The Phantom Solution: Climate Change and Nuclear Power

Alan Roberts

Resuscitating a Dinosaur?

It was once hailed as the solution to humanity's energy demands, promising electricity 'too cheap to meter'. But nuclear power has not lived up to its advance publicity. Thousands of stations, it was confidently predicted, would greet the millennium; but they neither exist nor are on order. After more than half a century of development, the nuclear industry can show less than five hundred power stations, yielding in 2002 around two per cent of the world's total energy production and only about a sixth of its electrical output. This last fraction had actually slipped back a little from the peak achieved by nuclear power fourteen years earlier in 1988. In its biggest market, the United States, no new nuclear stations have been ordered for over twenty-five years. In the whole world, only three new reactors came on line in the five years from 1998 to 2003.[1]

1. The data on reactor numbers and industry growth were downloaded in January 2005 from the website of the World Nuclear Association, which represents the industry. See <www.world-nuclear.org> , hereafter cited as 'WNA site'.

This is the picture of a stagnant or declining industry, one that many commentators, those opposed to the industry in particular, have labelled as a 'dinosaur', with all its future behind it. But in recent years, we have heard voices striking a far different note. A comment in the *Guardian* is typical:

> Nuclear power is back on the march. Reviled and rejected for 25 years as man's most dangerous and unsustainable fuel source … is it possible that public opinion is wrong, and that nuclear should be the fuel of choice of the future?[2]

Men of power have spoken up — as George W. Bush's vice president already did some years ago:

> Vice President Dick Cheney said on Wednesday his energy policy team was considering the future of U.S. nuclear power and that new nuclear plants could help cut greenhouse gases that cause global warming better than a 'seriously flawed' Kyoto treaty … President George W. Bush in January put Cheney in charge of a Cabinet-level task force to develop a long-term energy strategy.[3]

Delivering a similar message, the British prime minister was generous in acknowledging an influential source of his re-thinking:

> Tony Blair yesterday signalled that Britain may have to build a new generation of nuclear power stations to meet the challenge of climate change … 'I have fought long and hard, both within my party and outside, to make sure that the nuclear option is not closed off', he told the Westminster session … America was pressing Britain to re-examine the case for building a new generation of nuclear power stations. Nuclear must stay on the agenda 'if you are serious about the issue of climate change'.[4]

Other nuclear proponents have stressed how it can save the landscape from unsightly windmills and insulate the economy against future oil shocks. But the preponderant argument by far is that given by Cheney and Blair: to ward off climate change, we must go nuclear.

Now we could suspect bias here, since a nuclear weapon state like the United States or the UK has reasons other than environmental to favour a nuclear power industry. Even if it

2. *The Guardian*, 12 August 2004.
3. Cited on <www.commondreams.org/headlines01/0321-03.htm> as from Reuters, 21 March 2001.
4. *The Guardian*, 7 July 2004 and 12 August 2004.

dedicates special reactors to produce the uranium or plutonium needed for filling its bombs, it will still have an obvious interest in, for example, having a stream of technicians available with all levels of expertise, from which the military branch — including the research wing — can satisfy its personnel requirements.

It might be doubted, however, whether any such list of bonuses for the military side would really explain the special favour, above all in generous subsidies, that nuclear weapon states accord the 'peaceful atom'. Once a government commits to high-tech development as the path for reaching national goals, it has embraced an ideology that will shape its weapons and its industry alike.

Indeed, it was apparent in the earliest years how closely the peaceful and military branches of nuclear development intertwine. It was with great fanfare that the Queen launched in 1956 the British age of the peaceful atom, by switching current from the Calder Hall reactors into the national grid — the four reactors that had been designed specifically to maximize the output of plutonium for weapons. And the first US nuclear station, built at Shippingport in 1957, was simply a nuclear-submarine power plant adapted to life on land.[5]

