NUCLEAR ENERGY
In Brief

1. The world's endowment of uranium ore is now so depleted that the nuclear industry will never, from its own resources, be able to generate the energy it needs to clear up its own backlog of waste.
2. It is essential that the waste should be made safe and placed in permanent storage. High-level wastes, in their temporary storage facilities, have to be managed and kept cool to prevent fire and leaks which would otherwise contaminate large areas.
3. Shortages of uranium – and the lack of realistic alternatives – leading to interruptions in supply, can be expected to start in the middle years of the decade 2010-2019, and to deepen thereafter.
4. The task of disposing finally of the waste could not, therefore, now be completed using only energy generated by the nuclear industry, even if the whole of the industry's output were to be devoted to it. In order to deal with its waste, the industry will need to be a major net *user* of energy, almost all of it from fossil fuels.
5. Every stage in the nuclear process, except fission, produces carbon dioxide. As the richest ores are used up, emissions will rise.
6. Uranium enrichment uses large volumes of uranium hexafluoride, a halogenated compound (HC). Other HCs are also used in the nuclear life-cycle. HCs are greenhouse gases with global warming potentials ranging up to 10,000 times that of carbon dioxide.
7. An independent audit should now review these findings. The quality of available data is poor, and totally inadequate in relation to the importance of the nuclear question. The audit should set out an energy-budget which establishes how much energy will be needed to make all nuclear waste safe, and where it will come from. It should also supply a briefing on the consequences of the worldwide waste backlog being abandoned untreated.
8. There is no single solution to the coming energy gap. What is needed is a speedy programme of Lean Energy, comprising: (1) energy conservation and efficiency; (2) structural change in patterns of energy-use and land-use; and (3) renewable energy; all within (4) a framework for managing the energy descent, such as Tradable Energy Quotas (TEQs).

ACKNOWLEDGEMENTS

Thank you to my editor, Shaun Chamberlin, for his meticulous work in helping to get this book ready for publication.

Thank you to Jan Willem Storm van Leeuwen for many months of comments and expert advice. References for his work, and the work he has published jointly with the late Dr Philip Smith, are given on pages 41-42. This booklet is substantially guided by their research, but it builds on it and takes the discussion of energy policy options further. The conclusions I draw, including the concept of "energy bankruptcy", treatment of the backlog of waste, and the alternative vision of Lean Energy, are my own. All summaries sacrifice detail, some of which may be important. I make no claim that this booklet is beyond challenge in its representation of Storm van Leeuwen and Smith's exhaustive and careful analysis: the responsibility for the entire contents of this booklet is my own.

Thank you to the many readers who have commented on parts or all of the text. Special thanks for detailed technical comments to John Busby. Lucy Care supplied valuable comments and arranged for several scientific referees with knowledge of nuclear energy to comment on the text.

Thank you to Christopher White for his drawings.

Thank you to Geoff Lye for advice on publicity matters.

Thank you to the R.H. Southern Trust for financial support.

My work on the Lean Economy project has been aided and encouraged in various ways and over many years by Elm Farm Research Centre, and its director, Lawrence Woodward, initially with the support of the late David Astor.

ABOUT THE AUTHOR

David Fleming has an MA (History) from Oxford, an MBA from Cranfield and an MSc and PhD (Economics) from Birkbeck College, University of London. He has worked in industry, the financial services and environmental consultancy, and is a former Chairman of the Soil Association. He designed the system of Tradable Energy Quotas (TEQs), (aka Domestic Tradable Quotas and Personal Carbon Allowances), in 1996, and his booklet about them, *Energy and the Common Purpose*, now in its third edition in this series, was first published 2005. His *Lean Logic: The Book of Environmental Manners* is forthcoming.

THE
LEAN GUIDE
TO
NUCLEAR
ENERGY

A Life-Cycle in Trouble

David Fleming

THE LEAN ECONOMY CONNECTION

Published by

THE LEAN ECONOMY CONNECTION
P.O. Box 52449
London NW3 9AN
info@theleaneconomyconnection.net
www.theleaneconomyconnection.net

The Lean Guide to Nuclear Energy: A Life-Cycle in Trouble
ISBN 0-9550849-2-8

November 2007

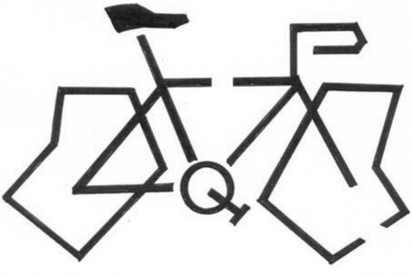
Drawings by Christopher White

Every care has been taken in the preparation of this booklet, whose findings have been reached in good faith, with no prior agenda. Neither the author nor the publisher can be held liable for any errors or decisions influenced by it.

COMMENTS AND REVISIONS

The lack of consensus in the nuclear industry on such fundamentals as the future of uranium supplies and its carbon intensity (greenhouse gas emissions per kilowatt hour) means that many, or most, papers on the subject must contain substantial errors. This paper will be no exception. However, if errors are brought to the author's attention and proved, the text will be amended accordingly, and new editions issued, both on the website and in the printed version.

CONTENTS



THE NUCLEAR LIFE-CYCLE

CAST LIST

ATOM. The smallest particle unique to a particular chemical element. An atom consists of a nucleus of protons and neutrons, surrounded by electrons.

ATOMIC MASS. The sum of neutrons and protons in the nucleus.

ATOMIC NUMBER. The number of protons in the nucleus of an atom: this is what gives an element its characteristic properties.

BACK END ENERGY. The energy needed to dispose of old reactors and to clear up all the wastes produced at each stage of the front-end process.

DEPLETED URANIUM. The waste uranium left behind after the enrichment process. (Not to be confused with uranium depletion – i.e. the decline in the global ore resource).

ELECTRON. A negatively-charged particle orbiting the nucleus of an atom.

ENERGY RETURN ON ENERGY INVESTED (EREI). The ratio between the energy derived from a process and the energy invested in that process.

FRONT END ENERGY. The energy needed to build reactors, to mine, mill, enrich and prepare the fuel, and for the other energy-using tasks needed to produce nuclear power.

GROSS ENERGY. The electricity fed by nuclear reactors into the grid.

HALF-LIFE. The time it takes, statistically, for half the atoms of a given radioactive isotope to decay.

ISOTOPES. Atoms with the same atomic number, but different numbers of neutrons and hence different atomic masses. They are identified by the sum of protons and neutrons, so that, for instance, "uranium-235" has 92 protons and 143 neutrons, whereas uranium-238 has 92 protons and 146 neutrons.

NET ENERGY. Gross energy minus front-end energy.

NEUTRON. A particle with a neutral charge (that is, no charge at all) found in the nucleus of every atom except that of the simple form of hydrogen.

PRACTICAL RETURN ON ENERGY INVESTED (PREI). A measure of the energy return on energy invested which takes account of practical questions of local geology, water problems and price in a market impoverished by energy scarcity.

PROTON. A particle with a positive electrical charge, found in the nucleus of every atom.

RADIOACTIVITY. Radioactive material radiates energy which has the ability to break up and rearrange cellular DNA and the atomic structures of elements.[1]

THEORETICAL RETURN ON ENERGY INVESTED (TREI). A measure of the energy return on energy invested, taking no account of the practical questions included in PREI.

URANIUM-235. The isotope of uranium which drives the nuclear reaction, and which needs to be present in an enriched concentration of 3.5 percent, in comparison with the 0.7 percent in which it is present in natural uranium.

1. INTRODUCTION

The main objectives of energy policy must be (1) to achieve a profound reduction in the release of the gases that are changing the climate, and (2) to find other ways of maintaining the energy services we need as supplies of oil and gas decline towards depletion. Nuclear power seems at first sight to have something to offer here. It does not depend on oil, gas or coal as its primary fuel.[2] It is based on a process which does not, in itself, produce carbon dioxide. It is concentrated in a relatively small number of very large plants, so that it fits easily into the national grid. And there is even the theoretical prospect of it being able to breed its own fuel. So – what's the problem?

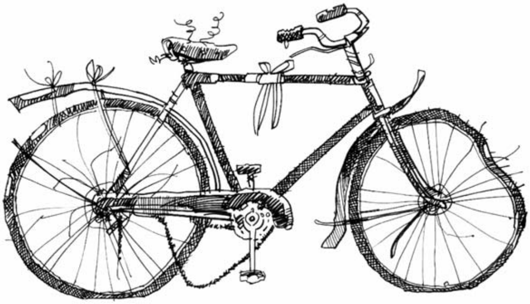
The question is considered here in the six chapters of this short study, which is intended as a readable introduction to the nuclear question for everyone interested in, or involved in, the debate about it. It starts here with a short description of the principles, explaining what nuclear energy is. Chapter 2 describes what has to be done in order to derive energy from uranium. Chapter 3 explains why the nuclear industry is in fact a substantial source of carbon emissions, and it makes the link with the problem of uranium depletion and the wider question of the amount of energy that has to be put into the process to get energy out of it. Chapter 4 asks whether there are alternative sources of the uranium fuel on which the industry depends, and chapter 5 sets nuclear energy in context with the energy problem as a whole. Chapter 6 draws conclusions.

Now for the principles. The form of nuclear power available to us at present comes from nuclear fission, fuelled by uranium. Uranium-235 is an isotope of uranium with the rare and useful property that, when struck by a neutron, it splits into two and, in the process, produces more neutrons. Some of these neutrons then proceed to split more atoms of uranium-235 in a chain of events which produces a huge amount of energy. We can get an idea of how much energy it produces by looking at Einstein's famous equation, $E=mc^2$, which says that the energy produced is the mass multiplied by the square of the speed of light. A little bit of mass disappears – we can think of this as the material weighing slightly less at the end of the process than at the beginning – and it is that "missing" mass which turns into energy which can be used to make steam to drive turbines and produce electricity.

While other neutrons from the reaction go their separate ways, some go on to do something very interesting: if one collides with an atom of uranium-238, one of the other isotopes of uranium, it may stay there, triggering a couple of decay cycles to form plutonium-239. And plutonium-239 shares with uranium-235 the property that it, too, splits when struck by neutrons, so that it begins to act as a fuel as well.[3]

The process can be controlled; the control is provided by a moderator consisting of water or graphite, which speeds the reaction up, and by neutron-absorbing boron control rods, which slow it down. Eventually, however, the uranium gets clogged with radioactive impurities such as the barium and krypton produced when uranium-235 decays, along with "transuranic" elements such as americium and neptunium, and a lot of the uranium-235 itself gets used up. It takes a year or two for this to happen, but eventually the fuel elements have to be removed, and fresh ones inserted. The spent fuel elements are very hot and radioactive (stand close to them for a second or two and you are dead), so there are some tricky questions about what to do with them. Sometimes spent fuel is recycled (reprocessed), to extract the remaining uranium and plutonium and use them again, although you don't get as much fuel back as you started with, and the bulk of impurities still has to be disposed of. Alternatively, the whole lot is disposed of – but there is more to this than just dumping it somewhere, for it never really goes away. The half-life of uranium-238, one of the largest constituents of the waste, is about the same as the age of the earth: 4.5 billion years.[4]

Those are the principles. Now for a closer look at what nuclear energy means. An informed discussion is especially needed, now that James Lovelock has produced his devastating challenge, arguing that climate change is so real, so advanced and potentially so catastrophic that the risks associated with nuclear power are trivial by comparison – and that there is no alternative. Nuclear energy, he insists, is the only large-scale option: it is feasible and practical; a nuclear renaissance is needed without



delay. Well, this is undoubtedly something we need to think about and decide on; however, that thinking must be firmly based on the practical realities of the nuclear fuel cycle. We do not need to get involved in the arcane physics of the nuclear reaction itself, but we do need to know – if we are to make any sense of this – what the production of electricity from nuclear power really involves. And who is “we”? It is all of us, scientists or not: this has to be an informed citizens’ decision.[5]

The principal source for what follows is the long-sustained programme of research on the nuclear energy life-cycle by the nuclear engineer Jan Willem Storm van Leeuwen and the nuclear scientist the late Dr Philip Smith. Their work, based on total immersion in the literature of the science and technology of nuclear power, is motivated not by the intention to make a case either for or against, but to bring the best available information on the energy balance of the nuclear industry to the attention of policy makers and into the public debate. This booklet does not rely exclusively on their research; it refers also to many other studies such as those of the University of Sydney and the U.K. Sustainable Development Commission, along with the work of the World Nuclear Association, the Uranium Information Council, Greenpeace and others. The quality of data about the nuclear energy cycle is poor, and every study reflects this in some way; nonetheless, the analysis by Storm van Leeuwen and Smith, which has benefited from several years of critics’ comments and answered questions and revisions, provides an exhaustive and well-researched guide to a sensible view of the future of nuclear energy.[6]

If there is to be proper and inclusive consultation on the question of nuclear energy, citizens and their representatives need to be aware of some of the principles; for instance, they need to be free of popular misconceptions about the nuclear process producing no carbon dioxide and being an unlimited source of energy. This gentle tour round the nuclear life-cycle explains what happens at each stage – and it turns out, at every stage, to be in trouble. But, as we shall see, a different sort of life cycle is available – a realistic way forward. It replaces the large-scale, central, uniform technical fix with small-scale, local judgment. It adapts to local conditions and enhances skills. It is a life-cycle with promise.

