problem that confronts them? Are they still dazzled by the contention that rates of increase are slowing, not grasping that all the time the numbers are mounting up?

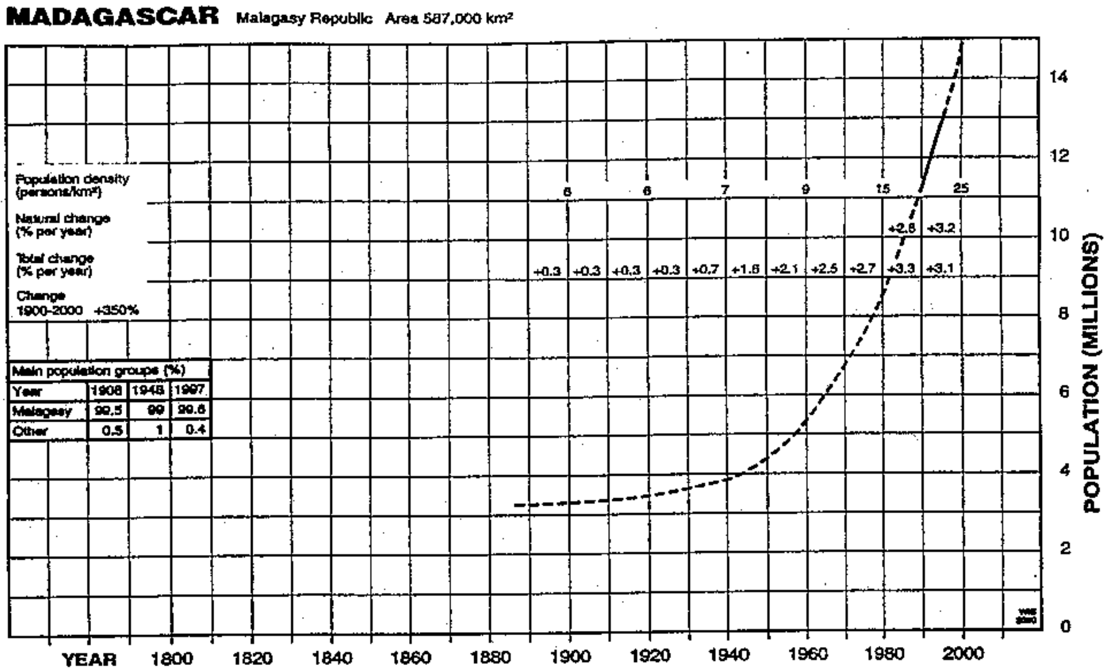
Stanton's graphic evidence so clarifies the issue that its central importance to humankind cannot be denied. A response needs to be made to apparently ever-growing populations, at policy level: what should it be?

What is missing from that introduction is a sense of the enormous scholarship that has gone into the book. A slight intimation of that is to be found in the first paragraph of Chapter 2:

The graphs are plotted using data from a wide variety of sources. Some of the oldest data sets are the most complete, being the findings of detailed censuses or 'enumerations' that were initiated around the beginning of the 19th century by the United States (1790) and certain North European nations (eg. Britain, 1801) and their colonies.

It remains for me to give an indication of the fine quality of the publication. That can be judged from the page opposite.

{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.



Madagascar, the world's fourth largest island, was initially settled by seafarers from Indonesia perhaps 1500 years ago. Portuguese navigators were the first European visitors, in 1500. European settlement was at first resisted by the native inhabitants but it became a French colony in 1896, ... 1960.

Population rose slowly unt... technologies and medicines trigge... growth that, with 86% of the labo... agriculture, and 70% below ... deforestation and soil erosion on ...

A unique flora and fauna developed on Madagascar during the 70 million years since it drifted away from Africa. Gerald Durrell, pioneer in captive breeding of endangered species, transferred Madagascan lemurs and tortoises to his Jersey Zoo, but although ...e threatened species, ...ng human population ...o survive for long. ...ely, and even in the ...uncertainty. In 2002, ...as chaotic, with two

Running through the book on the *upper parts* of the pages is new reference material: an assemblage of 235 graphs and tables showing, in detail, the recorded growth of population in each of the world's independent nations, as well as in 49 geographical regions which have, separately, useful and relevant records. Each graph is accompanied by a brief historical summary of political, cultural, ethnic and environmental change. The graphs appear in alphabetical order in four groups based on current population size, as indicated on the edge of each right-hand page.

Running through the book on the *lower parts* of the pages is the Commentary, which discusses how and why the evidence of the graphs amplifies or is at variance with conventional wisdom, and goes on to outline scenarios of population development based on the new evidence.

Three novel concepts are introduced:

WROG (Weak Restraints On Growth)
The global WROG period is the two and a half centuries since about 1750, during which populations have exploded.

DC (Death Control)
DC population surges, characteristic of the WROG period, were made possible by science-based improvements in agriculture, industry and medicine.

VCL (Violent Cutback Level)
A population cannot rise naturally above this level, due to civil strife, genocide, ethnic cleansing, etc.

Cross-referencing is made easy by naming target nations in capitals, e.g. RWANDA, and including section numbers at the top of the page.

were dying every da...

In 1995 an Iris... ...nt to apologise for the Irish Potato F... ...Minister, was forced to cancel his a... ...ctims, because of fears for his safety... ...a cutback that, given the context, w... ...d to have itself generated equal and... ...mbrance days' are sometimes desig... ...the Holocaust genocide of Jews (se... ...he Darwinian cause of such racist a...

The goals of si... ...rogative of the harlot: power withou... ...those they try to influence. Muslim... ...00 "We dream of an entire Islamic ... ...le the world if the fundamentalists ... ...hat if they die fighting in a holy wa... ...bombers have been so prominent i... ...SA.

Equally real to... ...er, who argue, credibly, that Earth ... ...g meat. What

"WORLD HISTORY: A NEW PERSPECTIVE" by Clive Ponting

a review by Andrew R.B. Ferguson

ABSTRACT: The extent of the population explosion is apparent from just a few figures. By 1800, population had reached about 900 million. During the next century it expanded almost as much, by 750 million. During the following century, the twentieth, it grew by 4400 million. Clive Ponting's great book, *A Green History of the World*, did a great deal to explain this phenomenon, which receives further amplification in William Stanton's recently published book, *The Rapid Growth of Human Populations 1750-2000*. Another book by Ponting, *World History* (2000), adds a useful perspective, and indicates where our efforts should be directed in order to mitigate the consequences.

There were many things that David Willey, the founder of the *Optimum Population Trust*, and I agreed upon; one of them was the importance of Clive Ponting's *A Green History of the World*. We thought it explained more completely than any other book the essence of the human problem that is the focus of OPT concerns, namely the impact of humans on the environment and vice-versa. This admiration led me to take a look at one of Ponting's more recent books, published by Chatto & Windus in 2000, *World History: A New Perspective*. Its 900 pages are not so focused on OPT concerns as *Green History*, but it nevertheless contains thoughts which are pertinent to our concerns.

The need for a sense of time

One thing which any world history does is to give a sense of time in relation to human existence. For instance, the meaning of 10,000 years — one hundred centuries — is brought to life by considering the empires which have come and gone during the last few millenia of that period: Abbasid, Achaemenid, Assyrian, British, Byzantine, Carolingian, Gupta, Islamic, Jürchen, Khitan, Macedonian, Mauryan, Mongol, Mughal, Mycenean, Ottoman, Parthian, Roman, Russian, Sasanian, Safavid, Shaybanid, Soviet, Tibetan, Turkic, Uzbek.

The significance of time becomes apparent when the growth of many millenia is compared to human expansion in the last two centuries. By 1800 CE (Common Era, synonymous with AD), world population was about 900 million. The following century saw human population grow by 750 million — that is almost as much as it had grown since humans first appeared on Earth. By 1900, with world population reaching 1650 million, the world was approaching a maximum sustainable population for the Earth,{1} but far from the growth slowing down, during the twentieth century population grew by 4400 million, to extend far beyond a sustainable limit. This is explained in chapter 23 of *World History*, titled *The Modern World Economy*, which provides the same lessons as Ponting's earlier book, *A Green History of the World*, demonstrating that human impact already greatly exceeds the Earth's ecological capacity.

The hubris of the developed world

Another vital point emanating from *World History* is the hubris of the western world, in regarding its temporary ascendency as the way things ought to be. While the USA is notable for this attitude, it tends to pervade most of the developed world. The reality is that other nations, citizens of China and India in particular, have an almost undeniable claim to an equal share in the Earth's capacity to absorb carbon emissions (and the use of energy underlies the wealth of nations). For at times, the cloak of civilization has gleamed as brightly in other lands as it may appear to shine in the western world today. To support that assertion, let us turn to *World History* page 377:

> By the tenth century China was by far the most developed region of Eurasia. Its economy and society were based upon a free peasantry and a highly productive agriculture, especially in the south. The development of high-yielding varieties of rice, gravity- and machine-fed irrigation systems and machinery such as the seed drill meant that two crops a year and a substantial food surplus were produced. The majority of peasants were no longer subsistence producers but were active participants in the monetary economy through selling their produce. Much of the agricultural surplus was moved along the Grand Canal to the great cities which were the largest in the world. China was also the most urbanized country in the world. Technologically it was the leading region of Eurasia and had a monopoly in many key areas — cast-iron production, piston bellows, suspension-bridge construction, the compass and printing. The impact of the latter was dramatic as knowledge spread widely through society. The wealth of China was unmatched even in the Islamic world and the level of external and internal trade was higher than elsewhere in Eurasia. The cumulative impact of all these developments was crucial and China was on the verge of even more fundamental changes. It was to become the first society in Eurasia to escape from many of the constraints of the early agricultural societies. . . .
>
> It is now clear that China in this period was on the edge of economic and social changes that occurred in Europe some six hundred years later and which led to the so-called 'commercial revolution' and 'industrial revolution'.