This intimate and toxic relationship has not weakened in the intervening years, as the media furore over North Korea and Iran should make quite clear. (What are these countries generating — peaceful power or a nuclear arsenal? It is obviously difficult to tell.) But this 'special relationship' is already apparent enough if we just review global distribution of nuclear power, of yesterday or today. As at 1 January 2005, electricity was nuclear-generated in 31 countries, but the greater part of its capacity — over 60 per cent in fact — supplied the grids of just six: the United States, the UK, China, France, Russia and Ukraine. Each is (or, in the case of Ukraine, formerly was part of) a nuclear-weapon state.[6]

Realizing this bias, we might doubt whether the nuclear advocacy of Bush or Blair is moved by nothing but environmental concern. We might even fail to be as impressed as spokesmen for the industry seem to expect when they cite French or Chinese data in arguing the superiority of nuclear over other sources of electricity generation: France with a massive nuclear industry

5. See index entries for Calder Hall and Shippingport in W. C. Patterson, *Nuclear Power*, 2nd edn, Harmondsworth, Penguin, 1983.
6. WNA site. Note that figures for 'China' include Taiwan.

supplying close to 80 per cent of its electrical power, China with stations under construction or planned that will see its nuclear capacity nearly double. For we might recall that these two, like Blair's Britain or Bush's United States, are nuclear-weapon states, and we could take such phenomena as testifying not so much to how desirable nuclear power is, but rather to how dubious industrial choices can be when prompted by nuclear armament — and the high-tech ideology that accompanies and drives it.

But we would be wrong to think that this new case for nuclear power is made only by the Bushs and Blairs of this world. Listen to quite a different sort of proponent, none other than the scientist and environmentalist responsible for the Gaia hypothesis:

> I hope that it is not too late for the world to emulate France and make nuclear power our principal source of energy. There is at present no other safe, practical and economic substitute for the dangerous practice of burning carbon fuels.[7]

Thus James Lovelock. And while his is not the only voice now advocating nuclear power on environmental grounds, he is certainly the one most distinguished and respected in both activist and scientific circles.

Another stream of environmental opinion, while not so emphatic, has unmistakably shifted away from a blanket condemnation of nuclear power. For example: 'Paul Allen, development director at the Centre for Alternative Technology in Machynlleth … says he is not endorsing nuclear, but is trying to keep an open mind'.[8]

It is evident that an informal body of 'Environmentalists For Nuclear Power' has emerged, even if it might not be unanimous on allowing the Bushs and Blairs into its ranks.[9] Are they right — has the unacceptable now become a lesser evil?

How we answer will obviously depend on how seriously we regard the prospect of climate change. To decide, there are two preliminary issues that need to be first clarified:

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7. James Lovelock, in his preface to the book *Environmentalists For Nuclear Energy* by Bruno Comby, quoted on the site <www.ecolo.org/lovelock/loveprefaceen.htm>.
8. *The Guardian*, 12 August, 2004.
9 A somewhat more formal body ('Environmentalists For Nuclear Energy') has a web site at <www.ecolo.org/>. It is interesting to note that its president, Bruno Comby, 'holds a higher degree in nuclear engineering'.

- Is there indeed a threat of human-induced climate change that would have disastrous effects on our own species and others?
- Can nuclear power significantly counteract this threat and thus help to avert or at least reduce the damage?

Is Climate Change Really Happening? Is it Human-Induced?

In 1988, the World Meteorological Organization and the UN Environment Program set up the Intergovernmental Panel on Climate Change (IPCC). The Panel's Third Assessment Report (2001) drew on the research, authorial and reviewing services of experts from 56 countries, including 16 people from Australia, and left little doubt that significant 'anthropogenic' (human-induced) climate change has already occurred.

The direct indicators are briefly listed in Table 2–1 of its Synthesis Report;[10] one is the global mean surface temperature, which increased by about 0.6˚C in the course of the 20th century. Other indicators include the decreased daily range of land surface temperature in the last half of the 20th century, and (listed as 'likely') the decrease of cold and frost days and the greater severity and frequency of droughts in some regions (such as parts of Africa and Asia).