2. WHAT IS REALLY INVOLVED IN NUCLEAR ENERGY?

To produce electricity from uranium ore, this is what you have to do.

1. Mining and milling. Uranium is widely distributed in the earth's crust, but only in minute quantities, with the exception of a few places where it has accumulated in concentrations rich enough to be used as an ore. The main deposits of ore, in order of size, are in Australia, Kazakhstan, Canada, South Africa, Namibia, Brazil, the Russian Federation, the USA, and Uzbekistan. There are some rich ores; concentrations of uranium oxide as high as 10 percent have been found, but 0.2 percent (two parts per thousand) or less is usual. Most of the usable "soft" (sandstone) uranium ores have a concentration in the range between 0.2 and 0.01 percent; in the case of "hard" (granite) ore, the usable lower limit is 0.02 percent. The mines are usually open-cast pits which may be up to 250m deep. The deeper deposits require underground workings and some uranium is mined by "*in situ* leaching", where hundreds of tonnes of sulphuric acid, nitric acid, ammonia and other chemicals are injected into the strata and then pumped up again after some 3-25 years, yielding about a quarter of the uranium from the treated rocks and depositing unquantifiable amounts of radioactive and toxic metals into the local environment.[7]

When it has been mined, the ore is milled to extract the uranium oxide. In the case of ores with a concentration of 0.1 percent, the milling must grind up about 1,000 tonnes of rock to extract one tonne of the bright yellow oxide called "yellowcake". Both the oxide and the tailings (that is, the 999 tonnes of rock that remain) are kept radioactive indefinitely by, for instance, uranium-238, and they contain all thirteen of its radioactive decay products, each one changing its identity as it decays into the next, and together forming a cascade of heavy metals with their spectacularly varied half-lives (see Radioactive Poem opposite).

Once these radioactive rocks have been disturbed and milled, they stay around. They take up much more space than they did in their undisturbed state, and their radioactive products are free to be washed and blown away into the environment by rain and wind. These tailings ought therefore to be treated: the acids should be neutralised with limestone and made insoluble with phosphates; the overburden of rock covering the ore strata should be replaced and the area should be replanted with indigenous vegetation. In fact, all this is hardly ever done, and it is regarded as an ideal rather than a requirement of best practice. It would require some four times the energy needed to mine the ore in the first place.[8]

2. *Preparing the fuel.* The uranium oxide (U_3O_8) then has to be enriched. Natural uranium contains about 0.7 percent uranium-235; the rest is mainly uranium-234 and -238, neither of which directly support the needed chain reaction. In order to bring the concentration of uranium-235 up to the required 3.5 percent, the oxide is reacted with fluorine to form uranium hexafluoride (UF_6), or “hex”, a substance with the useful property that it changes – sublimes – from a solid to a gas at 56.5°C, and it is as a gas that it is fed into an enrichment plant. About 85 percent of it promptly comes out again as waste in the form of depleted uranium hexafluoride, known as “enrichment tails”.[10] Some of that waste is converted into depleted uranium metal, some of which is in turn sometimes distributed back into the environment via its use in armour-piercing shells, but most of it is stored as enrichment tails in the form of gas. It reacts violently or explodes on contact with water (including water vapour in the air), so it ought to be transferred from its temporary containers to steel and concrete containers and buried in geological repositories. In fact, most is put on hold: each year, about 8,000 tonnes are added to France’s store of 200,000 tonnes of depleted uranium, and a further 8,000 tonnes are exported from Europe to Russia.[11]

RADIOACTIVE POEM
The decay sequence of uranium-238[9]

The sequence starts with uranium-238. Half of it decays in 4.5 billion years, turning as it does so into thorium-234 (24 days), protactinium-234 (one minute), uranium-234 (245,000 years), thorium-230 (76,000 years), radium-226 (1,600 years), radon-222 (3.8 days), polonium-218 (3 minutes), lead-214 (27 minutes), bismuth-214 (20 minutes), polonium-214 (180 microseconds), lead-210 (22 years), bismuth-210 (5 days), polonium-210 (138 days) and, at the end of the line, lead-206 (non-radioactive).

The 15 percent which emerges as enriched uranium is then converted into ceramic pellets of uranium dioxide (UO_2), packed in zirconium alloy tubes, and bundled together to form fuel elements for reactors.[12]

3. Generation. The fuel can now be used to produce heat to raise the steam to generate electricity. In due course the process generates waste in the form of spent fuel elements and, whether these are then reprocessed and re-used or not, eventually they have to be disposed of. But first they must be allowed to cool off in ponds to allow the isotopes to decay to some extent, for between 10 and 100 years – sixty years may be taken as typical. The ponds need a reliable electricity supply to keep them stirred and topped up with water to stop the radioactive fuel elements drying out and catching fire. In due course, these wastes will need to be packed, using remotely-controlled robots, into very secure canisters lined with lead, steel and pure electrolytic copper, in which they must lie buried in giant geological repositories considered to be stable. It may turn out in due course that there is one best solution, but there will never be an ideal way to store waste which will be radioactive for a thousand centuries or more and, whatever option is chosen, it will require a lot of energy. For example, the energy needed over the lifetime of a reactor to manufacture the canisters (each weighing more than ten times as much as the waste they contain), and to make the electrolytic copper, has never been verified, but it is estimated to be about equal to the energy needed to build the reactor in the first place.[13]

A second form of waste produced in the generation process consists of the routine release of very small amounts of radioactive isotopes such as hydrogen-3 (tritium), carbon-14, plutonium-239 and many others into the local air and water. The significance of this has only recently started to be recognised and investigated.[14]

A third, less predictable, form of waste occurs in the form of emissions and catastrophic releases in the event of accident. The nuclear industry has good safety systems in place; it must, because the consequences of an accident are so extreme. However, it is not immune to accident. The work is routine, requiring workers to cope with long periods of tedium punctuated by the unexpected, along with "normality-creep" as anomalies become familiar. The hazards were noted in the mid-1990s by a senior nuclear engineer working for the U.S. Nuclear Regulatory Commission: "I believe in nuclear power but after seeing the NRC in action, I'm convinced a serious accident is not just likely, but inevitable… They're asleep at the wheel." Every technology has its accidents; indeed, the Nuclear Regulatory Commission estimates the probability of meltdown in the U.S. in a twenty-year period as between 15-45 percent. The risk never goes away; society bears the pain and carries on but, in the case of nuclear power, there is a difference: the consequences of a serious accident – another accident on the scale of Chernobyl, or greater, or *much* greater – would take nuclear power towards being an uninsurable risk, even with the help of government subsidies for the premiums.[15]

And a by-product of this – “waste” in the fourth sense – is the plutonium itself which, when isolated and purified in a reprocessing plant, can be brought up to weapons-grade, making it the fuel needed for nuclear proliferation. This is one of three ways in which the industry is the platform from which the proliferation of nuclear weapons can be developed; the second one is by enriching the uranium-235 to around 90 percent, rather than the mere 3.5 percent required by a reactor. The third consists of providing a source of radioactive materials which can be dispersed using conventional explosive - a “dirty bomb”.

4. The reactor. Nuclear reactors at present have a lifetime of about 30-40 years, but produce electricity at full power for no more than 24 years; the new European Pressurised Water Reactors (EPR), it is claimed, will last longer. During their lifetimes, reactors have to be maintained and (at least once) thoroughly refurbished; eventually, corrosion and intense radioactivity make them impossible to repair. Eventually, they must be dismantled, but experience of this is limited. As a first step, the fuel elements must be put into storage; the cooling system must be cleaned to reduce radioactive corrosion residuals and unidentified deposits (CRUD). These operations, together, produce about 1,000 m^3 of high-level waste. After a cooling-off period which may be as much as 50-100 years, the reactor has to be dismantled and cut into small pieces to be packed in containers for final disposal. The total energy required for decommissioning has been estimated at approximately 50 percent more than the energy needed in the original construction.[16]

3. GREENHOUSE GASES, ORE QUALITY AND URANIUM SUPPLY

Greenhouse gases

Every stage in the life-cycle of nuclear fission uses energy, and most of this energy is derived from fossil fuels. Nuclear power is therefore a substantial source of greenhouse gases. The delivery of electricity into the grid from nuclear power produces, at present, roughly one third as much carbon dioxide as the delivery of the same quantity of electricity from natural gas...[17]

... or, rather, it *would* do so, if the full energy cost of producing electricity from uranium were counted in – including the energy cost of all the waste-disposal commitments (chapter 2). Unfortunately (in part because of the need to allow high-level waste to cool off) that is not the case. Nuclear waste-disposal is being postponed until a later date. This means that the carbon emissions associated with nuclear energy look rather good at the moment: at about 60 grams per kWh they are approximately 16 percent of the emissions produced by gas-powered electricity generation. The catch is that this figure roughly doubles when the energy-cost of waste-disposal is taken into account, and it grows relentlessly as the industry is forced to turn to lower-grade ores. What lies ahead is the prospect of the remaining ores being of such poor quality that the gas and other fossil fuels used in the nuclear life-cycle would produce less carbon dioxide per kilowatt-hour if they were used directly as fuels to generate electricity.[18]

Carbon dioxide is not the only greenhouse gas released by the nuclear industry. The conversion of one tonne of uranium into an enriched form requires the addition of about half a tonne of fluorine, producing uranium hexafluoride gas (hex) to be used in the centrifuge process. At the end of the process, only the enriched fraction of the gas is actually used in the reactor: the remainder, depleted hex, is left as waste. Not all of this gas can by any means be prevented from escaping into the atmosphere, and most of it will eventually do so unless it is packed into secure containers and finally buried in deep repositories.[19]

It is worth remembering here, first, that to supply enough enriched fuel for a standard 1GW (1 gigawatt = 1 billion watts) reactor for one full-power year, about 200 tonnes of natural uranium has to be processed. Secondly, hex is a halogenated compound (HC), one of several that are used at various stages of the cycle. HCs are potent greenhouse gases. The global warming potential of freon-114, for instance, is nearly 10,000 times greater than that of the same mass of carbon dioxide.[20]

There is no published data on releases of HCs from nuclear energy. There must be a suspicion that they reduce any advantage over fossil fuels which the nuclear power industry enjoys at present in the production of greenhouse gases. Given the unfounded but popular presumption that nuclear energy is carbon-free, it would be helpful if a reliable study of all releases of greenhouse gases from the nuclear fuel cycle, and their effect on the atmosphere, were commissioned and published without delay.