So there is a need for the western world, and particularly the USA, to shed its hubris with respect to present industrial power. Perhaps almost as dangerous, though in more subtle ways, is an excessive confidence in the superiority of monotheism. Ponting, like Gibbon, views religion with Olympian detachment (p. 275):

> 'Paganism' was highly tolerant and accepted all beliefs. Until the early centuries CE monotheism was merely a Jewish peculiarity. The problem in considering the evolution of monotheistic beliefs — Judaism, its offshoot Christianity and the closely related Islam — is that because much of the world now follows the latter two beliefs, they are usually seen as an 'advance' of human understanding. However, from a wider perspective they can also be seen as lacking the philosophical subtleties of Buddhism and Taoism. In addition, monotheism poses a number of acute problems which are not faced by other religions and which have never been wholly resolved. In particular, if God is omnipotent why is there evil and suffering in the world? Christianity was also to be plagued by endless disputes over the exact relationship between God and his son, made even more difficult by the introduction of a third element the Holy Ghost. Overall, the worst, the most vicious and long-lasting disputes, wars and persecutions in world history have occurred within this family of religions.

Analysing the population explosion

With the help of *World History*, we can analyse the nature of the population explosion by comparing the present moment in time with the averages that obtained over the first millenium. On page 350, Ponting says:

> 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.

From those figures, we see that during the first millenium the average rate of population growth was 223 per million per year, whereas the Population Reference Bureau gives the world population growth rate in 2002 as 1.3%, or 13,000 per million per year. Thus one element of the population explosion is the part played by better nutrition and health; this element has multiplied the rate of growth by a factor of 58. The other element is the growth in the size of the population base — from 250 million to 6200 million. That is a multiplication factor of 25. Combining these, population is now growing (or exploding) 1400 times as fast as it was, on average, during the first millenium. In actual numbers that is an increase from 56,000 per year to 80 million per year.

It is not idle to separate out the two factors, for with our greater understanding of nutrition and the mechanisms of disease, it seems unlikely that disease will have as great an effect as it did during the first millenium; so the human race needs, through wisdom and culture alone, to be more effective even than Nature was during the first millenium; more especially as what is required now is not just to stop population growing, but to return it to a sustainable size — of two or three thousand million.{1}

The lead up to the population explosion

William Stanton's recently published book, *The Rapid Growth of Human Populations 1750-2000*, details the extraordinary story of population growth in recent centuries. For the preceding several millenia, we can make use of the thirteen *Overviews* which Clive Ponting inserts at appropriate points in his text. I take from *World History* items relevant to population growth and technological progress, since technological progress is a vital factor in the capacity of humans to make a disastrous impact on their environment.

* * * * *

1. The World in 10,000 BCE. Population: 4 million.
   - Retreat of major ice-sheets under way, Britain still joined to European continent. No North Sea or Baltic.
2. The World in 5000 BCE. Population: 5 million.
   - First agricultural settlements in Yangtze and Yellow rivers of China — pig and chicken domesticated
   - Earliest farming villages in the Indus valley
   - First agricultural settlements in Italy, the Balkans, Danube valley and Central Europe.
3. The World in 2000 BCE. Population: 27 million.
   - Indus valley civilization at its peak
   - Farming villages across Europe
   - Spread of maize cultivation across Mesoamerica. First agricultural villages in the Americas
   - Early potatoes domesticated in the Andes.

4. The World in 500 BCE. Population: 100 million.
   - ■ First production of cast iron in China
   - ■ Metal goods (gold and copper) made in Peru
   - ■ Iron working in west Africa.
5. The World in 150 CE. Population: 180 million.
   - ■ First water mills in use across Eurasia
   - ■ First use of paper in China
   - ■ Compass in use in China.
6. The World in 600 CE. Population: 200 million.
   - ■ Rice cultivation across southern Japan
   - ■ Iron cables for suspension bridges in China
   - ■ Horse collar used in China
   - ■ Stirrup widely used in China, Central Asia and India
   - ■ Paper used in Korea and Japan
   - ■ Secret of silk production taken from China to Levant
   - ■ Heavy plough used in Europe.
7. The World in 750 CE. Population: 220 million.
   - ■ First wood block printing in China, Korea and Japan
   - ■ Paper manufacturing established in Islamic world
   - ■ First use of stirrup in western Europe.
8. The World in 1000 CE. Population: 265 million.
   - ■ First gunpowder weapons in China

■ Paper money in China

■ Paper first used in Islamic Spain

■ First tidal mill at Basra, increasing use of water-mills in western Europe and windmills in Islamic world

■ Horse collar used in Europe

■ Maize cultivation reaches north-east America.

9. The World in 1200 CE. Population: 360 million.

■ Multi-colour printing in China

■ European ships adopt Chinese stern-post rudder and compass

■ Horizontal axled windmill in western Europe

■ First bronze and metal weapons in Andes.

10. The World in 1400 CE. Population: 350 million.

■ Movable wooden type used in China

■ Movable metal type developed in Korea

■ First production of cast iron in Europe

■ First manufacture of paper in France, Germany and Italy.

11. The World in 1500 CE. Population: 440 million.

■ Early printing in Europe

■ First production of paper in England.

12. The World in 1700 CE. Population: 610 million.

13. The World in 1900 CE. Population: 1625 million.

* * * * *

A Green History of the World remains the pre-eminent book about human impact on the environment and the impact of the environment on humans; but Clive Ponting's recent World History, and William Stanton's The Rapid Growth of Human Populations 1750-2000, throw further light on the nature of the problems foreseen by Thomas Robert Malthus two hundred years ago, and by John Stuart Mill a century and a half ago. Since then, the prevailing consensus world view has been based on a grand delusion, similar in kind, but even more devastating in consequences, to those described by Charles Mackay in Extraordinary Popular Delusions and the Madness of Crowds (e.g. the Church's belief in witchcraft and the righteousness of the Crusades). The delusion this time is that technology can solve all problems — permitting perpetual growth. In the past several decades, David Pimentel of Cornell University has been in the vanguard in explaining the fragility of the system which is presently supporting so many humans, namely the use of fossil fuels (most notably with a 1979 book, revised 1996, written with his wife Marcia Pimentel, Food, Energy, and Society). Colin Campbell, with his books The Coming Oil Crisis (1997) and The Essence of Oil and Gas Depletion (2003), has been pre-eminent amongst those who are striving to show the world that the majority of petroleum geologists are unlikely to be wrong in their estimates of the demise of oil and gas. They say this will certainly occur within the present century and shortages are imminent. The question is whether this perspective can be made to pervade the thinking of the media, economists and politicians. There is room to doubt this, since human nature has probably not changed from when Thucydides, 2000 years ago, put these sentiments into the mouths of some Athenian envoys:

Our opinion of the gods and our knowledge of men lead us to conclude that it is a general and necessary law of nature to rule wherever one can. This is not a law that we made ourselves, nor were we the first to act upon it when it was made. We found it already in existence, and we shall leave it to exist for ever among those who come after us. (The Peloponnesian War, Book Five)

In updated terminology, William Stanton argues something similar. He says that Darwinism (survival of the fittest) has always ruled, except under the unusual circumstances of the past couple of centuries, during which the restraints on growth have been weak because the exploitation of fossil fuels has produced abundance.

Endnote

{1} Sustainable world population refers to the number of people who could enjoy a modestly comfortable lifestyle. Note I say that the world was approaching its carrying capacity at the start of the twentieth century. It was around 1940 that the world population actually reached an approximate safe limit of 2100 million; this is a limit set by carbon emissions, but there are other reasons. For more details see Perceiving the Population Bomb, in the OPT Newsletter, September 2001, which is archived at www.members.aol.com/optjournal2/optj1.doc.

By 1965, at the latest, it was evident that the compound growth of human numbers would lead to crisis within the lifetime of the newly born. In the 1970s, it was brought home to the world that our civilization was dependent upon oil. David and Marcia Pimentel were surely not alone in detailing, in 1979,{1} how easy access to energy has enabled humans to explode, in a manner unprecedented through 10,000 years of civilization. Yet neither media pundits nor governments have brought this to the public attention, and when goverments have required Commissions to report, they have subsequently ignored the recommendations of those Commissions. The following extracts show that history is replete with examples of such folly.