Why is this, in all probability, the result of human activity? The clues are in the same table, where the amounts of various gases in the atmosphere are given. Typical is the finding for carbon dioxide: over the last couple of centuries or so — that is, over the industrial era — its concentration in the air increased by around 30 per cent. Now, carbon dioxide acts like the glass roof of a greenhouse: it lets sunlight through easily, but blocks off the waves of milder heat travelling up from the ground. Thus it cuts down this 'upward' heat loss, so there results a higher temperature at ground level than would otherwise be the case. For obvious reasons, it is called a 'greenhouse gas'; so is methane, for example, of which the air now holds some 150 per cent more than in 1750.

The Synthesis Report suggests the most likely climatic sequels of the higher surface temperatures created by this more intense greenhouse effect. They include further ocean warming and glacier

10. The main page of the IPCC site is <www.ipcc.ch>. The Synthesis Report can be downloaded from its Publications page, or from <www.ipcc.ch/index.html>. Alternatively, a handsomely produced hardcopy can be obtained free of charge by emailing a request to the secretariat of the World Meteorological Organization at <IPCC-Sec@wmo.int>.

melting (with concomitant rise in sea level and risk to populations of small islands and low-lying coastal areas); increased threats to human health; greater risk of extinction for vulnerable species; exacerbated water shortage in dry areas; and more frequent occurrence of 'extreme' weather conditions (hurricanes, heat waves, heavy rainfall) implying increased risk of drought and floods.[11]

A particularly disturbing feature of global warming is the inertia the earth displays; in persisting on its altered course long after human intervention has been cut back. Even if greenhouse-gas emissions are significantly reduced, 'surface air temperature continues to rise slowly for a century or more'.[12] So the oceans continue to expand, ice sheets continue to melt and sea level continues its steady rise for many centuries. Thus, even after we have modified our behaviour at some future time, we cannot halt the unwelcome changes we have already initiated.

Perhaps more serious still is the possibility of non-linear effects waiting to surprise us. What this means is that, at a certain (unknown) stage of the warming process, the change may start to 'run away' — an acceleration of the warming effect and all its unwelcome results. This could happen, for instance, with the melting of tundra and peatlands which are at present frozen, causing them to release methane and carbon dioxide, adding their heating effect to what is already there. Just when would this happen — at what average surface temperature? How many additional megatonnes of greenhouse gases would thus be emitted? We don't know the answers to these and a hundred other relevant questions, even one as important and fundamental as exactly how carbon dioxide concentration affects the formation of cloud cover, for instance.

The IPCC is guiding and collating the research efforts of the world's leading climatologists needed to elucidate some of these vital questions. When the hundreds of factors involved interact with each other, computer modelling often has to make up for our depth of ignorance about the final results; when the problem is too complex for known theory to handle, it often has to be simulated in numbers and the upshot studied.

11. See the Synthesis Report's replies to Questions 3 and 4.
12. Quoted from the caption of Figure SPM-5, illustrating this unwelcome persistence. Compare also Figure 5-2.

Since 1988 when the IPCC was formed, a great deal has been added to our knowledge of the factors involved in climate change and their interaction. Unfortunately, two things can be safely said about this further knowledge — first, that it still leaves great areas of uncertainty; and second, that the likely overall picture it paints is of a world closer than had been thought to a crisis greater than had been thought.

This last disturbing implication of the work was strengthened in the first week of February 2005, when new observations and calculations were presented to a gathering at Exeter of hundreds of scientists from relevant fields. A *New Scientist* article quoted researchers emphasizing 'evidence that the danger is more pressing than was thought. "The sleeping giants are being woken," several said'. This last metaphor referred to the 'runaway' events mentioned above,

> triggering irreversible changes in natural systems, such as the melting of polar ice caps. Once we pass these thresholds there will be no return. And the conference heard that we could be closer to the brink than previously supposed.[13]

Climate Change is a Complex and Difficult Phenomenon

In its complexity and its urgency, the problem of human-induced climate change presents science with an unprecedented challenge, and we should not be surprised if science often cannot offer the certainty and precision of verdicts in other, simpler fields. Even the patterns elucidated in the elementary-particle theory of physics, or the wizardry shown by organic chemists in disentangling the structure of a large compound, rest on well understood laws governing the interactions between the entities they handle. Climatologists enjoy no such reliable framework of support when they try to work out what will happen in a far more complex system, as the uncertain relation between cloud and carbon dioxide exemplifies.