Ore quality

Both the quantity of greenhouse gases released by nuclear energy per kilowatt hour and the net energy return of the nuclear industry are determined

GREENHOUSE GAS EMISSIONS

By stage in the nuclear cycle

Estimates for the release of carbon dioxide from the nuclear cycle vary widely. The U.K. Government's 2007 Nuclear Power Consultation accepts estimates that, across its whole life-cycle, nuclear power emits between 7 and 22 g/kWh,[21] but empirical analysis of the energy intensity and carbon emissions at each stage of the nuclear cycle produces much higher figures. This is shown (for instance) in the Integrated Sustainability Analysis (ISA) by The University of Sydney, which concludes that the greenhouse gas (GHG) intensity of nuclear power varies within the range 10-130≈60 g/kWh.[22] The estimate (below) by Storm van Leeuwen and Smith (SLS) is higher because it reflects best practice, which may be better than standard good practice, especially for waste treatment and disposal, and because the reality of errors and problems in the nuclear cycle typically raises the energy cost well beyond the planned level.[23] A recent example of this is the construction of the new Olkiluoto reactor in Finland, where (owing to trial and error) much of the concrete has to be re-laid, raising the carbon emissions associated with the project well beyond the intention.[24]

The assumed reactor lifetime is 30 full-power years; the ore grade is 0.15 percent; at lower grades, emissions would rise sharply. SLS covers just CO2.[25] ISA's estimate includes all GHG emissions from the nuclear cycle.[26] GHG emissions gas-fired electricity generation are about 450 g/kWh.[27]

OPERATION	CO2 g/kWh
Construction	12-35
Front end[28]	36
Back end[28]	17
Dismantling	23-46
Total	88-134

primarily by the quality (grade) of uranium ore that is being used. The lower the grade of ore, the more energy is needed to mine and mill it and to deal with the larger quantity of tailings. The limit, in theory, is reached with an ore grade of about 0.01 percent for soft rocks such as sandstone, and 0.02 percent for hard rocks such as granite. If grades lower than those limits were to be used, more carbon dioxide per kilowatt hour would be produced by the nuclear cycle than by the same amount of energy produced from gas. The energy return on energy invested (EREI) would be less than the energy return you would get if you generated the electricity directly in a gas turbine.[29]

But these are only "theoretical" limits, because in practice the turning-point to a negative energy return may be substantially sooner than that. There are five key reasons why ore which is theoretically rich enough to give a positive EREI may in fact not be rich enough to justify exploitation: to yield a *practical* return on energy investment (PREI), a grade of ore is needed which is substantially higher than the 0.01/0.02 percent identified as the lower limits for a *theoretical* return. These "PREI factors" are as follows:

PREI FACTORS

1. *Deep deposits*. Deposits at great depth, requiring the removal of massive overburden, or the development of very deep underground mines, require more energy to mine the resource than is required by the shallower mines now being exploited. It is virtually certain that all uranium deposits near the surface have already been discovered, so any deposits discovered in the future will be deep.[30]
2. *Water*. You can have too little water (it is needed as part of the process of deriving uranium oxide from the ore) or too much (it can cause flooding). Some of the more promising mines have big water problems.[31]
3. *A trivial contribution*. If the EREI of an energy project is only slightly positive, the problem is that you get so little energy back that it can never make a useful contribution to meeting demand: even with a vast industry and inputs of resources and land, you still cannot derive energy in useful amounts.
4. *An investment that may not be available.* The poorer ores of the future will have to be derived from extremely large mines, which will require many years of investment before they produce any payback at all. There

has to be some doubt as to whether, in the difficult years following the oil peak, that scale of long-term financial investment will be available. This is particularly doubtful in view of the fact that nuclear energy is really suitable only for centralised electricity grids – which are likely to become increasingly obsolete in the future as supplies of natural gas (for generating grid electricity) become scarce and less reliable, and as the cost-effective alternative of improving energy efficiency locally is advanced with all speed under pressure of need.[32]

5. *Local geological conditions.* Practical local difficulties, such as flooding, can be expected to increase as deeper and more remote mines are exploited.

What all of this means is that an energy source – such as uranium ore – ceases to be useful well before it actually reaches the point where the theoretical return on energy invested – TREI – turns negative. It is the practical return on energy invested – PREI – that matters. So, where does the practical turning point lie, below which the ore quality is too poor to be useful? We know that this varies with local conditions; we know that uranium ores as poor as 0.03 percent are being mined now – but only as a by-product in mines being exploited with other minerals; we know that this will be a matter of perpetual debate; and we know that the average ore grade being worked worldwide is at present about 0.15 percent.[33] But for a worldwide average above which uranium ore can still provide a positive PREI, a suggested guideline is *no lower than 0.1 percent.*[34]

Uranium supply

So – how much uranium ore with a positive PREI do we have left?

The “Red Book” is the most authoritative source on the quantity and quality of the remaining uranium ore, and of future prospects for production. It is prepared by the OECD Nuclear Energy Agency (NEA) in partnership with the International Atomic Energy Agency (IAEA), and the 2005 edition was published in June 2006.[35] In its discussion of the availability of usable uranium ore, it suggests that there is 70 years’ supply at the current price.[36] It adds, however, that, when “prognosticated and speculative” resources are added in, there is enough to maintain current output for a further 270 years.[37]

Storm van Leeuwen and Smith acknowledge that there is more uranium ore to be discovered, and that there are massive quantities of uranium in the ground, but argue that the quality of the ore remaining after 60 years of further extraction is likely to be too poor to yield a positive TREI.[38]

We have, then, two rather similar estimates – 70 years and 60 years – but one of them then adds prognosticated and speculative reserves to give us 270 years supply at current rates; the other sees no evidence that the prognosticated and speculative reserves would in fact give us a positive TREI. Does this leave us in total confusion as to which to believe? Not quite. As we know, from experience of the parallel case of peak oil, the official agencies – in the case of oil, the United States Geological Survey and the International Energy Agency – have a strong and now widely acknowledged tendency for massive bias towards exaggerating future prospects.[39] Prognosticated and speculative reserves, if they exist, will be deep below the surface, requiring very large investments of time, capital and energy before they can be exploited. Those speculative resources – which the NEA hopes will one day becomes usable reserves – will need to be remarkably rich, relative to the vast deposits of very low-grade and useless ore of which we are already aware. That is, we know enough to err on the safe side and stick to the demonstrable 60-70 year estimate of remaining ore with a positive TREI, on which the NEA and Storm van Leeuwen and Smith are agreed…

… and yet, let us look again at what that 60/70-year estimate really means. Both the NEA and the Storm van Leeuwen and Smith estimates contain assumptions which tend to exaggerate the time remaining before depletion. First, both estimates are "reserves-to-production ratios" – current reserves simply divided by current annual production, which gives the misleading impression that production can continue at a constant rate before coming to an abrupt stop. In fact, it is well understood that, after reaching a peak well before the artificial cut-off point given by the reserves-to-production ratio, production of a resource in its latter years takes its time to decline towards zero; it is in the years *closely following the peak* that the trouble starts, not in the year when production finally comes to a stop.

Secondly, the growth in demand for uranium which the nuclear industry seems to expect would, in any case, foreshorten the whole sequence: if 70 years is a relevant guideline for the creation of reserves if usage remains constant, a likely cut-off point on the assumption of increasing demand is probably closer to 35 years.

Thirdly, both estimates are of the TREI limits, not the much earlier turning-point to negative PREI.

These three factors bring forward the period during which deep deficits in uranium supply can be expected, to the decade 2011-2020.

Supply crunch

And, indeed, there is a widely-shared recognition that there will be a severe shortage of uranium around 2013. This is frankly acknowledged by the NEA itself, and set in context by the First Uranium Corporation.[40]

Here are the reasons (remember that the numbers are approximations). At present, about 65,000 tonnes of natural uranium are consumed each year in nuclear reactors worldwide.[41] The number of reactors in existence in 2013 will be the product of (1) retirements of old reactors and (2) start-ups of new ones. There is no basis for a reliable estimate of what that net number will be, so we will assume that there is no change from the present.[42]

About 40,000 tonnes of this total demand of 65,000 tonnes are supplied from uranium mines, which leaves the remaining 25,000 tonnes to be supplied from other sources.[43] 10,000 tonnes comes from “military uranium” – that is, from the highly-enriched uranium salvaged from nuclear weapons, chiefly from the arsenal which the Soviet Union built up during the Cold War, and which is now being dismantled with the help of subsidies from the United States. The remaining 15,000 tonnes comes from a range of “secondary supplies”, consisting of inventories of uranium fuel that have been built up in the past, together with recycled mine tailings and some mixed-oxide fuel (MOX), a mixture of recycled plutonium and depleted uranium.[44]

The expectation is that neither of these crucial supplements to mined uranium have much longer to last. Military uranium is being depleted rapidly. At present, it is sold to the United States by Russia on a supply contract which expires in 2013. It is a blend of highly-enriched uranium (HEU) and low-enriched uranium (LEU), and it is supplied in the form of uranium hexafluoride. The deal is attractive to the United States, which not only gets an invaluable supply of nuclear fuel, but does not have to worry about disposing of the waste that arises in the enrichment process;

it is, however, becoming less attractive to Russia, which needs all the fuel it can get for its own expanding nuclear programme, and Russia is in any case getting towards to the end of her supply of obsolete nuclear warheads. There is no chance of the contract being renewed beyond 2013.[45]

Secondary supplies are also in decline. The inventories are approaching exhaustion, and this has been one of the drivers of the recent sharp rise in the price of uranium.[46] The amount of uranium derived from tailings has been falling, and it has been calculated that the scale of the task of increasing production of uranium-235 now would require arrays of continuously-operating gas centrifuge plants running into the millions.[47] The supply of MOX fuel, derived from a reprocessing which is already at its practical limits, is not expected to increase.[48]

URANIUM DEMAND AND SUPPLY BALANCE TO 2013 [49]

Demand (tonnes)		
Current demand, assumed unchanged from the present.		65,000
Supply (tonnes)		
Current supply (2007)		65,000
(of which 40,000 is produced from mines)		
Less loss of fuel from military uranium	-10,000	
Less loss of secondary supplies	-10,000	
Less decline in existing mines' output	-2,000	
Equals expected reduction in absence of new projects		-22,000
Deficit to be filled by new projects		**22,000**
Adding up to nominal supply by 2013		65,000

2013, the year in which the contract for military uranium expires, can be taken to be a crucial date for uranium prospects, as summarised in the table. Unless the production of mined uranium can be increased by some 22,000 tonnes per annum, there will be a 35 percent deficit in uranium supply. So, the question is whether the production of mined uranium can rise to compensate.

Can uranium production increase to fill the gap?

Although several of the medium-sized producers have in recent years roughly maintained their output, or slightly increased it – notably Kazakhstan, Namibia, Niger and Russia – the world's two largest producers – Canada and Australia – both show some evidence of being in recent decline, with uranium production falling by (respectively), 15 and 20 percent in 2005-2006.[50]

In both cases, hopes for expanding production have been pinned on major new projects – the new Cigar Lake mine in Canada, and the expansion of Olympic Dam in Australia. Cigar Lake is designed to produce nearly 7,000 tonnes per annum, and it was due to start in 2007. However, in October 2006, it flooded; the probable way of containing the water in the sandstone above the workings is by refrigeration, which will require large inputs of energy even before work can begin. It is now uncertain whether, even after long past and future delays, Cigar Lake will ever be a substantial source of uranium.[51]

The contribution of Olympic Dam is in some ways even more dubious. At present, it is an underground mine well past its maturity, and the management, BHP Billiton, is considering whether to move to an adjacent ore body with an open pit mine on a massive scale. The new mine would be three kilometres in diameter and one kilometre deep, with some 350 metres of rock overburden to be removed in order to get at the ore. The problem is that the uranium ore is very low-grade – only 0.06 percent and less, with an average of 0.029 percent, so that it would be uneconomic in money terms if it were not for the copper, gold and silver which the rock also contains. But that itself is a mixed blessing because it means that the copper is contaminated with small quantities of uranium, which has to be removed in a smelter constructed in the Australian desert, adding even greater energy-costs to the final energy yield.[52]

Doubts as to whether Olympic Dam is capable of yielding uranium with a positive energy balance are increased by a recent study by Storm van Leeuwen, who suggests that the energy return on the energy invested in the mine is only marginally better than that of gas. Moreover, the removal of 350 metres of overburden, followed by the milling of low-grade ore would require Australia to import diesel oil with an energy content not far short of the final energy-yield of the uranium it would produce. High oil prices, aggravated by actual outages in oil supplies as the effects of the oil peak mature, would cause problems for a project for which a large and reliable flow of diesel would have to be guaranteed.

Moreover, the mine is in an area of extreme drought: even if it does supply its own water by desalinating seawater, it is possible that the needs of agriculture will have a prior claim on South Australia's water resources.[53]

The BHP Billiton board has not yet made the final decision whether to go ahead, but the independent nuclear energy analyst John Busby concludes that it is "unlikely", and that, even if it did, uranium production would "certainly" be closer to 5,000 tonnes per annum than to the 15,000 tonnes which was originally planned.[54]

On this evidence is seems probable that, far from expanding in order to sustain the flow of energy following the oil peak, the nuclear industry will indeed begin to falter during the decade 2010-2019, with some nuclear reactors being closed down for lack of fuel, and some of the reactors now in the planning stage and under construction remaining unused indefinitely.