THE MARCH OF FOLLY: FROM TROY TO VIETNAM

by Barbara W. Tuchman{2}

p. 4 A phenomenon noticeable throughout history regardless of place or period is the pursuit by governments of policies contrary to their own interests. Mankind, it seems, makes a poorer performance of government than of almost any other human activity. In this sphere, wisdom, which may be defined as the exercise of judgement acting on experience, common sense and available information, is less operative and more frustrated than it should be. Why do holders of high office so often act contrary to the way that reason points and enlightened self-interest suggests? Why does intelligent mental process seem so often not to function?

p. 5 Misgovernment is of four kinds, often in combination. They are: ... (4) folly or perversity. This book is concerned with the last in a specific manifestation; that is, the pursuit of policy contrary to the self-interest of the constituency or state involved. Self-interest is whatever conduces to the welfare or advantage of the body being governed; folly is a policy that in these terms is counter-productive.

p. 209 Insistence on a rooted notion regardless of contrary evidence is the source of self-deception that characterizes folly. By hiding reality, it under-estimates the needed degree of effort.

p. 234 The question raised is why did the policy-makers close their minds to the evidence and its implications? This is the classic symptom of folly: refusal to draw conclusions from the evidence, addiction to the counter-productive.

p. 380 If pursuing disadvantage after the disadvantage has become obvious is irrational, then rejection of reason is the prime characteristic of folly. According to the Stoics, reason was the ‘thinking fire’ that directs the affairs of the world, and the emperor or ruler of the state was considered to be ‘the servant of divine reason [appointed] to maintain order on earth.’ The theory was comforting, but then as now ‘divine reason’ was more often than not overpowered by non-rational human frailties — ambition, anxiety, status-seeking, face-saving, illusions, self-delusions, fixed prejudices. Although the structure of human thought is based on logical procedure from premise to conclusion, it is not proof against the frailties and the passions.

p. 386 In America, where the electoral process is drowning in commercial techniques of fund-raising and image-making, we may have completed a circle back to a selection process as unconcerned with qualifications as that which made Darius King of Persia [between the contenders, he was chosen by the fact that it was his horse which neighed first].

{1} Pimentel D, Pimentel M. 1979. *Food, Energy, and Society*. New York, John Wiley and Sons.

{2} *The March of Folly: from Troy to Vietnam*, 1984. Barbara W. Tuchman. United Kingdom, London: Michael Joseph Ltd.

The first extract below is taken from a letter to the *Scotsman* by James P. Duguid (15th October 2003). He gives some reasons for not cluttering our countryside with wind turbines. Edmund Davey circulated an article from *Reader's Digest*, by John Dyson, November 2003, titled *Tilting Against Windmills*, from which I give an extract. Next are some further thoughts of my own. However note that this is a simplified exposition. The fairly obvious weaknesses arising from the simplification are tackled in the accompanying paper, *The Meaning and Implications of Capacity Factors*.

LIMITS TO WIND POWER

by James P. Duguid, John Dyson, and Andrew R.B. Ferguson

Abstract

Wind is only one of several 'time-dependent' renewable energy sources. If wind were to be used by itself, then it could provide 20% of the electricity supply in the UK without causing problems. This 20% could easily be supplied by offshore wind turbines. It is noted, too, that this 20% would save only 7% of current UK fossil fuel consumption.

Since the other sources of renewable energy are also time-dependent, were they also to be used then the part that wind could play would have to be reduced accordingly. So the variable output of renewable energy sources is an intractable problem.

This is what Jim Duguid said in the *Scotsman*:

> Spoiling countryside with the turbines, power lines and access roads of wind farms will have almost no effect in checking global warming. Only about a third of our use of fossil fuels is for the production of electricity, and it would not be feasible or safe to depend on wind to generate more than about a fifth of our electricity. Because there are many times when the wind is too weak for generation, the output from it needs to be covered by instantly available fossil fuel generators, which stand idle at other times.
>
> The cost, materials and input of fossil-fuel energy required to construct and maintain wind farms is thus increased by the requirement for the construction and maintenance of the back-up generators.
>
> Offshore wind farms could easily provide the maximum feasible amount of wind electricity. Onshore developments should be stopped. Their promotion seems to be just a sop to poorly informed environmentalists.

The *Reader's Digest* article contained facts which tend to support Jim's assertion. This is what John Dyson had to say:

> As long as the wind-power feeding into a system is minor — as in the UK, where it is currently three and a half per cent — existing power stations have the flexibility to cope with day-to-day, hour-by-hour fluctuations. But once dependency on wind is high, the problems can become acute, as in Denmark.
>
> In the Danish town of Fredericia, Henning Rasmussen sits in the control room of a transmission system operator, balancing the input of wind energy with demand for power. "In strong winds, our windmills provide as much as five power stations," he says. "But when the wind arrives one or two hours later than forecast, we get nothing and we have to ask our neighbours to save us." Rasmussen gets on the phone to negotiate extra power from Nordic countries and Germany. Ironically, this means that Danes often use hated

> nuclear power from Sweden and Finland. When there's too much wind, surplus power is given away. "A couple of years ago, we even had to pay Sweden to take it," says Rasmussen. "It was crazy."
>
> Germany, with up to 15 per cent of its power now wind-generated is approaching the same threshold. For the moment, it's buying balance power on the market — at up to 20 times the wholesale cost — and selling surplus power very cheaply.
>
> But what happens when the wind dies and the windmills stop?" asks Helmut Alt, science engineer at RWE, one of Germany's largest utility companies. Most of Europe can lie under high-pressure with not a breath of wind for days. In winter these conditions bring frost and fog, so demand for heat and light soars. The only thing power companies can do is bring conventional systems back into play, "Even if the wind fails to blow for no more than one hour a year," Alt says, "we can't afford to shut down existing plants."

The inveterate wind enthusiast might still argue that these constraints are only economic, and that although it is true that while fossil fuels are cheap the open market cannot tolerate a system in which wind power has to be backed up by alternative generating capacity, things will change once fossil fuels become really expensive, or if governments have the foresight to see that this is going to happen and so take steps to influence the market to give wind power the advantages necessary to make it happen. In such cases, the enthusiast would say, wind power will achieve the great things planned for it, supplying at least half of our electricity. Could this be right?

As a first cut at analysing what might be possible in dealing with variability, we can look at a system in which wind power is never allowed to go to waste, on account of more wind power being available than is required (which could occur during periods of low demand). It could be argued, that such an assumption is misleading, even as a rough approximation, for two reasons: (a) that the excess power could be stored; (b) that the wind capacity could be increased without losing a significant amount of the energy generated. Storage is a problematic field in itself, with respect both to quantity and cost. One oft-mooted possibility is to use the energy carrier hydrogen. That is treated on pages 26-29. The second possibility, a straight increase in capacity, is treated on page 23, section 8. The simplified assumption that we are making here will suffice for present.

The idea is easier to keep track of if we take some illustrative figures. Let us suppose that the power demands of a " Community," as we shall call it, sometimes drops to 1 GW (gigawatt or 1 x 10^9 watts). That means that there is a base-line demand for energy, over the year, of 1 GWyr (i.e. 24 x 365 gigawatt hours). However, most of the time the power demand would be more than this minimum, and sometimes it would rise to a far higher figure than 1 GW, say during the break in some favourite TV program in the middle of winter.

We now need a datum. Unfortunately it can only be an estimate (see *The Meaning and Implications of Capacity Factors* for details), but it seems likely that over the year the total demand for energy would be not 1 GWyr, but rather 1.5 GWyr. In other words, we have assumed that because power demand is not always flat at the lowest level throughout the year, total energy consumption is 50% higher than it would be were power consumption to remain always at the lowest level.

As already explained, the simplified view we are taking of the wind system is that the output from the wind turbines, when the whole system is operating at its rated capacity, should not exceed the minimum demand for power, namely 1 GW. That is not the only assumption that could be made (see page 23, section 8), but were the Community to build 1

GW of capacity (together with the 1 GW of alternative supply for when the wind was not blowing), how much of its demand for electrical energy would be satisfied by wind?

Throughout Germany, the Netherlands, Denmark, and Sweden, the capacity factor (proportion of rated output which is delivered to the grid), averaged over a two year period, was 22% (OPTJ 3/1, April 2003, p. 4). There are indications that were the slightly windier UK to keep such detailed records, the equivalent figure would be about 25%. Offshore capacity factors are somewhat higher; 30% would be in the right ballpark, so let us use that figure, and thus conclude that the wind turbines would actually deliver to the Community, each year, 0.30 GWyr of electricity. The alternative system would need to supply not only the remaining 0.70 GWyr, but also the 0.5 GWyr for when demand rose above the lowest level. Thus the wind system, which the Community has built, would supply 0.30 / 1.50 = 20% of its total electricity demand. As Jim said, only about a third of the fossil fuel we consume is used to produce electricity, so the saving in fossil fuels would be 0.20 x 0.33 = **7%**. One can sympathise with the strong feelings aroused by those who see their landscape being degraded, when the end goal is only a 7% reduction in fossil fuel use.

But is there a relatively painless solution, as Jim suggests? Could there be sufficient offshore wind power available in the UK for us to be able to avoid the blight of wind turbines situated on every hill? The facts are available and the indisputable answer is Yes.

The Department of Trade and Industry (DTI), in their *Wind Energy Fact Sheet 1*, dated June 2001 gave data to show this to be true. Indeed they show it to be true with such an easy margin to spare, that there is no need to update their figures. We can accept their figure for UK electricity demand as being about 300 TWh (300 x 10^{12} Wh). Then, from their table of "**Estimated practicable offshore wind resource**", we can note the overall figure of 100 TWh, and conclude that there would be sufficient *offshore* wind to supply 33% of the UK electricity demand (were it not for the 20% cut-off which we calculated a couple of paragraphs ago.

It is possible to analyse the situation in more detail, because the DTI's table breaks down the practicable offshore wind resource according to distance from the shore.

Let us look first at the 'near shore' category of wind turbines, those which could be situated no more than 10 km from the shore. The table estimates that 49 TWh would be available from these turbines. So they alone would supply 16% of the UK's electricity supply, leaving only 4% to be covered by turbines situated in the next distance category, 10-20 from the shore. 36 TWh is shown to be available from that category. Moreover we would only need to use a third of it to get to the cut-off limit of 20% of UK electricity demand. We certainly have no need to broach the last category, 20-30 km from the shore.

Thus we have reached our first conclusion, namely that all those who are striving to save our onshore landscape from being peppered with wind turbines have an overwhelmingly strong case, for all that needs to be done can be covered by offshore turbines.