This lack of clear-cut predictive ability is not, of course, a reason to simply press on regardless, taking a punt on humanity's future. It is certainly not rational to insist that the evidence must leave no room for doubt, to demand that a logically airtight case be there

13. *The New Scientist*, 12 February 2005, p. 8.

before remedial action is taken. This might well be equivalent to requiring that matters must first reach the point of no return — the 'runaway' phase. Such a demand for 'rigorous' proof is logically highly inappropriate — even if useful for world leaders wanting an excuse for their refusal to safeguard the future of humanity.

They can cite support from such people as Michael Crichton, whose novel *State of Fear* revolves around environmentalist conspiracies.[14] They are more likely, however, to quote a man like David Bellamy, with his former reputation as an environmentalist:

> The link between the burning of fossil fuels and global warming is a myth. It is time the world's leaders, their scientific advisers and many environmental pressure groups woke up to the fact.[15]

Bellamy is, of course, a botanist. It is much harder (though not completely impossible) to locate a climatologist, atmospheric scientist or ecologist within the 'contrarian' ranks. Robert May, president of the Royal Society, a physicist and ecologist, has summed up the situation thus:

> On one hand, we have the IPCC, the rest of the world's major scientific organisations, and the government's chief scientific adviser, all pointing to the need to cut emissions. On the other, we have a small band of sceptics, including lobbyists funded by the US oil industry, and a sci-fi writer, who deny the scientists are right. It is reminiscent of the tobacco lobby's attempts to persuade us smoking does not cause cancer.[16]

If you incline to the sceptics' view, then of course the question of turning to nuclear power for the solution of the climate-change crisis does not arise, since there is no such crisis needing solution. My own view is that, on the contrary, there is now an overwhelming case that human activities are changing the climate, and that a catastrophic outcome is likely if massive remedial action is not promptly undertaken.

It will become apparent below that this article reaches conclusions quite different from Lovelock's, but it is hard to reject one at least of his views: 'whatever the objections there are to nuclear, it's nothing like as great a danger as just leaving things as

14. M. Crichton, *State of Fear*, London, HarperCollins, 2004.
15. *The Daily Mail*, 27 September 2004. See his debate with George Monbiot featured on <www.zmag.org/MonbiotBellamyDebate.htm>
16. *The Observer*, 30 January 2005. If May's remarks sound a little sharp for the Royal Society, note that he is an Australian.

they are and going on burning fossil fuel'.[17] He is right to insist that, if nuclear power is to be rejected, it should not be out of some fundamentalist abhorrence that has it necessarily worse than any other evil. But ironically, the argument that follows is that turning to nuclear power as the answer to climate change would, in practice, carry the danger of essentially the policy Lovelock (rightly) fears: 'just leaving things as they are and going on burning fossil fuel'.

Most Greenhouse Gases Do Not Come from Electrical Power

Before showing this, first let us note an apparently widespread idea — that, if we switched to all-nuclear power stations, the dangerous injection of greenhouse gases into the atmosphere would then be eliminated, or effectively so at least.

This is far from the truth. The bulk of greenhouse gases are produced by human activities quite unrelated to electrical generation. A few figures will indicate how subsidiary the climate-changing role of electricity generation is:

> On 25 February 2004 the European Economic and Social Commission of the European Union (EU) issued a report (called an 'Opinion') on nuclear power and electricity generation.[18] It showed inter alia that its fifteen constituent countries discharged over four million tonnes of greenhouse gases into the atmosphere in 1999; out of this amount, the generation of network electricity was responsible for less than a million — in fact, for under 21 per cent of the total.

This tells us the maximum that nuclear power could achieve in the way of reducing EU emissions. Let us suppose that all the non-nuclear stations in the EU countries are replaced by nuclear ones, and that these new stations are constructed, fuelled and operated without any greenhouse gases ever being generated, though we will see below how unreal and indefensibly optimistic this latter point is. Then even so, if this sweeping change in electricity generation were the only step taken, the EU countries would still be pouring into the atmosphere just on 80 per cent of their present load, or over 3 200 000 tonnes of greenhouse gases each year.