In the light of this, a judgment has to be made as to whether hopes of a revival of uranium supply are a sufficiently realistic foundation on which to base expectations that the nuclear industry has a long term future as a major energy provider. Even the NEA hedges its bets about this. Readers are invited to read the following two sentences from the Executive Summary with care and to decide for themselves whether they are reassured that the uranium needed to fuel the industry's recovery after the coming shortfall will in fact be available:

> The long lead-times needed to bring resources into production continues to underscore the importance of making timely decisions to increase production capability well in advance of any supply shortfall. Improved information on the nature and extent of world uranium inventories and other secondary sources would improve the accuracy of the forecasting required to make these timely production decisions.[55]

And this brings us to the critical question of whether there will be enough uranium to provide the energy to clear up the nuclear industry's own accumulated waste.

Can the industry supply the energy to clear its own waste?

First of all, we need some definitions. We can define the "net" energy produced by the nuclear industry as the electricity generated *minus* "front-end" energy – the energy needed to build reactors, to mine, mill, enrich and prepare the fuel, and to carry out all the other energy-using tasks needed to produce nuclear energy. "Back-end" energy – the energy needed to clear up all the wastes produced at each stage of the front-end processes, including the disposal of old reactors – is of two kinds: (1) the energy needed to dispose of the *new waste* – that is, the waste produced in the future, and (2) the energy needed to dispose of the whole *backlog* which has accumulated since the nuclear industry started-up in the 1950s. Back-end energy is the combined total of both of these.[56]

Most of the energy needed for these front-end and back-end processes actually comes from derivatives of fossil fuels such as diesel oil to power mining and milling machines, and coal or gas to make steel and concrete. But it is the total energy balance that matters, not the question of which source of energy will be needed for any particular part of the nuclear cycle, so it makes sense to think of all the front-end and back-end energy needs as if they were supplied from nuclear electricity.

This means that some of the energy produced by nuclear reactors will not actually be available for sale because it will be required for those processes. To keep the explanation simple and in round numbers, we will use the estimate that the industry has another 60 years during which it could in practice sustain current rates of extraction, getting more energy out of the entire process than it puts into it – a positive PREI. Remember that, for reasons explained above, this is an optimistic estimate, and the implications of other estimates will be discussed in chapter 6. But, for now, let us call 60 years the "nominal" estimate and use it to help us concentrate on the principles:

The first question to ask is, "How long would the industry be able to sustain its current output if the front-end energy costs had to be met out of the electricity generated by nuclear reactors?" Well, this varies with circumstances but, as an approximate guideline, the front-end processes require about one quarter of the gross energy output of nuclear reactors, so the answer to this question is: three quarters of 60 years – that is, about 45 years.[57]

Now we come to the back-end processes: the energy cost of disposing of the 60 years-worth of new waste is approximately the same as that of the front end – that is, about one quarter of the gross output, or 15 years of energy supply, so that brings the supply of available energy down to 30 years.

But then there is still the backlog – the 60 years-worth of waste produced since 1950, and dealing with this will this require yet another 15 years of energy supply. That brings us finally down to the amount of energy we have available for use in the grid: 15 years.

In other words, even if the industry really had 60 years' supply of uranium left for its use, it would only have some fifteen years left before the decisive moment; from that turning-point, its entire net output of energy would have to be used for the essential task of getting rid of its stockpile of wastes, plus the wastes produced in the future.[58]

If, in its attempt to supply as much energy as possible, the industry were to postpone the task for more than that fifteen years, it would become energy-bankrupt: it would owe more energy to the planet than it could generate: it would *never* be able to produce enough net energy to dispose of its life-time waste. This means that, even if the nominal estimate of 60 years were correct, the industry would face a turning-point to energy-bankruptcy in about 2025.

The task of clearing up the remaining waste – the alternative to converting the planet into an open-plan waste-dump – is non-negotiable. The time we have left in which to do it depends on how much uranium with a positive PREI remains – and the short time we have left, even if there is as much as sixty years' supply remaining, is set in context with other estimates, both shorter and longer, in chapter 6. Meanwhile, we should not forget the money-cost of this. If the nuclear industry in the second half of its nominal 120-year whole-life span (1950-2070) were to commit itself (as it must) to the cost of clearing up its current and future waste, any electricity left over and available for sale would become exceedingly expensive, and the industry would soon reach the point at which it had no spare energy to sell anyway.

Meanwhile, governments will have to keep the clear-up programme going well into the future, whatever the other priorities. They will probably have to buy-in much of the needed net energy from other sources, at which point, of course, the industry will change from being a net supplier of energy to being a net consumer. And yet, in an energy-strapped society, the non-nuclear energy needed to dispose of the nuclear industry's legacy will be hard to find. The prospect is opening up of massive stocks of unstable wastes which – since the energy is lacking – are impossible to clear up.

Nuclear energy is therefore caught in a depletion trap – the depletion of rich uranium ore, on a timescale similar to that of oil and gas. So the question to be asked is: as the conventional uranium sources run low, are there alternative sources of fuel for nuclear energy?

4. ALTERNATIVE SOURCES OF FUEL?

At this point, the natural thing to do is to turn to James Lovelock's robust dismissal of the idea that the growth of nuclear power is likely to be constrained by depletion of its raw material. This is how he deals with it:

> Another flawed idea now circulating is that the world supply of uranium is so small that its use for energy would last only a few years. It is true that if the whole world chose to use uranium as its sole fuel, supplies of easily-mined uranium would soon be exhausted. But there is a superabundance of low-grade uranium ore: most granite, for example, contains enough uranium to make its fuel capacity five times that of an equal mass of coal. India is already preparing to use its abundant supplies of thorium, an alternative fuel, in place of uranium.[59]

Lovelock also urges that we have a readily-available stock of fuel in the plutonium that has been accumulated from the reactors that are shortly to be decommissioned. And he might have added that other candidates as sources of nuclear fuel are seawater and phosphates. So, if we put the supposed alternatives to uranium ore in order, this is what we have: (1) granite; (2) fast-breeder reactors using (a) plutonium and (b) thorium; (3) seawater; and (4) phosphates.

Granite

It has already been explained above that granite with a uranium content of less than 0.02 percent cannot be used as a source of nuclear energy, because that is the borderline at which the energy needed to sustain the whole nuclear energy life-cycle is greater – and in the case of even poorer ores, much greater – than the energy that comes back. But Lovelock is so insistent and confident on this point that it is worth revisiting.

Storm van Leeuwen, basing his calculations on his joint published work with Smith, considers how much granite would be needed to supply a 1 GW nuclear reactor with the 200 tonnes of natural uranium needed as a fuel source for a year's full-power electricity production. Ordinary granite contains roughly four grams of uranium per tonne of granite (4 ppm or 0.0004 percent). One year's supply of uranium extracted from this granite would require 100 million tonnes of granite (assuming, very optimistically, that you can get the granite to yield as much as half the uranium it contains). So, Lovelock's granite could indeed be used to provide power for a nuclear reactor, but there are snags. The minor one is that it would leave a heap of granite tailings (if neatly stacked) 100 metres high, 100 metres wide and 4 kilometres long. The major snag is that the extraction process would require some 650 PJ (a petajoule = 1,000,000 billion joules) energy to produce the 26 PJ electricity provided by the reactor. That is, the process would use up some 25 times more energy that the reactor produced.[60]

As for the comparison between granite and coal: well, a 1 GW coal-fired power station needs about 2 million tonnes of coal to keep it going for a year, compared with 100 million tonnes of granite. Far from the practically-available fuel capacity of a tonne of granite being five times that of a tonne coal, it is 50 times less. Lovelock's calculation is adrift by a multiple of around 250.

Fast breeder reactors

(a) Plutonium

Lovelock's proposal that we should use plutonium as the fuel for the nuclear power stations of the future can be taken in either of two ways. He might be suggesting that we could simply run the reactors on plutonium on the conventional "once-through" system which is standard, using light-water reactors. It is debatable whether this can be done; it has never been attempted, and it would involve a significantly different process, including the use of a different moderator. A more plausible approach would be to use it in some kind of combination with uranium – but then it is not solving the problem of uranium becoming scarce, and the very small contribution (2 per cent) which has been successfully reprocessed from spent fuel into mixed oxides (MOX) shows that this is not going to be a replacement for uranium.

There are about 240 tonnes of plutonium in the world held in stock for civilian use. In principle, this could be increased from two sources; (a) the ex-weapons plutonium (about 150-200 tonnes); and (b) from the plutonium in spent fuel – but the problem here is that extracting it adds yet another layer of difficulty to the aim of a smoothly-running commercial operation for fast-breeders. The UK's extraction plant, Thorp, has closed down after a massive leak and is unlikely to be reopened; extraction of plutonium is done to some extent in France, Russia, Japan and India, but it is such a tricky process that the United

States has made it illegal.[61]

But breeding is a potentially attractive technology. Let us suppose, then, that the best estimate for the amount of available plutonium in the world is 240 tonnes, and that there is enough uranium or MOX around to use it in reactors. You don't get many functioning reactors for that. The UK's stocks of 106 tonnes, along with MOX, would be enough to fuel just two reactors for their lifetime (so there would be enough for four reactors worldwide). Then, at the end of their life (say, 24 full-power years), the plutonium would have been used up; they would then be closed down and not replaced, because at that time there will be no uranium left to fuel them, apart perhaps from very small quantities of MOX. This would scarcely be a useful strategy, so it is more sensible to suppose that Lovelock has in mind the second possibility: that the plutonium reactors should be breeder reactors, designed not just to produce electricity now, but to breed more plutonium for the future.

Breeders are in principle a very attractive technology. In uranium ore, a mere 0.7 percent of the uranium content consists of the useful isotope – the one that is fissile and produces energy – uranium-235. Most of the rest consists of uranium-238, and most of that simply gets in the way and has to be dumped at the end; it is uranium-238 which is responsible for much of the awesome mixture of radioactive materials that causes the waste problem. And yet, uranium-238, as we saw in the introduction, also has the property of being fertile. When bombarded by neutrons from a "start-up" fuel like uranium-235 or plutonium-239, it can absorb a neutron to become uranium-239, which quickly decays to neptunium-239 and then to plutonium-239. This means that plutonium-239 can be used as a start-up fuel to breed more plutonium-239, more-or-less indefinitely. That's where the claim that nuclear power would one day be too cheap to meter comes from. The Nuclear Energy Agency (NEA) and International Atomic Energy Agency (IAEA) suggest that if all available sources of ore are exploited, and fast-breeder reactors perfected and developed, we may look forward to 20,000 years of nuclear energy at current rates of output.[62]

But there is a catch. It is a complicated technology. It consists of three operations: breeding, reprocessing and fuel fabrication, all of which have to work concurrently and smoothly.

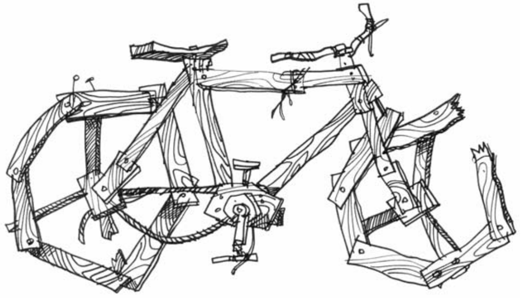
First, breeding: this does not simply convert uranium-238 to plutonium-239; at the same time, it breeds plutonium-241, americium, curium, rhodium, technetium, palladium and much else. This fiercely radioactive mixture tends to clog up and corrode the equipment. There are in principle ways round these problems, but a smoothly-running breeding process on a commercial scale has never yet been achieved.[63]

Secondly, reprocessing. The mixture of radioactive products that comes out of the breeding process has to be sorted, with the plutonium-239 being extracted. The mixture itself is highly radioactive, and tends to degrade the solvent, tributyl phosphate. Here, too, insoluble compounds form, clogging up the equipment; there is some debate about how great the danger is of plutonium accumulating into a critical mass, and setting off a nuclear explosion. The mixture gets hot and releases radioactive gases; and significant quantities of the plutonium and uranium are lost as waste. As in the case of the breeder operation itself, smoothly-running reprocessing on a commercial scale has never yet been achieved.

The third operation is to fabricate the recovered plutonium as fuel. The mixture gives off a great deal of gamma and alpha radiation, so the whole process of forming the fuel into rods which can then be put back into a reactor has to be done by remote control. This, too, has yet to be achieved as a smoothly-running commercial operation.