Other time-dependent renewable energy sources

Important though that conclusion is, OPT's main concern is to look ahead to the fairly imminent time when fossil fuels become scarce; so let us go on to ask whether the situation could be alleviated by some of the other time-dependent energy sources. Note that the only renewable energy source which is not time-dependent is biomass, but that suffers from problems of low net energy-capture, which we will not dwell on here.

It is sometimes proposed that wind should be considered as only a part of the 'renewable energy solution', because there are hopefuls on the horizon, including tidal power, solar power, and wave power. We must first observe that solar, in the guise of photovoltaics, is even more of a problem than wind, for its capacity factor (the amount of energy it produces as a fraction of what it would produce operating at maximum capacity) is only 14% even in fairly sunny locations such as Spain, compared to wind's 22-35% (again depending on location). It is likely that tidal power would have a higher capacity factor than wind, and also, were wave power to prove viable, that a considerably higher capacity factor could be achieved. However, none of that makes much difference, as can be illustrated with a simple example.

Suppose that tidal power had a significantly higher capacity factor than wind, as well as favourable economics, inducing us to enhance the part it plays in the renewable energy mix, even to the extent of fulfilling half of the 20% of total electrical supply that we have seen as the cut-off limit for wind. Overall that would improve things slightly, but only slightly, because, in order to prevent the maximum output of wind from exceeding the lowest level of demand, we would need to halve the part that wind plays, from 20% to 10%. In other words, if there is to be supplementary power from other time-dependent sources, this strengthens the argument of those who say that all useful wind energy could be generated offshore. Perhaps it should be stressed again that we are presently excluding the possibility of storage.

Let us meet another objection which is likely to be raised. The point might be made that, when spread over a large area, the wind turbines would never, even for a short time, produce anything like 100% of their rated capacity. This is a valid point, but not one of tremendous significance. It brings the maximum output of the system down, allowing us to build more turbines while still keeping under the base-line figure for electrical demand. The effect is useful as it reduces the gap between the maximum output and the actual output. However, the effect is not so great as to invalidate the above as a general analysis. The matter is treated in greater detail in the next paper, *The Meaning and Implications of Capacity Factors*; an even more sophisticated analysis is available in the paper, *Wind/biomass Energy Capture: an Update* (OPTJ, 3/1, April 2003. pp. 3-10), but whether such a sophisticated analysis is really necessary is a moot point.

Another objection might be that we are presently spoilt by having electricity on demand, and that in future we will need to accept the need to adjust our use of electricity so that demand more closely matches supply. There is some truth in that, but a sophisticated analysis would be needed to account for it, and worse, such an analysis would require some largely speculative assumptions. Thus we can take this analysis as a useful first cut at the essence of the problem of variable but non-flexible supply. Those who are trying to tell us that renewable energy is likely to solve the world's energy problems (e.g. *New Scientist* and the *Worldwatch Institute*), need to come up with figures showing to what extent there may be relief on account of possible variations in demand.

Conclusion

The function of OPT is mainly to persuade society to look ahead to the not-so-distant future, when fossil fuels become scarce. This paper is one of many which show that we are living in cloud-cuckoo-land if we think that renewable energy is going to support the large population which has been made possible by abundant supplies of fossil fuels.

THE MEANING AND IMPLICATIONS OF CAPACITY FACTORS

by Andrew R.B. Ferguson

Abstract

In general terms, 'capacity factor' means the amount of energy that is actually produced — or alternatively delivered — measured as a proportion of the capacity which a specified plant, or group of plants, has to transform energy. The fact that even offshore wind turbines achieve a capacity factor of only about 30% means that wind is unlikely to contribute more than 17% to 29% of electricity demand, which implies wind could satisfy only 6% to 10% of current UK total energy demands. Corollaries are that (a) sufficient wind turbines could be installed offshore without placing any onshore, and (b) we cannot escape from the need to reduce populations to match future carrying capacity. It is also noted, in passing, that wind turbines may not actually reduce natural gas consumption (and therefore not reduce emissions).

Jim Duguid, a pillar of strength in OPT, and author of the booklet, *Population, Resources, and the Quality of Life*,{1} suggested to me that the concept of 'capacity factors' could do with some amplification. A more sophisticated treatment of capacity factors is to be found in *Wind/biomass Energy Capture: an Update*,{2} but there is clearly a need for a simple exposition of the capacity factor concept, especially as it is the foundation of much of OPT thinking on renewable energy, so I have been pleased to accept his suggestion. This attempt at a simple exposition has been made with the help of Edmund Davey and other OPT members.

When used in the context of energy, there is no difficulty with the idea of 'capacity' (more fully called 'rated capacity'). When you buy something, whether it is a car, or an industrial-scale electricity generating plant, you need to know what it is capable of. For cars, the performance of the engine would be expressed in terms of horsepower or kilowatts (1 kW = 1000 watts); for power plants the measure would be in megawatts (1 MW = 1 million watts). In neither case does the claimed capacity imply that the device is likely to be run at that capacity day in and day out. But it could. Hence it has a 'capacity' (or 'rated capacity') for doing work, at least in theory, although in practice that is unlikely to be attained. 'Rated capacity' is not exactly the same as 'maximum capacity'. For example, an aircraft engine has a 'rated capacity', at which it can be operated without restriction, but there is a higher capacity which can only be used for short periods of time — during take-off for instance. Similarly wind turbines have mechanisms to feather their propellers well before they become likely to fly off!

1. Capacity factor applied to photovoltaics

With regard to energy production, what sometimes concerns us as much as the capacity is the proportion of the capacity that is captured in day-to-day operation — or *alternatively* it is the proportion actually fed to the grid. Perhaps the simplest case study is photovoltaics, so let us start by considering the 'capacity factor' of photovoltaics (PV). It may be useful at this stage to try to get hold of the preliminary essence of a useful definition of the term 'capacity factor'. It is the amount of energy that is actually produced or *alternatively* delivered (in either case averaged over a sufficient period of time to be representative) as a fraction, or percentage, of the rated capacity. The 'sufficient' period of time over which the assessment is made is not critical provided it is long enough to be representative. For instance, measuring the output from a photovoltaic array over one year would suffice unless the amount of sunshine in one year varied greatly from another year. Measurements at Toledo, Spain, where the most thorough investigation of PV took place, continued over four years. The results indicated that a single year would provide a useful guide.

PV capacity is measured with a bright light illuminating a panel at 1 kW per square metre. It is the output under these conditions which is normally announced in the media when they tell you about a new installation. A typical output from 1 square metre of module under 1000 W/m^2 illumination is about 140 watts (depending on the quality of the module). However, realists ask the question: Well yes, but the sun does not produce 1 kW/m^2 day and night, so how much of that potential capacity is actually produced? The answer is that, in a sunny place like Spain, the 'capacity factor' is about 14% (you may like to note that 14% of 140 watts is 20 watts, and 20 watts is about 10% of the 200 W/m^2 insolation in Spain. Actually it is a general rule of thumb that PV modules, suitably oriented to catch the sun, capture about 10% of the insolation that would fall on a horizontal plate of the same area). If the level of insolation — the energy from the Sun — is less than in Spain, then the capacity factor will be proportionately less (although the proportion of insolation will remain the same at 10%).

There is another way to look at the capacity factor of photovoltaics. Starting from the point that rated capacity is measured at 1000 W/m^2, at first cut we would expect the mean power from the sun at Toledo, 200 W/m^2, to produce one fifth, 20%, of rated capacity. But out of doors the insolation is often hitting the panels at a less than ideal angle and intensity; also there will at times be some dust on the surface of the panel. These factors reduce the output to about 70% of what one would otherwise expect, with a resultant output of 20% x 0.70 = 14% of the rated capacity. This will remain true whether the modules are high efficiency ones with, for example, 14.3% efficiency, or roof tiles with about 7% efficiency. *Capacity factor is related to insolation*, thus 100 W/m^2 would halve the Toledo capacity factor.

That seems nice and simple, but it does hide a few complexities. Is the 14% the proportion which gets fed into the grid? This needs to be asked, since as the sun goes in and out it may not be easy to make use of all the energy produced by the PV. For instance, if the operator anticipates that it will remain cloudy, and thus orders more power from the fossil fuel generators, that order will not be cancelled because the sun comes out occasionally. We will deal with this problem again in the context of wind. Indications were that 14% of capacity was the amount that was actually fed into the grid (from the experimental arrays at Toledo, Spain). The exact figure is not that important, because 14% is so low that it immediately tells us that photovoltaics are not going to be much use. However, we will leave further details on short term variability to our next consideration**,** wind power, for that introduces a clearer insight into the extent of this problem.

2. Capacity factor applied to wind turbines

The Netherlands, Denmark, Germany and Sweden keep detailed records of the output of their turbines. Over a couple of years, taking these nations together, the turbines produced 22% of their rated capacity. The report made it appear pretty certain that this 22% represented what was actually fed into the grid. What are the factors that reduced the output from the full capacity? The obvious one is that the wind does not always blow at the optimum strength. Also wind turbines need a certain amount of maintenance and so are sometimes out of use. Another factor is that to actually use the electricity, those controlling the grid require some warning of what is coming their way. When the UK introduced a requirement that those supplying electricity from wind power should forecast what they can guarantee to supply four and a half hours in advance, this alone sufficed to drop their delivered output by 14%, e.g. if the initial output was 25%, then the delivered output would be 0.25 x 0.86 = 22%. So which of these is the ‘capacity factor’? The answer is that either can be referred to as the ‘capacity factor’ — 25% or 22% — provided you make your meaning clear. That provides the explanation for our use of the word *alternatively* in the definition attempted above.

3. Capacity factor applied to nuclear plant

Let us next consider the capacity factor of nuclear plant. The National Grid Company lists the response time of nuclear plant as 48 hours. Once a nuclear power plant has been started up, the most efficient way to operate it is to allow it to produce at its rated capacity, limited by the need for maintenance (including replacing fuel rods). Due to necessary ‘downtime’ a nuclear generator is likely to produce about 80% of its rated capacity, that is to say achieve an 80% capacity factor. However, it could be that because electricity is being produced more cheaply from gas-fired plants, the nuclear operator has difficulty selling all the electricity produced. In that case, the operator may decide to shut down and do some maintenance, hoping for better electricity prices. Thus, besides such things as hairline cracks in cooling pipes, there are several reasons why the capacity factors might be lower than 80%; in fact it was much lower for many years. So it is always necessary to provide background information to clarify the framework within which any reported capacity factor has been achieved.

4. Fluctuations in output and demand

Wind systems not only have a low capacity factor due to the uncontrollable fluctuations of their output, that is they are *variable*, but to an even greater extent than nuclear they are *non-flexible*, for one cannot persuade the wind to blow when it is needed.

A sensibly designed energy program would attempt to ensure that all the available energy from both sources is used. This has enormous implications in the case of wind because the output is variable. Let us consider a widely spread wind turbine system with a capacity factor of 22%. The wide spread makes it unlikely that the whole system will, at any time, produce more than 80% of its rated capacity (by the same token it is unlikely that the whole system will produce *no* electricity even when conditions are generally calm). But since the whole system is only going to produce 22% of its rated capacity, rather than 80%, there is a shortfall of 58% of rated capacity which has to be filled by flexible plant — that is plant with a demand-following capacity. As we shall see, in practice that means fossil-fuel-fired plant. Figure 1 (p. 25) helps to explain that, and the relationship between power and energy.[{3}] So far we have been making the analysis in terms of *mean power*. Let us deal with the same ideas in terms of *energy* (see below for a further discussion of energy units). Were wind turbines with a total 100 GW (1 gigawatt = 10^9 watts) rated capacity able to run at 80% power through the year, they would produce 80 GWyr of electricity. But because their capacity factor is 22% they produce only 22 GWyr of electricity. Thus flexible plant would have to produce the remaining 58 GWyr of electricity.

There is an important point to note here, which is immediately apparent from looking at the middle section of Figure 1. *So far*, all we have required the demand-following plant to do is to compensate for the variability of the wind turbines. The aim is that working together the wind turbines and fossil-fuel plant should produce a constant output. There is another variability which has to be dealt with, namely the variability of demand, which changes with the time of year and the time of day (the top section of Figure 1). To deal with that, we again need the demand-following capability of fossil-fuel-fired plant. In the renewable energy sector, the only truly demand-following — that is flexible — energy source is biomass.

5. Capacity factor of fossil fuel plant

So how about the capacity factor of fossil-fuel-fired plant? There are several things which will affect its capacity factor: (a) how much of the demand is being taken up by wind and other inflexible generating systems; (b) how much spare capacity has been built into the system to meet combinations of unusually high demand with an unusually high proportion of generating plant being out of service; (c) the extent of the market demand for the energy at the price at which it is being offered by a particular plant.

By now, we have seen that while there is a common thread running through the concept of the capacity factor of a plant, it is necessary to have a background understanding of the differences between types of plant. For instance, one might have an old gas-fired plant which is kept in reserve for no other purpose than selling electricity at about twenty times the normal price when demand is so exceptionally high that those running the grid are starting to tear their hair out! The low capacity factor of that plant would say nothing about its commercial efficiency. A low capacity factor becomes a problem with plant which has a *variable* but *inflexible* output, as explained below.

6. The implications

Now that we have a thorough grasp of the range of meaning of ‘capacity factor’, we can study the implications. Wind is generally accepted as the most promising source of renewable energy, but photovoltaics are often mentioned, and the possibility of tidal energy is mooted. All three provide variable but non-flexible power. Note that their power is *variable* but not *flexible* so as to satisfy human dictates. Were we to attempt to combine all three, we would need to consider the *mean* capacity factor of the particular mix we had selected. But since PV has such a low capacity factor, and since significant quantities of tidal energy is more of a hope than a fact, it will suffice to confine our attention to wind power; anyhow wind will establish the principle.

It is easier to grasp the notions if we consider some actual figures, and since we are only concerned with proportions, it does not matter if the figures are right in absolute terms. Let us therefore consider that the low point of power demand during the year, in say the UK (although the figure is not realistic for the UK), is 100 GW (100 billion watts). That means that we can say with certainty that every year there will be a demand for at least 100 GWyr. Since a GWyr is a somewhat unfamiliar unit of energy, let us observe that 100 GWyr = 100 x 365 x 24 = 876,000 GWh; or if you are only happy with the most familiar measure of energy, namely the kilowatt hour (kWh), 876 billion kWh; but remember the actual figure is not, and does not need to be, right.

Let us now suppose that nuclear power is capable of providing a steady output of 25 GW, i.e. 25 GWyr each year. That leaves only 75 GWyr of guaranteed demand each year for the wind to attempt to fill.

As we have already observed, wind turbines spread over a wide area will never produce 100% of their combined rated power because the wind will not be blowing everywhere at optimum strength. It is probably in the ball park to say that an extensive system, as a whole, will never produce more than 80% of its total rated power (or of its 'rated capacity' if you prefer). Thus we could order turbines with a total rated capacity of 75 / 0.80 = 94 GW, without risking the total output of the turbines going to waste because output was exceeding demand (see section 8 below for variations on this).

We now need to decide what capacity factor the wind turbines are likely to produce. If we place most of them offshore, then a capacity factor of 28% (over at least a year) would be in the ball park. Thus the 94 GW of rated capacity would actually deliver 94 x 0.28 = 26 GWyr each year.

Above the level of lowest demand, there is a variable demand, occasioned by human interaction with the environment, driven by such desires as keeping warm in winter and cold in summer and sleeping at night and working by day (the top section of Figure 1).

As a rough estimate, we can say that above the lowest demand (i.e. the guaranteed requirement), there is a variable demand for energy amounting to about 50% of the lowest level of demand (see Figure 1 to visualize this). This is an estimate, but reasonably well supported by indicative data. That means that the total energy required in the scenario we are analysing would be 150 GWyr each year. Of this, nuclear would produce 25 / 150 = 17%; fossil fuel would have to produce (75 - 26 + 50) / 150 = 66%; and wind would produce 26 / 150 = 17%.

It may be rather a shock that the best we can hope for — on this preliminary analysis — from wind power is to contribute 17% of our electricity supply. But it is important that we appreciate this to be the case, because, in conjunction with even a cursory examination of the offshore wind capacity available, it proves the thought raised by James Duguid, that there is no need to cover the UK landscapes with wind turbines, since there is plenty of available space offshore to install all the wind turbines that we could make use of — namely sufficient to supply 17% of our demand for electricity. We should also note the other point he made, namely that since only about 35% of fossil fuel is used to produce electricity, the saving in fossil fuel would be 0.35 x 0.17 = 6% of total fossil fuel use.

7. Storage

One thing we have not covered is the possibility of storing electricity produced by the wind turbines in the form of hydrogen. Transformation efficiencies immediately suggest that this is problematical. Transforming electricity to hydrogen gas is about 70% efficient, and using expensive fuel cells to change the hydrogen to electricity, including inverting the DC current to AC current, is unlikely to be more efficient that 60%, thus the combined efficiency is 0.70 x 0.60 = 42%. So it would be necessary to go to the expense of producing about 2.4 times as much electricity as could eventually be delivered from storage. Nevertheless there is a widely prevalent belief that the process would become viable with sufficient technological effort. For this reason, the problems are looked at in depth in a separate paper, *Hydrogen and Intermittent Energy Sources*, pages 26-29.

8. A plausible objection concerning wind variability

An objection which has some plausibility is that there is no need to be fastidious about keeping the likely total output of the wind system below the level of minimum demand for power. Indeed it may be obvious, looking at Figure 1, that we could go a bit higher without often getting into the situation where wind was being generated to excess, and thereby wasted. Let us therefore consider what would happen if we went so far as to increase the maximum probable wind output (of the group of turbines) to the level of mean power demand (which we are assuming in our example to be 150 GW). That means we are going to try to fill as much as we can of 150 - 25 (nuclear) = 125 GW with wind power.

On the same basis as before, we might anticipate never getting more than 80% of rated capacity from the wind system, and therefore install 125 / 0.80 = 156 GW of wind capacity. At 28% capacity factor this would produce 156 x 0.28 = 44 GW of power. 44 GW is 44 / 150 = 29% of the total electricity consumption. However, wind would not actually satisfy exactly that proportion of the energy demand, because some wind energy would go to waste when high winds coincided with low demand. Little more than that can be said about wind energy wastage, until someone models several typical years of wind output and ascertains just how much would go to waste.

What can be said is that the fossil fuel electricity which wind might supplant lies within the bracket of 17% to a theoretically possible 29% of electricity demand. At the 29% figure, this would satisfy 29 x 0.33 = 10% of our fossil fuel demands.

9. Will wind turbines significantly reduce the consumption of natural gas?

Both the UK and the United States will, within the next couple of decades, be heavily dependent on imported gas, so we might ask the question whether wind power will substantially reduce this dependency. The surprising answer is maybe not.