And, of course, it follows that the whole fast-breeder cycle, consisting of three processes none of which have ever worked as intended, has itself never worked. There are three fast-breeder reactors in the world: Beloyarsk-3 in Russia, Monju in Japan and Phénix in France; Monju and Phénix have long been out of operation; Beloyarsk is still operating, but it has never bred.

But let us look on the bright side of all this. Suppose that, with 30 years of intensive research and development, the world's nuclear energy industry could find a use for all the reactor-grade plutonium in existence, and fabricate it into fuel rods. You can see straight



away how seductive this technology is because when plutonium is used in fast breeders, wrapped in large “blankets” of uranium-238, you need (in theory) just three tonnes of plutonium to drive the process along, so you could (in theory) start up 80 fast-breeder reactors at the same time. So, they start breeding in 2035. But the process is not as fast as the name suggests (“fast” refers to the speeds needed at the subatomic level, rather than the speed of the process), and the outcome is by no means certain; but let us give the technology the benefit of the doubt: everything goes according to plan. Forty years later, each breeder reactor would have bred enough plutonium to replace itself and to start up another one. With the benefit of these magical assumptions becoming reality, by 2075 – long after reaching the depths of the coming energy famine – we would have 160 breeder reactors in place worldwide (there are 439 nuclear reactors in operation now). And that is all we would have, because the ordinary, uranium-235-based reactors would by then be out of fuel.[64]

SAFETY CATCH

The complexity of preventing accidents can make the system impossible

There is a systemic problem with the design of breeder reactors. Nuclear accident is potentially so destructive that the possibility has to be practically ruled out under all circumstances. This means that the defence-in-depth systems have to be extremely complex, which means that the installation must be large enough to derive economies of scale – otherwise it would be uneconomic. However, that in turn means that no confinement dome can be built on any acceptable design criterion on a scale and with the structural strength to withstand a major accident. Therefore, the defence-in-depth systems have to be even more complex, which in turn means that they become even more problem-prone than the device they were meant to protect.

A study for the nuclear industry in Japan concludes: “A successful commercial breeder reactor must have three attributes: it must breed, it must be economical, and it must be safe. Although any one or two of these attributes can be achieved in isolation by proper design, the laws of physics apparently make it impossible to achieve all three simultaneously, no matter how clever the design.”[65]

(b) Thorium

The other way of breeding fuel is to use thorium. Thorium is a metal found in most rocks and soils, and there are some rich ores bearing as much as 10 percent thorium oxide. The relevant isotope is the slightly radioactive thorium-232. It has a half-life three times that of the earth, so that makes it useless as a direct source of energy, but it can be used as the starting-point from which to breed an efficient nuclear fuel. Here's how:

- Start by irradiating the thorium-232, using a start-up fuel – plutonium-239 will do it. Thorium-232 is slightly fertile, and absorbs a neutron to become thorium-233.
- The thorium-233, with a half-life of 22.2 minutes, decays to protactinium-233.
- The protactinium-233, with a half-life of 27 days, decays into uranium-233.
- The uranium-233 is highly fissile, and can be used not just as nuclear fuel, but as the start-up source of irradiation for a blanket of thorium-232, to keep the whole cycle going indefinitely. [66]

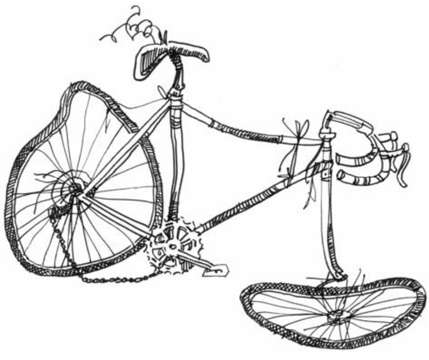
But, as is so often the case with nuclear power, it is not as good as it looks. The two-step sequence of plutonium-breeding is, as we have seen, hard enough. The four-step sequence of thorium-breeding is worse. The uranium-233 which you get at the end of the process is contaminated with uranium-232 and with highly-radioactive thorium-228, both of which are neutron-emitters, reducing its effectiveness as a fuel; it also has the disadvantage that it can be used in nuclear weapons. The comparatively long half-life of protactinium-233 (27 days) makes for problems in the reactor, since substantial quantities linger on for up to a year. Some reactors – including Kakrapar-1 and -2 in India – have both achieved full power using some thorium in their operation, and it may well be that, if there is to be a very long-term future for nuclear fission, it will be thorium that drives it along. And yet, the full thorium breeding cycle, working on a scale which is large-enough and reliable-enough to be commercial, is a long way away.[67]

And even if that day does come, its contribution, for the foreseeable future, will be tiny. This is because it has to begin with some start-up fuel – a source of neutrons to get the whole thing going. That could come in any of three forms. It could come from uranium-235, which is going to be scarce, but there could perhaps be a case for using some in a breeder, even if the process for the first generation of reactors used more energy than it generated. Or, it could come from plutonium, but (a) there isn't very much of that around either; (b) what there is (especially if we are going to do what Lovelock urges) is going to be busy as the fuel for once-through reactors and/or fast-breeder reactors, as explained above; and (c) it is advisable, wherever there is an alternative, to keep plutonium-239 and uranium-233 – an unpredictable mixture – as separate as possible. The third, and ideal, option is uranium-233, the final fuel produced by the thorium cycle, but the problem here is that it doesn't exist until the cycle is complete, so it can't be used to start it.

But let's suppose that enough uranium-235 or plutonium-239 were made available to provide a full load for one reactor and to keep it going for its lifetime. There is no good foundation for forecasting the rate of growth but, taking account of all the assumptions about technical solutions that are intrinsic to this subject, there is the possibility that by 2075 there could be two thorium-cycle breeder reactors delivering energy to the grid.[68]

Seawater

Seawater contains uranium in a concentration of about thirty parts per billion, and advocates of nuclear power are right to say that, if this could be used, then nuclear power could in principle supply us with the energy we need for a long time to come. Ways of extracting those minute quantities of uranium from seawater and concentrating them into uranium oxide have been worked out in some detail. First of all, uranium ions are attracted – "adsorbed" – onto adsorption beds consisting of a suitable material such as titanium hydroxide, and there are also some polymers with the right properties. These beds must be suspended in the sea in huge arrays, many kilometres in length, in places where there is a current to wash the seawater through them, and where the sea is sufficiently warm – at least 20°C. They must then be lifted out of the sea and taken on-shore, where, in the first stage of the process, they are cleansed to remove organic materials and organisms. Stage two consists of



“desorption” – separating the adsorbed uranium ions from the beds. Thirdly, the solution that results from this must be purified, removing the other compounds that have accumulated in much higher concentration than the uranium ions. Fourthly, the solution is concentrated, and fifthly, a solvent is used to extract the uranium. The sixth stage is to concentrate the uranium and purify it into uranium oxide (yellowcake), ready for enrichment in the usual way.[69]

But the operation is massive and takes a lot of energy. Very roughly, two cubic kilometres of sea water is needed to yield enough natural uranium to supply one tonne of fuel, prepared and ready for action in a reactor. A 1 GW reactor needs about 200 tonnes of natural uranium for one full-power year, so each reactor would require some 400 cubic kilometres of seawater to be processed – that is 40,000 cubic kilometres of seawater being processed in order to keep a useful fleet of 100 nuclear reactors in business for one (full-power) year.[70]

And what is the energy balance of all this? One tonne of natural uranium is needed to produce to produce approximately 160 TJ (1 terajoule = 1,000 billion joules), *less* the energy costs of the front-end processes (defined in chapter 3) – giving a net electricity yield of some 120 TJ, while the back-end processes have to come out of that. The energy needed to supply the uranium from seawater, ready for entry into that fuel cycle, is in the region of 195-250 TJ, so that the use of seawater as a source of energy would require more energy than it could produce.

Phosphates

The claims for phosphates as a source of uranium are impressive. The Red Book published by the NEA and the IAEA concludes that, by including phosphates as a uranium source, their already high estimate for the supply of uranium, including prognosticated resources (275 years at current rates) could be more than doubled to 675 years.[71]

The first thing to note is that the process of extraction is difficult. The phosphate ores are used to produce phosphoric acid, which is then concentrated in uranium, a process which requires solvents including toxic organophosphate compounds, and produces organofluorophosphorus and greenhouse gases in the form of fluorohydrocarbons.[72]

And then there is the even deeper problem of supply. Phosphates are, at best, a poor source of uranium. The largest deposits contain uranium ore concentrations of between 0.007 percent and 0.023 percent; they average around 0.01 percent.[73] That is to say, this is a low-grade uranium ore, giving a negative PREI. Moreover, there is now increasing concern that the production of phosphates, which are an essential requirement for agriculture too, is close to its peak, and is poised for the decline characteristic of a depleting resource.[74]

The ultimate, iconic error for a society in trouble is to “eat its seed corn”. The evidence so far suggests that the use of phosphates as a source of the uranium for nuclear fuel would be like burning it.

If we bring the above brief review of alternative sources of uranium together with the analysis of chapter 3, it is reasonable to conclude that, even if the nuclear industry presented no other problems, “peak uranium” would rule out the prospect of the nuclear industry being in any way an answer to “peak oil”, and to scarcities of gas and coal.

It is now decision-time for many nations confronting the fierce certainty of climate change, the depletion of oil and gas, and the ageing of their nuclear reactors. Why should the decision-makers take any notice of this analysis, written from a global perspective? Well, one of the problems is that it is not a decision that can be made in isolation. Nuclear power could in theory be sustained by a few individual nations: they could perhaps export their wastes, and reduced competition for rich ores would mean that the supply of uranium could be spun out for a long time. So, for an individual nation looking at the choice in isolation, the nuclear option may seem to be attractive. But there is a “fallacy of composition” here: an option that is available to one cannot be supposed to be available to many; on the contrary, it is only available to the one *because* it is not adopted by many – and if it *is* adopted by many, then everyone is in trouble, deep trouble.

5. IN CONTEXT

The priority for the nuclear industry now should be to use the electricity generated by nuclear power to clean up its own pollution and to phase itself out before events force it to close down abruptly. Contrary to what you might think, given the huge scale of its problems and its supposed status as a fall-back position which could solve our energy problems the nuclear energy industry is small, providing a mere 2½ percent of the world's final energy demand.[75] Nuclear power is not a solution to the energy famine brought on by the decline of oil and gas. Nor is it a means of reducing emissions of greenhouse gases. It cannot provide energy solutions, however much we may want it to do so.

But the conclusion that the nuclear industry cannot provide the energy we need over the next three or four decades means that we have a problem. An energy gap lies before us, for two reasons. First the damage done to the self-regulating systems of the climate is already so great that we are at or near the tipping point at which global heating will get out of control, moving relentlessly but quickly towards a new equilibrium state possibly lethal to the majority of the inhabitants of the planet and to its civilisations. Secondly, we are at or near the "oil peak" at which supplies of oil and (slightly later) gas will turn down into a relentless decline with consequences on a scale comparable to those of climate change. In this situation, we have little choice. If there is any energy source at all which could operate on the scale and in the time needed to fill this energy gap, then we must take it, even if it comes with enormous disadvantages.

Nuclear energy certainly has disadvantages, quite apart from the clincher problem of the depletion of its fuel. It is a source of low-level radiation which may be more dangerous than was previously thought. It is a source of high-level waste which has to be sequestered. Every stage in the process produces lethal waste, including the mining and leaching processes, the milling, the enrichment and the decommissioning. It is very expensive. It is a terrorist target and its enrichment processes are stepping stones to the production of nuclear weapons.[76]

And yet, so great is the need for some way of closing-off the demand for fossil fuels and filling the energy gap, and so serious are the consequences of not doing so, that Lovelock can argue that it would be better to develop nuclear energy, even with these disadvantages, than to fail to stop carbon emissions – or else fall into the energy gap and take the consequences. Lovelock writes: “We need emission-free energy sources immediately, and there is no serious contender to nuclear fission”.[77] He suggests that the decision is much clarified for us if we recognise the risk of climate change for what it is, and he adds that we will not succeed in doing this if we do not in the process move beyond the intellectual analysis and, instead, feel the fear:

> Few, even among climate scientists and ecologists, seem yet to realise fully the potential severity, or the imminence, of catastrophic global disaster; understanding is still in the conscious mind alone and not yet the visceral reaction of fear. We lack an intuitive sense, an instinct, that tells us when Gaia is in danger.[78]

Lovelock’s argument is persuasive. But there are three grounds on which it is open to criticism.