Fred Starr, of *European Technology Development Ltd*, says in a paper available on the web, that combined cycle gas turbine (CCGT) generating plant is extremely good at turning chemical into electrical energy. Currently about 50% efficiency is achieved, and he says the best run at an efficiency of 60%; moreover he estimates that 70% will be possible by 2020. The problem is their response time. The older style of gas generator has a response time of about 2 minutes, whereas CCGTs, which work in conjunction with Heat Recovery Steam Generators, have a response time of 6 hours (figures from the National Grid Company). The reason is their complexity. Starr says, "it is reasonable to claim that CCGT type gas turbines are more sophisticated than the best military jet engines." Also they are liable to be damaged by constant changes in output, and they are very expensive to repair.

It is very difficult to use CCGT plant in combination with wind power, the output of which, as the Danes and Germans have discovered, can vary enormously during the course of a day. It thus becomes possible that more gas will be saved by foregoing wind power and using CCGT plant than using wind power and foregoing CCGTs. According to our previous wind analysis, to fill *a* specified *constant power* demand, we could increase the rated capacity of the wind turbines to 1 / 0.80 = 1.25 of that demand. Assuming a capacity factor of 28%, this would allow the wind to fill 1.25 x 0.28 = 35% of the demand (with the rest being satisfied by the older style of gas turbine, which operate at about 40% efficiency). This 'wind option' would thus save 35% of the gas that would otherwise be used. However, the 'CCGT option' would, at present efficiency, save 20%; at 60% efficiency it would save 33%; and at 70% it would save 43%.

10. Biomass

Another thought which occurs to people is that there is one form of renewable energy which could be demand-following, namely biomass. The trouble with biomass is low energy-capture (the amount of energy that can be captured per hectare per year). In order to replace a 2000 MW power station which is operating at 50% capacity factor, and thus producing 1000 MWyr of energy each year, would require an area of forest of 15,150 km^2 or 76 miles by 76 miles Being able to satisfy that requirement in Britain is out of the question in view of this information taken from Jim Duguid's booklet, page 48:

> With 10% of its own land under forest and woodland, the UK in 1995 produced about 7 million cubic metres of wood a year. Production is rising and is expected to peak at 15-20 million cu.m. a year by 2025, but that output would be only a third to a half of its present rate of consumption.

So even with the currently negligible demand for fuel wood, the UK cannot produce enough timber to supply its population, which leaves no chance for it to produce adequate biomass to burn as fuel to produce electricity.

11. Conclusion

Britain is not likely to drop off a precipice with energy supplies, but by 2020, it will be importing about 80% of its natural gas, often across insecure terrain, and by that time oil will at least start to become expensive. Our nuclear future is speculative, but anyhow limited in time. Neither is it likely to be easy to restart the UK coal industry, with the best seams having already been exploited and additional difficulties with using it because there will most likely be a requirement to burn coal with greater attention to capturing its pollutants.

Taking all these factors together, OPT sees clearly that the UK should have started a long time ago to reduce its population to about 20 million, a level which might be sustainable with mainly renewable energy resources. The United States is importing 60% of its oil and 17% of its natural gas and needs to reduce its population to about 200 million.

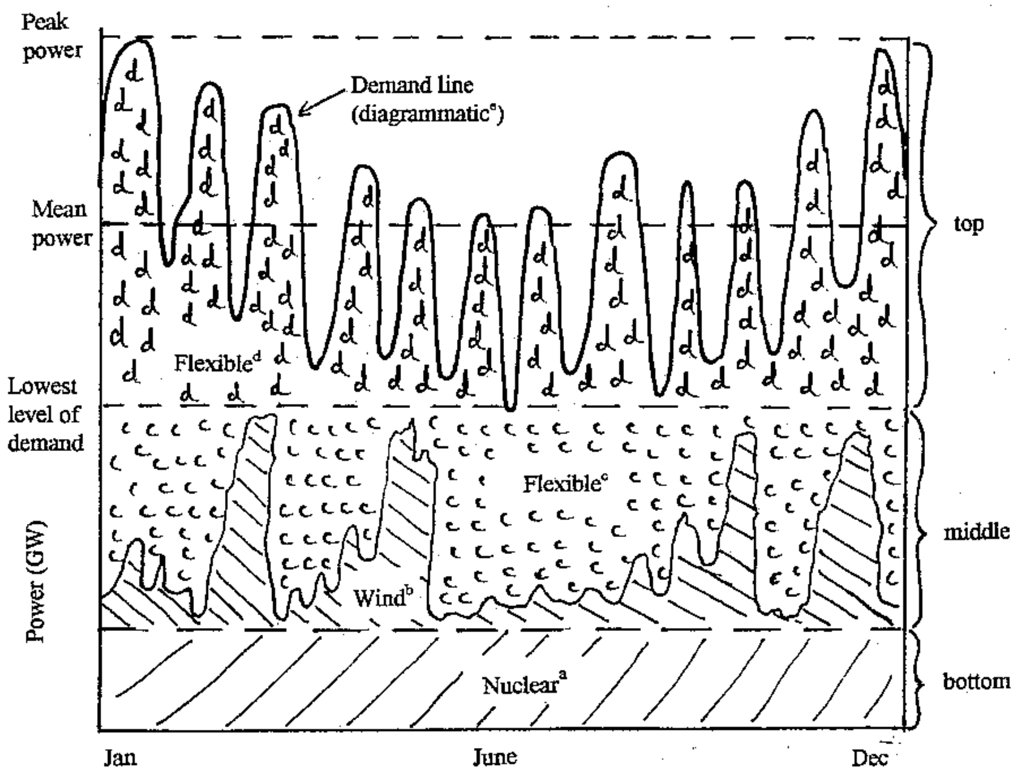
Endnotes

{1} James P. Duguid's (CBE, MD, BSc FRCPath) booklet was published in 2002 by Population Policy Press, Llantrisant, Pontyclun, CF72 8LQ, UK <info@popolpress.com> (£5 incl. p&p). It is a digest of information and interpretations from publications of the Optimum Population Trust UK, and others.

{2} *Wind/biomass Energy Capture: an Update*, is available on pp. 3-10 of the April 2003 OPT Journal, Vol. 3, No 1. This issue of the journal is archived at www.members.aol.com/optjournal2/optj31.doc

{3} Most people find power and energy confusing. The distinction between them is treated extensively as Question 2 of the FAQs (Frequently Asked Questions) in a Word document available at www.members.aol.com/optjournal/faqs.doc.

Figure 1. The problem of satisfying demand for electricity when incorporating a variable, non-flexible, power source like wind. Seasonal variation shown is more akin to the UK rather than the US, which has a subsidiary peak in summer due to the demand for air conditioning. In certain aspects the diagram is purely diagrammatic — see note e.



Notes

a Nuclear plant needs to be allowed to produce at a fairly constant output for maximum efficiency. The National Grid Company records the reaction time as 48 hours (coal 12-24 hrs; CCGT 6 hrs, gas turbines 2 minutes; pumped storage 10 secs).

b The wind profile will vary from year to year but, as argued in the main text, with a capacity factor of 30%, for example, wind would fill 30% of the middle section of Figure 1, leaving 70% to be supplied by a flexible power generator.

c "Flexible" in practice, means fossil fuel while it is available and biomass thereafter. Note that "Flexible[c]" is only part of the flexible requirement – namely that part occasioned by the variability of wind output. The next note covers the flexible requirement arising from changing human demands over 24 hours.

d Flexible power is required for this top section, but this time in order to account for the variation in demand caused by the diurnal pattern of human life.

e Note that the demand line shown is diagrammatic. It contains certain elements of truth, such as that daily fluctuations are larger in range than the seasonal variations. However about 12 days of the year are taken and highly stretched out horizontally, because were the full 365 daily fluctuations to be shown, it would look like a continuous mass of black, showing only the seasonal variation and losing the detail of the daily fluctuations.

HYDROGEN AND INTERMITTENT ENERGY SOURCES

by Andrew R.B. Ferguson

Abstract: Hydrogen is frequently proposed as an energy carrier that could solve the problem of intermittent output from renewables. This paper shows that were hydrogen to be generated from wind and then used in conjunction with fuel cells to provide flexible-output power, for the purpose of backing up a *variable* but *non-flexible* output source such as wind power, the dollar and energy costs would escalate to such an extent that any proposal to use wind turbines as the source of back-up electrical power, with hydrogen as an energy carrier, must be judged an improbable solution to the problem of the intermittent supply from renewables.

This paper could have been included as a part of *The Meaning and Implications of Capacity Factors*, see pages 18-25, but it is so commonly assumed, both in scientific papers and in the popular media, that hydrogen will provide an answer to the problem of intermittency of renewable energy (e.g. compensating for the variability of wind and sun), that it seems best to discuss the matter at some length in this separate article, despite the fact that the matter is vitally relevant to the previously mentioned paper. Indeed the previous paper is sufficiently related to this one, that it will be handy to refer to it as the 'parent paper'.

What we need to consider here is the middle section of Figure 1 of the parent paper, that is the segment of electrical energy which can be held constant only because the variability of the output of the wind turbines is smoothed out by a flexible power plant. In this paper, we will consider the flexible power plant to comprise fuel cells powered by hydrogen which has been produced by electrolysis using electricity from wind turbines.