1. The nuclear fuel cycle

Uranium depletion is not a “flawed idea”; it is a reality that is just a little way ahead. Lovelock’s otherwise brilliant analysis of climate change displays no knowledge of the nuclear fuel-cycle. His optimism about the feasibility of nuclear power in the future is a case of whistling in the dark.

2. Alternative energy strategies

Lovelock may underestimate the potential of the fourfold strategy which can be described as “Lean Energy”, an application of “lean thinking” – perceptive intelligence applied to systems. It consists of four aims:

(1) Energy efficiency: to achieve the decisive improvements in the efficiency of energy-services made possible by the conservation and energy-saving technologies.

(2) The proximity principle: to develop the potential for local provision of energy, goods and services. This major structural change, reducing the transport-dependency of goods, people and electricity, is difficult but necessary. It is achievable only incrementally, building local competence across the whole range of economics and culture. Deep reductions in travel and transport can be expected to come about rapidly and brutally as the oil market breaks down; adapting to them – and crucially, preparing for them before the event – will take longer.

(3) Renewable energy: to design and build renewable energy systems to match the needs and resources of the particular place and site.

(4) Tradable Energy Quotas (TEQs): to define a secure energy budget for the whole economy, involving every energy-user in the common purpose of achieving deep reductions in energy demand.[79]

It cannot be expected that this strategy will fill the energy gap completely, or neatly, or in time, but nor is Lovelock suggesting that nuclear energy could do so. Even if there were neither a uranium-supply problem to restrain the use of nuclear energy, nor a waste-problem, and even if it were the overriding priority for governments around the world, nuclear energy would still fall far short of filling the gap. It would be impossible to build all the nuclear power stations needed in time, and the energy required for construction and for building the mining-milling-enrichment-transport systems would mean that a rapidly-growing nuclear energy industry would be using more energy than it provided throughout most of its period of growth – the more rapid the growth, the deeper the energy deficit it would cause.

There are good reasons to believe that Lean Energy could do better. It would start to get results immediately. Per unit of energy-services produced, it would be about ten times cheaper. It would be flexible and sensitive to detail, making the best possible use of local conditions, skills and ingenuity. It would be able to call on the skill and cooperation of the entire population. And it would be part of an environmental and practical evolution towards reduced transport, environmental protection and strengthened local economics all coming together in a joined-up programme.

3. The oil peak

Lovelock does not give enough weight to the significance of the oil peak. As this weighs in, it will establish conditions in which there is no choice but to conserve energy, whether the urgency of climate change is recognised or not. Without the oil peak to concentrate the mind, action to save the climate could be leisurely at best. With the oil peak reminding us, by repeatedly turning out the lights and stopping us filling up our cars, we will have an incentive to follow the one available option of Lean Energy with all the will and determination we can find.

What appears to follow from this is a best-of-both-worlds strategy: to develop nuclear energy as far as the uranium supply allows, and at the same time to develop Lean Energy. But the problem is that the two strategies are substantially incompatible. A dash for nuclear energy would reduce the funds and other resources, and the concentrated focus, needed for Lean Energy. Nuclear energy relies on the existence of a fully-powered-up grid system into which it can feed its output of electricity – but the grid itself is mainly powered by the electricity from gas-fuelled power stations, so that if gas supplies were to be interrupted, the grid would (at least partially) close down, along with the nuclear reactors that feed into it; Lean Energy, on the other hand, is flexibly organised around local minigrids.

Nuclear energy inevitably brings a sense of reassurance that, in the end, the technical fix will save us; Lean Energy calls on the whole range of technology from the most advanced to the most labour-intensive, along with adaptations in behaviour, in the economy, in the use of land and distance, in the way food is grown and materials are used, and in the sinews and culture of society itself. Nuclear energy's potential contribution to energy services in the future, starting from its present level of 2½ percent of final energy demand, is small; the potential for Lean Energy is at least twenty times greater. Nuclear energy is about conserving the bankrupt present; Lean Energy is about inventing and building a future that works.[80]

For these reasons, the best-of-both-worlds strategy of backing both nuclear energy and Lean Energy could be expected to lead to worst-of-both-worlds consequences. Lean Energy would be impeded by nuclear energy; nuclear energy would be hopelessly ineffective without Lean Energy. Result: paralysis. This should not be overstated: a few token nuclear reactors to replace some of those that are about to be retired would make it much harder to develop Lean Energy with the single-minded urgency and resources needed, without necessarily ruling out progress towards it entirely. But the defining reality of the energy future has to be an acknowledgment that no large-scale technical fix is available. Energy cannot any longer be delegated to experts. The future will have to be a collective, society-transforming effort.

6. IT'S TIME TO TURN TO THE WIT AND ENERGY OF THE PEOPLE

The strategic matters discussed in chapter 5 are important, but it is the waste problem which is decisive. There is a turning-point when the nuclear industry will become energy-bankrupt, if it has not already done so. After that, it will never be able to generate the energy needed for permanent disposal of its backlog of waste, even if it diverts its whole energy output into the task.

This prospect needs to be researched urgently and by more than one research centre with the authority to get at the facts, but otherwise working independently of industry or government interests. Research should also, with all speed, get evidence about the global warming and ozone impacts of uranium hexafluoride and other solvents, both in use and as leaking waste. And here is a hypothesis to which we need an answer at some speed: if the worldwide backlog of nuclear wastes were simply left to leak, catch fire and spread into the environment, the resulting levels of radiation and toxicity would in principle require the evacuation of the planet. True, or not?

Waste and depletion are two aspects of the same problem. For the timing of depletion, we will consider four estimates, starting with one which suggests that the industry will not recover from the 2011-2020 outages, giving an estimate of 10 years before the industry ceases to be a significant producer of electrical power owing to depletion of uranium giving a positive practical return on energy invested (PREI). The second estimate suggests that the industry does recover from the coming outages and continues as an energy producer at roughly current rates for 30 years. Thirdly, we take the estimate discussed in chapter 3, which has a time-horizon of 60 years. Fourthly, let us suppose that this present analysis is completely misguided, and that the industry will continue on its present scale for another 200 years.

These estimates are now brought together with the estimates of the net energy yielded by the nuclear industry, after the costs of the front-end processes (procuring the fuel and producing energy from it) and back-end processes (dismantling reactors and dealing with wastes) are taken into account. They are summarised in the Energy Balance Sheet.

ENERGY BALANCE SHEET: YEARS OF NET NUCLEAR ENERGY REMAINING FROM 2010

at current rates of extraction.
(Assumed start-date for industry 1950. Assumed present 2010. Numbers in years)

1. Estimate: years of positive PREI ore remaining	**10**	**30**	**60**	**200**
2. Front-end process energy (25% of remaining years)	2.5	7.5	15	50
3. Energy to clear new waste (25% of remaining years)	2.5	7.5	15	50
4. Energy to clear old waste (25% of past 60 years)	15	15	15	15
5. Total needed for front end plus back end (2+3+4)	20	30	45	115
6. Years remaining (1-5)	-10	0	15	85
7. Year of energy-bankruptcy: all energy produced is needed to dispose of new and old waste (6+2010)	2000	2010	2025	2095

Suppose the industry, starting with no waste, has 200 years before its usable ore runs out. During that time, it generates a *gross* amount of energy which it feeds into the grid, but at the same time it must (a) provide the energy needed for its own front-end operation, (b) pay back the energy it used to mine its ore, build its reactors, etc., and (c) clear up its own wastes. As explained in chapter 3, pp 17-18, each of these amount to about 25 percent of its gross energy output. Therefore that amount – 75 percent of its gross output, must be subtracted to find the number of years for which the industry can continue before using the whole of its output to pay back its energy debt and clear up its wastes.

There are other ways in which this could be calculated – for instance, using net output (gross output less the front-end energy cost factored in over time); or the back-end work could start sooner. These would tell slightly different stories, but they would be equally valid. The method shown in the table is a reminder that the industry actually supplies less energy (net) than the gross energy that it puts into the grid. At a time of energy scarcity, this is a key consideration. And it tells us how long the industry has left before waste-disposal becomes the reason for its existence.

We have, then, four dates for the turning-point at which the industry will never be able to supply the energy needed to get rid of its own wastes: that is, energy-bankruptcy: 2000, 2010, 2025 and 2095.

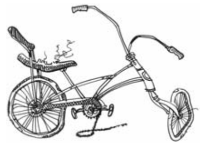
- If it is 2000, the industry is already deep into its energy-bankruptcy. It will never be able to get rid of its own waste from its own resources. There is the prospect of having to call on the supplies of fossil fuel energy, at a time of deepening scarcity, to deal with the nuclear waste which the waning nuclear industry cannot clear up.

- If it is 2010, the whole of the energy produced by the industry over its remaining life of 30 years must be directed into clearing up its own wastes, starting now.
- If it is 2025, the industry has some fifteen years before the onset of energy bankruptcy.
- If it is 2095, we are looking at an industry facing, in 85 years time, an inheritance of waste whose treatment will demand a flow of energy equal to some 115 years of electricity output – and with no electricity left over to sell.

In other words, the greater the estimate of remaining reserves, the longer the period of energy debt. In the event of the recklessly optimistic estimate of there being 200 years uranium remaining with a positive PREI, the last 115 years of the nuclear industry's operation would be committed to paying back its energy debt, dealing with the backlog of wastes, and with the large accumulation of its new wastes accrued during the final 200 years of its life. An energy debt on this scale is scarcely good news. Nor is the financial debt that would go with it.

With some justice, the nuclear industry could point out that the task of dealing with its wastes has already started, and that high-level waste has to be allowed to cool off. An experimental deep repository for high-level waste has been excavated in Sweden; Finland has started on a real one at Olkiluoto; plans to build one in Nevada are being debated; and research is being done into ways of dealing with uranium hexafluoride. And yet, the questions of where exactly it will go, who will take responsibility for the waste held in deteriorating stockpiles in unstable regions, how to pay for it and, above all, where the energy will come from, remain unanswered. Meanwhile, the industry continues to *add* to the problem. And suitable sites – stable, preferably dry, and enjoying the support of the local population – are rare; the vast size of a permanent repository, the technical difficulty, the energy needed and the cost all bring this massive task of long-term disposal to the edge of what is possible. It may in fact never be possible to find a permanent resting-place for all, or even for a decent proportion, of the waste that has already been produced.

The nuclear industry should therefore focus on finding solutions to the whole of its waste problem before it becomes too late to do so. And hold it right there, because this is perhaps the moment to think about what "too late" might mean. Notwithstanding the emphasis placed on



depletion in this booklet, it is climate change that may well set the final date for completion of the massive and non-negotiable task of dealing with nuclear waste. Many reactors are in low-lying areas in the path of rising seas; and many of the storage ponds, crowded with high-level waste, are close by. Estimated dates for steep rises in sea levels are constantly being brought forward. With an angry climate, and whole populations on the move, it will be hard to find the energy, the funds, the skills and the orderly planning needed for a massive programme of waste disposal – or even moving waste out of the way of rising tides. When outages in gas supplies lead to break down in electricity supplies, the electrical-powered cooling systems that stop high-level waste from catching fire will stop working. It will also be hard to stop ragged armies, scrambling for somewhere to live, looting spent fuel rods from unguarded dumps, attaching them to conventional explosives, and being prepared to use them.

All this will have to be dealt-with, and at speed. There may be no time to wait for reactor cores and high-level wastes to cool down. But, then, it may be a frank impossibility to bury them until they *have* cooled down…

In any event, the task of making those wastes safe should be an unconditional priority, equal to that of confronting climate change itself. The default-strategy of seeding the world with radioactive time-bombs which will pollute the oceans and detonate at random intervals for thousands of years into the future, whether there are any human beings around to care about it or not, should be recognised as off any scale calibrated in terms other than dementia.

Nuclear power is the energy source that claims a significance and causes trouble far beyond the scale of the energy it produces. It is a distraction from the need to face up to the coming energy gap, to inform the public and to call on the wit and energy which is available to develop a programme of Lean Energy. Of the many shortcomings in the response to energy-matters, a central one has been the failure to involve the public in doing what it could, given a chance, be good at – inventing solutions and making them happen in realistic local detail. Determined attempts are being made to rectify this (the U.K. Government's Climate Change Communication Initiative is an example) but the construction of nuclear reactors, presented as almost carbon-free fixes for the energy problem, is not a good way of involving the public. It is only when we are free of such narcotic fallacies that there will be a commitment to the one option for which there is a prospect of success: tapping the energy of the people.

We have to integrate energy, economics and society, and to enable them to develop in a way which copes with the reality of the energy gap that is now almost upon us. That calls for an effective framework which makes it clear to all of us – citizens, firms, the government, everyone – what the energy limits are now, and achieves an orderly descent to the low limits that will apply in the future. It is then up to us to bring all the skill, ingenuity and judgment we can to negotiating our way down the energy descent. We need to discover a common purpose. All this is possible if there is an appropriate framework for it, a system in which individual motivations are aligned with the collective need. There are various names for it. One of them is Tradable Energy Quotas (TEQs).

We need to enable small-scale actions to build up onto a scale that gets results; we need a robust, simple, system for recruiting ingenuity and intelligence, and the common purpose to make it happen now. Such a design exists. There is a non-nuclear life-cycle ready and waiting.[81]

THE NON-NUCLEAR LIFE-CYCLE

SOURCES

AFX News 2007), "TVO says won't share nuclear reactor cost overruns with Areva", at http://www.forbes.com/markets/feeds/afx/2007/09/28/afx4165822.html (http://tinyurl.com/2w2kl4).

Areva (2007a), "The first generation III+ reactor currently under construction", at http://www.areva-np.com/scripts/info/publigen/content/templates/show.asp?[-]P=1655&L=US&SYNC=Y (http://tinyurl.com/y557hh).

Areva (2007b) Presentations: "Business and Strategy Overview" http://www.areva.com/servlet/BlobProvider?blobcol=urluploadedfile&blobheader=application%2Fpdf&blobkey=id&blobtable=Downloads&blobwhere=1141726537731&filename=Overview+July+2007.pdf (http://tinyurl.com/3y855b). (Reference became unavailable at 25/10/07).

Australia Uranium Association (2007), "Australia's Uranium Mines", www.uic.com.au/emine.htm.

BHP Billiton (2007), Annual Report, at http://www.bhpbilliton.com/bbContent[-]Repository/bhbpannualreport07.pdf (http://tinyurl.com/26f2mz)

Boyle, Godfrey (2004), *Renewable Energy*, Oxford.

Bunn, Matthew (2003), "Reducing Excess Stockpiles", Nuclear Threat Initiative (NTI), www.nti.org/e_research/cnwm/reducing/heudeal.asp

Bureau of Air Quality (2007), "Greenhouses Gases and their Global Warming Potential Relative to CO_2" at www.state.me.us/dep/air/emissions/ghg-equiv.htm .

Busby, Chris (1995), *Wings of Death*, Aberystwyth: Green Audit.

Busby, John (2006), "Rip van Winkel Wakes", http://www.sandersresearch.com/index.php?option=com_content&task=view&id=993&Itemid=105). http://tinyurl.com/2lkbml).

Busby, John (2007a), "A Little Makes a Lot?" http://www.sandersresearch.com/index.php?option=com_content&task=view&id=1300&Itemid=105. (http://tinyurl.com/35gunk)

Busby, John (2007b), "An Even Bigger Hole", http://sandersresearch.com/index.php?option=com_content&task=view&id=1323&Itemid=103 (http://tinyurl.com/35pefj).

Cameco's website: www.cameco.com.

Canadian Nuclear (2007), FAQ at http://www.nuclearfaq.ca/cnf_sectionG.htm .

Collell, Marcel Coderich (2005), "The Nuclear Mirage and the World Energy Situation", Real Instituto Elcano, http://www.realinstitutoelcano.org/analisis/925.asp.

Committee Examining Radiation Risks of Internal Emitters (CERRIE), (2004), Report, at www.cerrie.org.

Committee on Radioactive Waste Management (July 2006), "Managing Our Radioactive Waste Safely", Final Report 31/7/06. www.corwm.org.uk.

Déry, Patrick, and Bart Anderson (2007), “Peak Phosphorus”, *Energy Bulletin*, http://energybulletin.net/33164.html.

Dzhakishev, Moukhtar (2004), “Uranium Production in Kazakhstan as a Potential Source for Covering the World Uranium Shortage”, World Nuclear Association, at http://www.world-nuclear.org/sym/2004/dzhakishev.htm.

Edwards, Gordon (2004), “Health and Environmental Issues Linked to the Nuclear Fuel Chain”, Section A: Radioactivity, at www.ccnr.org/ceac_B.html .

First Uranium Corporation (2007), *Annual Information Form* at http://www.firsturanium.com/downloads/2007_annual_information_form.pdf (http://tinyurl.com/28xmy8).

Fleming, David (2007), *Energy and the Common Purpose: Descending the Energy Staircase with Tradable Energy Quotas (TEQs)*, third edition, London: The Lean Economy Connection, www.teqs.net.

Greenpeace (2005), International Briefing Paper (18th November), “Europe’s Radioactive Secret: How EDF [Électricité de France] and European nuclear utilities are dumping nuclear waste in the Russian Federation”, at http://www.greenpeace.[-]org/international/press/reports/european-rad-secret. (http://tinyurl.com/2adgea).

Grimston, Malcolm (2005), Memorandum to the Select Committee on Environmental Audit, U.K. House of Commons.

Huwyler, S., L. Rybach and M. Taube (1975), “Extraction of uranium and thorium and other metals from granite”, EIR-289, Technical Communications 123, Eidgenossische Technische Hochschule, Zurich, September, tr. Los Alamos Scientific Laboratory, LA-TR-77-42, 1977), cited in Storm van Leeuwen (2006E).

Institute for Energy and Environmental Research (2005), Uranium Fact Sheet at http://www.ieer.org/fctsheet/uranium.html [sic - the typo may have been corrected by the time you read this].

International Energy Agency (2007), *Key World Energy Statistics*, http://www.iea.org/textbase/nppdf/free/2007/key_stats_2007.pdf (http://tinyurl.com/2vqztn)

International Atomic Energy Agency (2001), *Analysis of Atomic Energy Supply to 2050*, at http://www-pub.iaea.org/MTCD/publications/PDF/Pub1104_scr.pdf.

ISA, University of Sydney (2005), *Life-Cycle Energy Balance and Greenhouse Gas Emissions of Nuclear Energy in Australia,* University of Sydney, at http://www.pmc.gov.au/publications/umpner/docs/commissioned/ISA_report.pdf (http://tinyurl.com/2omtaq)

King, David (2004), “Global Warming, the science of climate change, the imperatives for action”, Greenpeace Business Lecture, Royal Society of Arts, 12 October.

Lean Economy Connection (2007), www.theleaneconomyconnection.net/links.html

Lidsky, Lawrence M., and Marvin M. Miller (1998), “Nuclear Power and Energy Security: A Revised Strategy for Japan”. (Website no longer available).

Lovelock, James (2006), *The Revenge of Gaia,* London: Penguin.

Maeda, Haruo (2005), The Global Nuclear Fuel Market: Supply and Demand to 2030, World Nuclear Association Symposium 2005, http://www.world-nuclear.org/sym/2005/maeda.htm .

Miller, G. Tyler (2000), *Living in the Environment: Principles, Connections and Solutions*, (eleventh edition), Pacific Grove, CA: Brooks/Cole.

Mudd, Gavin and Mark Diesendorf (2007), "Sustainability Aspects of Uranium Mining: Towards Accurate Accounting?", Second International Conference on sustainability Engineering and Science, Auckland, 20-23 February http://civil.eng.monash.edu.au/about/staff/muddpersonal/2007-SustEngSci-Sust-v-Uranium-Mining.pdf (http://tinyurl.com/ynsv77)

NEA/IAEA (2006): Nuclear Energy Association / International Agency, *Uranium 2005: Resources, Production and Demand*, (the "Red Book"), available from the OECD in Paris.

Executive Summary at http://www.nea.fr/html/general/press/2006/redbook[-]/welcome.html (http://tinyurl.com/23rdxk)

Slide Presentation at http://www.nea.fr/html/general/press/2006/[-]redbook/redbook.pdf (http://tinyurl.com/ysbxbe)

Nicolet, Jean-Paul and Douglas Underhill (1998), "Balancing Needs: Global Trends in Uranium Production and Demand", IAEA Division of Nuclear Fuel Cycle and Waste Technology, at http://f40.iaea.org/worldatom/Periodicals/Bulletin[-]/Bull401/article4.html. (http://tinyurl.com/2scmcl)

Nielsen, Rolf Haugaard (2006), "Final Resting Place", *New Scientist*, No 2541, 4 March, pp 38-41.

Nuclear Fuel Energy Balance Calculator (2007) at http://www.wise-uranium.org/nfce.html .

Oxford Research Group, ed (2006a), Storm van Leeuwen, "Energy Security and Uranium Reserves", Factsheet 4, at http://www.oxfordresearchgroup.org.uk/[-]publications/briefing_papers/energyfactsheet4.php (http://tinyurl.com/2ntqkt).

Oxford Research Group, ed (2006b), Storm van Leeuwen, "Energy from Uranium", http://www.stormsmith.nl/publications/Energy%20from%20Uranium%20-%20July%202006.pdf (http://tinyurl.com/3atnrd)

Pearce, Fred (2006), *The Last Generation*, Eden Project.

Rio Tinto (2005), "Increase in Ranger Mine's Reserves and Resources", (press release), http://www.riotinto.com/documents/Media/PR444g_ERA_Increase_[-]in_Ranger_mine_reserves_resources.pdf (http://tinyurl.com/yrb59c)

SLS. Abbreviation for Jan Willem Storm van Leeuwen and Philip Smith (2005).

Stern, Nicholas (2007), *The Economics of Climate Change*,http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate[-]_change/stern_review_report.cfm . (http://tinyurl.com/ye5to7).

Storm van Leeuwen, Jan Willem and Philip Smith (2005), Nuclear Power: The Energy Balance", at http://www.stormsmith.nl/ . This is being revised and replaced by Storm van Leeuwen (2007), but the original is still available on this site. Abbreviated in these notes and references to SLS.

Storm van Leeuwen (2006B), “Greenhouse Gases from Nuclear”, Appendix B, in Evidence to the IPCC Working Group III, Fourth Assessment Report Draft for Expert Review. (2006B*) is a subsequent revision. For accessible and edited versions of these appendices, see Storm van Leeuwen (2007).

Storm van Leeuwen (2006C), “Breeders”, Appendix C.

Storm van Leeuwen (2006E), “Uranium Resources and Nuclear Energy”, Appendix E.

Storm van Leeuwen (2006E2), “Uranium from Seawater”, Appendix E2.

Storm van Leeuwen (2006F), “Reprocessing”, Appendix F.

Storm van Leeuwen (2007), Jan Willem, Nuclear Power: The Energy Balance”, at http://www.stormsmith.nl/ . Abbreviated in these notes to SAL. At 21/10.2007, only Parts A-D are yet on-line.

Strahan, David (2007), *The Last Oil Shock*, London: John Murray.

Sustainable Development Commission (2006), (1) *The Role of Nuclear Power in a Low Carbon Economy*; (2) *Is Nuclear the Answer?* a commentary by Jonathon Porritt, Chairman, Sustainable Development Commission; (3) Evidence-Based Papers (1-8) – see www.sd-commission.org.uk/

SVL. Abbreviation for Storm van Leeuwen (2007).

Uranium Information Council (2004), “Thorium”, www.uic.com.au/nip67.htm.

Womack, James and Daniel Jones (2003), *Lean Thinking*, second edition, London: Simon & Schuster.

World Nuclear Association (2007a), at http://www.world-nuclear.org/

World Nuclear Association (2007b), “World Nuclear Power Reactors and Uranium Requirements, http://www.world-nuclear.org/info/reactors.html.

World Nuclear Association (2007c): “Uranium Production Figures (1998-2006), www.world-nuclear.org./info/uprod.html.

World Nuclear Association (2007d), “Thorium”, http://www.world-nuclear.org/info/inf62.html

Zittel, Werner and Jörg Schindler (2006), *Uranium Resources and Nuclear Energy*, Energy Watch Group, http://www.energyshortage.com/uran/docs2006/REO-Uranium_5-12-2006.pdf (http://tinyurl.com/2uggkd).