Because, as we see later, there are various parameters which are hard to tie down precisely, let us accept that we can do no better than make a ball-park assessment of the problem, thereby entitling us to use a somewhat simplified assumption, namely that if wind turbines provide 30% of the energy (capacity factor 30%), then the other 70% will be provided by a flexible plant (hydrogen powered fuel cells for the purpose of this analysis). Note that while the above assumptions are loose, they are not unrealistically unfavourable to wind. In *Wind/biomass Energy Capture: an Update*,{1} Tables 1 and 2 showed that over two years the mean capacity factor for wind turbines in Germany, Denmark, Sweden and the Netherlands was 22%.

In order to set about quantifying the relationship, let us choose some nominal figures, starting with the assumption that for supplying 1000 MWyr electricity per year, we are to install wind turbines with a rated capacity of 1000 MW (e.g. 500 turbines each of 2 MW power); that is to say, the turbines would produce 1000 MWyr per year were they to run continuously at maximum capacity, but at a capacity factor of 30% they will actually produce 300 MWyr per year. The remaining 700 MWyr per year is assumed here to be produced from fuel cells using hydrogen as the energy-carrier and wind turbines as the power source.

Hydrogen production by electrolysis is around 70% efficient. About the best efficiency that we can expect from fuel cells, including the need to invert their direct current output to AC, is 60%. That makes an overall efficiency of 0.70 x 0.60 = 42%.

With this efficiency, the electricity required to produce the hydrogen for the flexible supply would be 700 / 0.42 = 1667 MWyr per year. The rated capacity of the turbines that would produce 1667 MWyr per year, again at a 30% capacity factor, would be 1667 / 0.30 = 5557 MW. The fully installed cost of wind turbines is about US$1 per watt of capacity, thus the cost of this capacity would be about $5550 million. The 1000 MW of turbine capacity, that could supply 300 MWyr per year of output for direct supply, would cost a further $1000 million, thus the total turbine cost for 1000 MWyr per year would be $6550, or $6.55 per watt of output.

Further costs, for that part of the output which cannot be delivered directly, would arise from electrolysis equipment, hydrogen storage facilities, and fuel cells, the latter adding the largest cost. The best evidence available at present puts the capital cost of fuel cells at about 4 times that of conventional plant. The capital cost of conventional plant is about US$1 per watt of capacity (as we have noted this is true of wind turbines, but in the case of wind turbines, actual output is in the region of thirty per cent of the capacity).

At a cost factor of 4 times, that means that the 700 MWyr per year of output which is produced via fuel cells will have a burden of additional capital cost of $700 million x 4 = $2800 million. That additional cost can conveniently be spread over the whole 1000 MWyr per year output, thus producing a mean additional cost of $2.80 per watt of output. Putting these costs together, the capital cost is $6.55 + 2.80 = $9.35 per watt of actual output, rather than the $1000 / 300 = $3.33 for directly delivered electricity.

Before we go on to consider further factors — serious but hard to quantify precisely — let us consider whether a nearly three-fold increase in cost is bearable, remembering that for wind power nearly all the cost is capital cost, so increased capital cost roughly reflects increased cost of electricity. A Green Paper, *Towards a European Strategy for the Security of Energy Supply*, 2000, gave the following cost figures per kilowatt hour (here converted from Euros to US cents):

Coal, 4.0¢, Nuclear 4.7¢, Wind 8.3¢, Photovoltaics 77¢, Bio-energy 5.6¢.

The high figure for photovoltaics applies to European insolation. Adjusting for the insolation in Arizona reduces the 77¢ to ¢43.{2} Note chiefly the *relative* costs, as few consumers would expect to pay only 4¢ per kWh for electricity from coal. Since wind power is mainly capital cost, we can see that the 'wholesale' cost of electricity from the 'composite' system we have been analysing will be 8.3¢ x 9.35 / 3.33 = 24¢ per kWh.

Other cost factors

24 cents per kilowatt hour already makes it look somewhat unlikely that we can solve the intermittency problem of wind turbines by using wind power with hydrogen as an energy carrier. There remain other important factors to weigh in the balance.

One consideration with renewable energy is the ratio of the amount of energy which has to go into construction and maintenance of the equipment as compared to its output. On occasions, some misleadingly reassuring figures have been published for wind turbines, by the ruse of increasing the output figure to its primary energy equivalent (i.e. the amount of energy that would be needed to generate the electricity produced by the wind turbines); however, in relation to the inputs that is clearly illogical; indeed it could be convincingly argued that the value of a significant part of the output should be scaled down rather than scaled up, because a substantial part of the input would need to be in the form of 'liquid' energy (e.g. liquid hydrogen), and there are substantial losses in producing 'liquid' energy from electricity. However, we don't need to go into the niceties of such arguments, other than to say that earlier estimates of a 1 to 6 input to gross output ratio were probably in the right ball park (P&P, 1996, p. 206, gave a 1:5 ratio). Anyhow, at the very least, commonsense indicates that input is a significant part of output, since the inputs must cover the construction of the wind turbines, access roads, transmission lines, and maintenance of the plant.

Next we need to note that since wind turbines cost about one US$ per watt of capacity, for directly produced electricity there is an output of 300 MWyr per year for a cost of $1000 million. Considering the flexible-output component separately, we get 700 MWyr per year output for around $5557 million of installed wind turbine. Since we are accounting only for increased turbine requirements, it is evident that for the electricity produced via a fuel cell, input to output ratio has gone up by a factor of (5557 / 700) / (1000 / 300) = 2.4. Thus instead of a 1:6 ratio we get 2.4:6 or 1:2.5. So for this larger component of the total electricity (700 MWyr per year out of 1000 MWyr per year), it seems likely that the energy input will approach half the value of the energy output. It might be argued that the datum used is insecure, but we have built in a large margin for error, because we have not accounted for the energy cost of making the electrolysis equipment, inverters, hydrogen storage facilities, and fuel cells.

Yet there are indeed additional energy and dollar costs due to: (a) the electrolysis plant (operated only when there is adequate wind — a fact which will necessarily add to the cost, as equipment and people will be operating sub-optimally most of the time); (b) inverters to change AC output from the wind turbines to DC for electrolysis and the DC output of the fuel cells to AC; (c) hydrogen storage facilities.

The energy density of hydrogen at normal atmospheric pressure is 10.8 kilojoules per litre, as compared to the approximate 38 kJ per litre of methane (natural gas). Thus unless energy is expended on compression, large containment volume will be required. Moreover containment will not be easy, because of hydrogen's small molecular size, it has a diffusivity about three times that of natural gas (Schultz et al., 2003) Also it would be important not to allow it to leak, because hydrogen has a low ignition energy, 1/17 that of methane (so it could be ignited by a static spark), and it is flammable in air at concentrations in the range 4-75% (Schatz). Incidentally, there is one plus point for hydrogen, it burns at a low temperature, so is less likely than natural gas to cause damage when it does ignite.

Another aspect of the whole operation which would add to costs is that the hydrogen-powered fuel cells would be under utilised insofar as 30% of their energy output capacity would be supplied directly by the wind turbines.

By this stage of the analysis, I think most people would conclude that smoothing out the variable supply of renewables by using wind turbines, combined with the energy-carrier hydrogen, is not a viable proposition, but doubtless there will be some who will wish to continue to defend what the media and various authorities{3} see as the 'bright new future of the hydrogen economy'. May I suggest that they should also bear the following points in mind:

a) It could be that the cost of fuel cells could come down, but the human race needs to make decisions about future energy supplies on the basis of what is *likely* rather than what *might be*. Moreover, the catalyst used in fuel cells is platinum, so account should be taken of the probable cost of platinum when it is being used on a large scale to make fuel cells to replace power stations.

b) 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 has passed (Campbell 1997, Heinberg, 2003), and therefore we will soon be entering the age of scarcity of fossil fuels. This will inevitably make *everything* more costly, so estimations of what is acceptable by way of cost need to take account not only of the increased cost of turbines, transmission lines, access roads, electrolysis equipment, inverters, hydrogen storage, fuel cells, and maintenance, but also the lower purchasing power of everyone once energy becomes more expensive.

Conclusion

It is hard to quantify the energy and dollar cost of running a composite system, yet a composite system was shown to be necessary in the parent paper, *The Meaning and Implications of Capacity Factors*. A ball-park calculation of the cost of producing *useful* electricity, using the composite system considered here, indicates that the use of wind turbines as the power source, with hydrogen as the energy carrier, is not going to be viable. Incidentally, neither is using biomass on any substantial scale. While that aspect is outside the scope of this paper, it has been covered in *Wind/biomass Energy Capture: an Update* (OPTJ 3/1, pp. 3-10).

Epilogue

The purpose of the OPT Journal is well illustrated by the three interrelated papers, *Limits to Wind Power*, *The Meaning and Implications of Capacity Factors*, and *Hydrogen and Intermittent Energy Sources*. That purpose is not to contribute to debates which are being properly conducted in scientific journals. It is rather to shine a light on matters which can be categorized as 'extraordinary popular delusions'. To my knowledge, there is no scientific paper which addresses the essential points of this paper, yet in many scientific papers there is either explicit or implicit acceptance of a position which is contrary to the above conclusion. In other words, there is a gap in scientific thinking which has allowed an 'extraordinary popular delusion' to flourish; it is the purpose of the OPT Journal to bring such delusions to the attention of readers.

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Endnotes

1. *Wind/biomass Energy Capture: an Update* is contained in the April 2003 issue of the OPT Journal, Vol. 3, No 1, pp. 3-10. This issue is archived on the web, as a Word file, and can be accessed directly at www.members.aol.com/optjournal2/optj31.
2. PV has already been treated in some detail in the October 2002 issue of the OPT Journal (Vol. 2, No 2), pages 23-37. The issue is archived on the web. The Word file can be accessed directly at www.members.aol.com/optjournal2/optj22.
3. One such 'authority', with misplaced faith in hydrogen, is the estimable founder of the Worldwatch Institute, Lester Brown. See the article *Monograph on Brown's Eco-economy* in the April 2002 issue of the OPT Journal (Vol. 2, No 1), pages 11-13. The issue is archived on the web. The Word file can be accessed directly at www.members.aol.com/optjournal2/optj21.