NOTES AND REFERENCES

1. Radioactivity is a property of minute particles in the dust, food and water which we take into our bodies every day. Some is natural background radiation, released by local rocks, and in most cases our bodies have had millions of years' practice in coping with them or secreting them. Some radioactive particles, however, products of the fission of uranium, are not just intensely toxic; they are new elements against which our bodies have no defences. For a controversial view of the health impacts of radioactivity, see Busby (1995), chapters 6-7.
2. Note that some 65 percent of global greenhouse gas emissions arise directly from the generation and use of energy. See Stern (2007), executive summary, p iv.
3. Edwards (2004).
4. Institute for Energy and Environmental Research (2005).
5. Lovelock (2006).
6. Storm van Leeuwen and Smith (2007) abbreviated to SLS. Sustainable Development Commission (2006).
7. SVL, Part D5. World Nuclear Association (2007a), "How it works: getting uranium from the ground".
8. Treatment of tailings and restoration, SVL, Part D6. Considered ideal rather than best practice, ISA, Sydney University (2006), p 98. (In SLS, chapter 4, p 4, there is also the requirement to seal the mine floor with clay).
9. For more detail on the decay products of uranium-238, see Edwards (2004), Section A.
10. World Nuclear Association (2007), "How It Works: Conversion and Enrichment"; also Storm van Leeuwen and Smith (2005), chapter 2.
11. France's store of 200,000 tonnes, and 8,000 tonnes p.a. addition: Greenpeace (2005): "At the end of 2003, the inventory of the French nuclear waste agency Andra stated that there were 220,000 tonnes of DU stored in France. According to forecasts, this gigantic stock will exceed 350,000 tonnes by 2020 only as a result of enrichment for EDF." (p 3).

    A further 8,000 tonnes exported: Greenpeace (2005): Net annual imports of uranium waste from Europe to Russia are "in excess of 8,000 tonnes" (p 7). This is based on Peter Diehl (2005), "Re-enrichment of West European Depleted Uranium Tails in Russia" Eco Defence (at Appendix 1 of Greenpeace 2005).

    Greenpeace (2005) also points out that the trade is illegal: "The Russian legislation prohibits the import of foreign nuclear materials for storage. According to paragraph 3 of article 48 of the federal law of 2001, "On Environmental Protection", import of nuclear waste and foreign nuclear materials to the Russian Federation for the purpose of its storage or disposal is prohibited." Ostensibly, the material goes to Russia only for re-enrichment, but the bulk remains and has to be stored as uranium hexafluoride. The transport arrangements are also illegal: the containers are Type 48G, a lower specification than the required IAEA TS-R-1, which is itself grossly inadequate in the case of fire (e.g.) on a container-ship on route from Le Havre to St. Petersburg.

12. World Nuclear Association (2007), “How It Works: Conversion and Enrichment”; also SLS chapter 2.
13. Disposal of high-level waste: For detail of the energy costs, see SLS, chapter 4; this is now conveniently summarised in SVL, Part C4. See also World Nuclear Association (2007), “How It Works: used fuel management”; and (for the UK), Committee on Radioactive Waste Management (July 2006), esp. chapters 14-15. For overview see Nielsen (2006). A variant is GeoMelt (see Google references). See also Busby (2006b).
14. Committee Examining Radiation Risks of Internal Emitters (CERRIE) (2004), Report.
15. The Nuclear Regulatory Commission is cited by Miller (2000), p 385-386. Nuclear engineer: George Gallatin, senior nuclear engineer, cited by Miller (2000), p 386. Flooded nuclear power stations: King (2004).
16. SLS, chapter 3; chapter 4. Storm van Leeuwen (2006B), pp 4-5, in Evidence to the IPCC Working Group III, Fourth Assessment Report Draft for Expert Review. For EPR see Areva (2007a) and web references. Summary/revision/clarification in SVL Part F.
17. This summary relies substantially on SLS. For “30 percent” see references below.
18. 16 percent: Storm van Leeuwen (2006a), “Energy from Uranium”, Ceedata Consulting, p 8, now summarised in Oxford Research Group, ed (2006a). See also Storm van Leeuwen (2006), Appendix B, and Oxford Research Group (2006b). The ideal source for this is, when available, will be SVL, Part G).
19. See SVL, Part C5. Note the question-marks.
20. Natural uranium per GW/annum: see Nuclear Fuel Energy Balance Calculator (2007); the approximation used here of 200 tonnes differs from SLS’s 162 tonnes. Global warming potential of HCs: see Bureau of Air Quality (2007). Nuclear reactors do not run continually over their lifetime; so “full-power years” are used as a measure of the time for which a particular reactor is actually producing electricity at full power during its lifetime.
21. The Consultation accepts estimates derived from the Sustainable Development Commission (2006), *The Role of Nuclear Power in a Low Carbon Economy,* chapter 2, p 22: “The Nuclear Energy Agency, (NEA), Foratom and the International Atomic Energy Authority (IAEA) all agree that nuclear power emits low amounts of carbon – between 2-6 g of carbon equivalent per kWh.” (See p 36 of the SDC report for sources).
22. ISA, University of Sydney (2005), pp 7, 171.
23. ISA, University of Sydney (2005) pp 63-67; Storm van Leeuwen (2006B*).
24. Concrete: AFX News (2007).
25. Storm van Leeuwen (2006B*).
26. However, knowledge of the whole set of emissions from nuclear energy, including GHGs from the solvents, is rudimentary. The ISA report is comprehensive, and includes an impressive critique of other estimates including SLS (pp 55-76), but it is

not as clear as might be hoped with respect to a statement and derivation of its own estimate of g/kWhs and its distribution through the nuclear cycle. Clarification from the authors would be welcome.

27. The estimate of 451 g/kWh of GHG emissions for combined cycle gas fired electricity generation comes from ISA, Sydney University (2006, p 122), and it covers only the combustion of gas. If losses incurred during extraction and in the distribution grid are included, the greenhouse gas emissions (in CO2 equivalents) is estimated at 577 g/kWh (p 136). The range of estimates for gas turbines comes from Grimston (2005).
28. For definitions of "front-end" and "back-end" see the Cast List and pp 17-18.
29. SLS chapter 2. Storm van Leeuwen (2006B). SVL, Parts D4 and G. Note that the concept of EREI becomes more complex when applied to comparisons between two energy sources. If a given amount of energy, contained in gas, could produce *more* electricity if used directly in a combined cycle gas turbine than if used in the nuclear energy cycle, nuclear energy becomes an expensive way of reducing the supply of electricity to the grid.
30. Mudd and Diesendorf (2007), p 8.
31. *Ibid*, p 9.
32. Oil peak: see Lean Economy Connection (2007).
33. World average ore grade: see Canadian Nuclear (2007).
34. Note that Rio Tinto (2005) announced a "cut-off grade" of 0.08 percent for its existing stocks of ore at its Ranger mine in Namibia. The use of "existing stocks" means that the ore has already been mined and is waiting to be milled, so that a lower-grade ore can be tolerated.
35. NEA/IAEA (2006). References to this are taken from accessible but authoritative summaries available on the Web.
36. It estimates that there are 4,743.000 tonnes available at a price of $ 130/kg. Nuclear Energy Agency (2006), Executive Summary. The World Nuclear Association (2007b) reports that current demand is 66,500 tonnes per annum. Note that this calculation of "the reserves to production ratio" is extremely crude, for reasons explained on p 12.
37. NEA (2006), Executive Summary; the calculation is shown at NEA (2006), Slide presentation.
38. This is accessibly summarised in Oxford Research Group, ed (2006a).
39. For the story of optimistic estimates of oil resources from the United States Geological Survey and the International Energy Agency, and the years squandered in debate about this, see Strahan (2007).
40. Nuclear Energy Agency (2006), Executive Summary. First Uranium Corporation (2007); see pp 14-16.
41. World Nuclear Association (2007b).
42. World Nuclear Association (2007b) estimates 439 working reactors operable in

September 2007. Areva (2007b) measures this as about 370 gigawatts of installed capacity.

43. World Nuclear Association (2007c).
44. See Dzhakishev (2004) table 2, and other references at note 36.
45. See Bunn (2003).
46. See Collell (2005); Zittel and Schindler (2006), pp 11.12.
47. Busby (2007a).
48. For a description of reprocessing, see chapter 4, p 18-23.
49. Sources for the table. Uranium supply: World production from mines: World Nuclear Association (2007c); additional sources and their availability Dzhakishev (2004); Collell (2006); Bunn (2003), Nicolet and Underhill (1998); International Atomic Energy Agency (2001); Zittel and Schindler (2006); Busby (2006).
50. World Nuclear Association (2007c).
51. See Zittel and Schindler (2006). For updates on Cigar Lake from the developer's point of view, see Cameco's website.
52. For quality of the ore in Olympic Dam see Australia Uranium Association (2007). This reports an average of 0.4 percent, but the more recent annual report for 2007 from BHP Billiton (2007), p 63, reports the average of 0.29 kg of uranium oxide per tonne (i.e. 0.029% uranium oxide). Yield: SVL, Part D8. Copper: Busby (2007b).
53. SVL, Part D8.
54. Busby (2007b).
55. Nuclear Energy Agency (2006), Executive Summary, p 3
56. For clarity "back-end including the backlog" should be made explicit to distinguish it from back-end without the backlog. In the industry, the backlog is often called the "legacy".
57. The energy-costs of each stage in the nuclear energy cycle are set out in SLS and summarised in Storm van Leeuwen (2006B) and in Oxford Research Group (2006b). See also SVL, Part C4, figure C11 and table C2, and (when available) Part G. Appendix B splits the energy costs conveniently into front-end and back-end. Part C lumps much of the front-end and back-end energy costs together as "lifetime operational energy input". The lifetime operational energy investments of 460 PJ is given as 45 percent of the gross output of 1030 PJ; the present analysis rounds up to 50 percent, but estimates vary greatly (higher and lower), and energy costs will rise rapidly as the ore quality used declines from the present average of 0.15 percent.
58. See Oxford Research Group (2006a); and Storm van Leeuwen (2006B), and (2006E). SVL, Parts C2, C4.
59. Lovelock (2006), p 103.
60. See SVL, Part D9, Storm van Leeuwen (2006E), and a significant source for their work: Huwyler, Rybach and Taube (1975).
61. Storm van Leeuwen (2006C), (2006F).

62. NEA/IAEA (2006), Slide Presentation.
63. Storm van Leeuwen (2006C), (2006F).
64. *Ibid.* Similar problems affect mixed-oxide fuel (MOX) ≈ 2% of current capacity. The number of reactors in operation now: World Nuclear Association (2007b).
65. Lidsky and Miller (1998).
66. Storm van Leeuwen (2006C). Uranium Information Council (2004). See also World Nuclear Association (2007d).
67. *Ibid.*
68. Storm van Leeuwen (2006D).
69. SVL (2007), Part D10. Storm van Leeuwen (2006E2), "Uranium from Seawater", Appendix E2.
70. *Ibid.*
71. NEA/IAEA (2006), Slide Presentation.
72. SVL, Part D9. See also SVL, Part D9 for a summary of prospects for shales as a source of uranium ore.
73. SVL, Part C5. Storm van Leeuwen and Smith (2006E).
74. See, for instance, Déry and Anderson (2007). The author has not, at the time of going to print, been able to find reliable information on: (a) to what extent the extraction of uranium from phosphate ore makes it unsuitable for subsequent use in agriculture; (b) what the nuclear cycle's energy balance would be, using phosphates as a low-grade uranium ore, (c) what the pollution implications of the organophosphates in the process are, and (d) fully-endorsed information on whether a global phosphates resource exists on a scale which would make it significant for nuclear energy in the future. Commercial enterprise is usually alert to opportunity, and the lack of development of phosphates as an ore strongly suggests that phosphates will not solve the nuclear industry's fuel problem, but a firm conclusion on this is being held over for later editions.
75. See IEA (2007), pp 6-7. Note that nuclear's share (p 6) seems inconsistent with this. There are two ways of estimating shares of nuclear power and renewables: (a) the (fossil fuel) inputs needed to produce the outputs at a notional 38% plant efficiency; (b) their actual electricity output. The second method has been chosen here for its better estimate of final demand, but it produces smaller numbers. For a text using method (a), and an explanation of the difference between them, see Boyle (2004).
76. Low-level waste: see Busby (1995).
77. Lovelock (2006), p 99.
78. *Ibid*, p 135. See also Pearce (2006).
79. See Fleming (2007). For lean thinking see Womack and Jones (2003).
80. The effect of nuclear reactors in sustaining a large-scale grid, and making it harder to build localised energy systems, is discussed by the SDC as "network lock-in". Sustainable Development Commission (2006), (2), p 10.
81. Tradable Energy Quotas (TEQs), see Fleming (2007).

INDEX