HYDROGEN FANTASIES

by Andrew R.B. Ferguson

David Pimentel kindly sent me fifteen pages that he had extracted from the January/February 2003 edition of *E Magazine*, concerning the mooted ‘hydrogen economy’. For reasons that will soon become manifest, these pages can appropriately be referred to as ‘hydrogen fantasies’.

The pages provide a valuable insight into how, and by whom, the hydrogen-fuel-cell myth is being spread. The contributors to ‘hydrogen fantasies’ include Jeremy Rifkin, whose recent book is titled, *The Hydrogen Economy: the Creation of the Worldwide Energy Web and the Redistribution of Power on Earth*.

Rifkin, president of the *Foundation on Economic Trends*, we learn, is adviser to Romano Prodi, the president of the European Commission. We also learn that Rifkin was “the architect of the strategic white paper that launched” the European Union into a “$2 billion commitment to a renewable hydrogen-based energy economy.”

Quoted with approval, although not contributing to ‘hydrogen fantasies’, was Peter Hoffman, author of a book titled, *Tomorrow’s Energy: Hydrogen, Fuel Cells and the Prospects for a Cleaner Planet*.

‘Hydrogen fantasies’ contains an interview with Amory Lovins, the well known energy ‘expert’ from the Rocky Mountain Institute. An analysis of Lovins’ high-flown optimism is to be found in Vaclav Smil’s essay, in Population Development Review, *Rocky Mountain Visions: A Review Essay*, (2000); it serves to amplify the observations below.

Jim Motavalli, editor of *E Magazine*, and author of *Breaking Gridlock: Moving Toward Transportation that Works*, contributed two articles, also interviewing Amory Lovins and James Cannon. The latter’s 1995 book was titled, *Harnessing Hydrogen*. Now that we have sketched the contributors, we can evaluate their contributions.

In the articles, hydrogen was often described as an “energy carrier.” However, although this descriptive phrase appears from time to time, scant attention is given to its implications. I have not come across anyone who advocates making more buckets to solve the problems of people who live in parts of the world where there is water shortage, but, as we can see from the titles of the books just mentioned, there are plenty of people who recommend hydrogen — the energy carrier — as a cure for the coming shortage of energy! The unfortunate reality is that energy is needed to make hydrogen gas, and buckets are no good without water.

Here is an example of the sort of technique employed to evade the question of where the energy is to come from. At the end of the interview with James Cannon, Motavalli asks:

> Are you ultimately optimistic that China will develop a hydrogen energy economy?

To that Cannon replies,

> Yes, China has become very sensitive about this, and is grappling with it early on. They’re hitting some of the dramatic warning signs about oil dependence. It’s fortunate that so much is now available in demonstration programs and in the literature about the true potential of the hydrogen economy. So it’s happening much quicker than we were thinking 10 or 20 years ago.

That’s a blatant evasion of reality, but, if Rifkin reports him correctly, Lovins must surely take the prize for evasion of reality:

> It would work like this: Commuters drive their cars to work, then plug them into the hydrogen line coming out of the natural gas reformer installed as part of the building's fuel cell. While they worked, their cars would produce electricity, which they could then sell back to the grid. The car, instead of simply occupying space, would become a profit center. "It does not take many people doing this to put the rest of the coal and nuclear plants out of business, says Lovins, who's been trying to do just that for decades. "The hypercar fleet will eventually have five to six times the generating capacity of the national grid."

When readers recover from their amazement at this fairly obvious fantasy, I trust they will note that the suggested source of energy is natural gas. Rifkin might be partially excused for quoting this absurd idea, on the assumption that he had no knowledge of the pending shortage of natural gas; but the excuse is untenable, because, on page 29, Rifkin makes the assertion (broadly accurate) that, "global production of natural gas is likely to peak sometime between 2020 and 2030."

At this point, it might be helpful to offer readers a simple test whether those who write about hydrogen are engaged in fantasy. What is required is to peruse the piece asking whether it addresses these two questions:

a) How much energy is required to make the amount of hydrogen (in an appropriate form) needed to drive a car as far as 1 liter of gasoline?
b) Is there likely to be sufficient *renewable* energy available to make anything like the amount of hydrogen that is going to be required?

If these questions are not addressed, then the article falls into the pipe-dream category. Insofar as those questions were addressed at all, in 'hydrogen fantasies', they were based on the sort of airy-fairy, loosely quantified hopes that flourished in Lester Brown's book *Eco-economy* (reviewed in OPTJ 2/1, pp. 11-13).

'Hydrogen fantasies' contained an observation that may repay study. Motavalli told us that General Motors were producing a sedan called *Hy-wire*, which incorporates a high-pressure, 5000 pounds per square inch (psi) hydrogen tank. Furthermore, GM are experimenting with tanks at 10,000 psi (680 atmospheres).{1}

This is interesting information, because if a tank is completely filled with liquid hydrogen, and allowed to warm to 50°C, the pressure would increase to about 930 atmospheres. By filling the tank only three-quarters full with liquid hydrogen, at 50°C the pressure would only rise to the 680 atmosphere pressure of GM's projected tanks.{2} In other words, it appears to be economically viable to contain liquid hydrogen safely, without keeping it refrigerated (I have long been seeking confirmation on that point).

Let us look at the energy densities that would be achieved by these gas pressures. At 340 atmospheres, the hydrogen would have an energy density of 3.67 MJ/liter (megajoules per liter), compared to 8.4 MJ/liter for liquid hydrogen (and 33 MJ/liter for gasoline).{3} Since — when hydrogen is used in a fuel cell — it takes 2.3 liters of liquid hydrogen to provide the same motive energy as 1 liter of gasoline (OPTJ 3/2, p. 24), at 340 atmospheres it would require 5.3 liters of tank space to provide the same motive energy as 1 liter of gasoline.{4} And since the volume of a gas is inversely proportional to the pressure, by increasing the pressure to 680 atmospheres, the energy density would be doubled, so at this pressure it would require only 2.6 liters of tank space to provide the same motive energy as 1 liter of gasoline (getting close to the 2.3 of liquid hydrogen).

But no mention is made of the energy that would be needed to compress the gas to 10,000 psi (680 atmospheres). It seems likely that the most energetically frugal method of achieving this would be first to liquefy the hydrogen (by at least reducing its temperature to below the critical point of hydrogen, -240°C). If that is the case, then we are back to the situation which was summarized in the Abstract of *Verdict On The Hydrogen Experiment: An Update* (OPTJ 3/2, p. 21):

> It would take 9.14 kWh of electricity, = 32.9 MJ *of electricity*, to produce hydrogen with the same motive energy as 1 litre of gasoline (which has an energy density of about 33.5 MJ/litre). This almost equal requirement for energy is a viable proposition when renewable energy can be generated directly as electricity from renewable sources, as in Iceland, but generating the electricity from fossil fuels would call for the use of about 32.9 / 0.33 = 99.7 MJ of fossil fuel energy, about three times the energy in gasoline, and that would be prohibitive both in consumption of fossil fuels and emissions of carbon dioxide.

It is hardly necessary to say that none of these unpleasant realities were allowed to intrude into 'hydrogen fantasies'!

It seems rather a waste not to make use of the potential energy contained in the hydrogen by virtue of its high pressure. An interesting speculation is that an internal combustion engine might be designed to make use of the pressure in the hydrogen. If so, it may be possible to enhance the efficiency of a hydrogen-burning internal combustion engine to the extent of reducing the volume of liquid hydrogen — which provides the same motive energy as 1 liter of gasoline — from 3 liters, down to the approximate 2.3 liters which can be achieved with a fuel cell. If so, internal combustion would probably be cheaper. That is but idle speculation because, as cannot be reiterated too frequently, *the primary problem is to find a source of renewable energy to make the hydrogen*.

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Endnotes

{1} 1 atmosphere = 14.7 psi, so 5000 psi = 5000 / 14.7 = 340 atmospheres; and 10,000 psi = 680 atm.

{2} The pressure of 930 atm at 50°C was calculated according to ideal gas laws, assuming that initially the tank is entirely full of liquid hydrogen. If it was only 73% full, then the pressure would not reach 930 atmospheres but rather 930 x 73 / 100 = 679 atmospheres. ("Three-quarters" is thus an approximation).

{3} At standard temperature (0°C) and pressure (14.7 psi or 1 atmosphere), (STP), hydrogen has a heat content of 10,800 J/liter (joules per liter).
So at 340 atmospheres it has a heat content of 10,800 x 340 = 3.67 MJ/liter.

{4} Liquid hydrogen has an energy density of 8.4 MJ/liter.
When used in a fuel cell, it takes 2.3 liter of liquid hydrogen to provide the same motive energy as 1 liter of gasoline.

To provide the same energy with natural gas at 5000 psi would require 2.3 x 8.4 [MJ/liter] / 3.67 [MJ/liter] = 5.26 liters of hydrogen gas.

<u>Cross-check</u>. 2.3 liters of liquid hydrogen weighs 2.3 x 70 [g/liter] = <u>161</u> g. At STP hydrogen density is 0.0899 g/liter. So at 340 atm, 5.26 liters of hydrogen gas would contain 5.26 x (340 x 0.0899) = <u>161</u> g.