17. Interviewed on ABC Radio National's AM program, 25 May 2004. Download from <www.abc.net.au/am/content/2004/s1115187.htm>.
18. Downloadable from <eescopinions.esc.eu.int/>.

This figure for Europe is a pointer to the global role — significant but subsidiary — that power generation plays in inducing climate change. In other regions it can loom larger or, as in the state of California, smaller still. (California's power stations are responsible for only 16 per cent of its greenhouse gas emissions, less than a third of the 58 per cent due to transportation.)[19] On the other hand, the coal-fired stations in Victoria, Australia, reportedly achieve 55 per cent of the state's total emissions.[20] If this figure is accurate it may be an unenviable world record for which Victorians can thank their abundant supplies of inefficiently-burning brown coal. Less dominating, and far less than the total weight of emissions, are the figures from the International Energy Agency (IEA) for 1999, which give the world emissions by electrical networks as something less than 39 per cent of the total.[21]

Whichever figures we go by, it is evident that even total removal of the fossil fuel stations from the equation would still see a vast amount of greenhouse gases pouring into the atmosphere every year, and the fatal and barely understood process of changing our planet's climate. If catastrophe were waiting for us, this nuclear substitution could achieve no more than to delay its arrival — perhaps, if we were lucky, by a few years.

In looking at the role nuclear power could play in the climate change problem, then, it is not as a sweeping solution but at best an alleviating measure that might postpone the 'runaway' moment. It is as well to be clear about this, although it does not in itself rule the option out; perhaps only a piecemeal series of partial remedies is available anyway, to avoid the disasters of climate change. While nuclear power has well-known dangers and costs, these have to be balanced against the unarguably graver risks of climate change. 'Lesser evil' policies are sometimes reasonable; it is easy to think of medical treatments designed to cope with a serious condition that produce ill-effects as well, sometimes severe — even the risk of death for some patients. The euphemism of 'side-effect' hardly fits

19. See the California Energy Commission booklet *Global Warming and Greenhouse-Gas Emissions*, p. 14. Downloadable from <www.energy.ca.gov/global_climate_change/documents/AB1493_PRESENTATION.PDF>.
20. 'The Dirty State We're In', *The Age*, 14 February 2005.
21. International Energy Agency (IEA), CO2 Emissions from Fossil Fuel Combustion (2001 Edition), Paris, OECD. Downloaded from <earthtrends.wri.org/pdf_library/data_tables/>.
    Note that the percentage given overestimates the electrical contribution, for two reasons: firstly, the figure used is for 'Public Electricity and Heat' — it is not stated whether it includes any heat of non-electrical source; and secondly, the total does not include the emissions from the Agriculture and Commercial sectors, which do not appear.

cases of the latter kind, but nevertheless the rationality of 'statistically beneficial' treatments is generally accepted.

However, it would be disturbingly novel in both its ethical depth and its social sweep if we actually had to choose between these two fates: risking the destruction of the biosphere, or bequeathing to our descendants the unwelcome effects of one attempted remedy — the poisonous wastes, genetic dangers and virtually permanent responsibilities associated with an expanded nuclear industry.

Is this really the decision we have to make? One editorial writer believes so (after 'more than a week's worth of news on climate change'), and offers an unhesitating verdict:

> Since nuclear power, for all its faults, does not contribute to greenhouse gas production, it may be used to make up the gap between today's carbon-bearing energy generators and tomorrow's green power sources.[22]

The editorial does not say anything about the other emissions pouring the bulk of gases into the air — as we have just seen, measured in millions of tonnes each year. And contrary to its bald assertion, nuclear power can give a massive contribution to greenhouse gas production, as will appear below. But first, a few, not uncommon assumptions made in this passage should be examined.

The Missing Nuclear Fuel

The editorialist in question seems to assume that the uranium is available to fuel and operate enough nuclear stations to replace those using coal, oil or gas at present. Where is all this uranium to be found?

The first place to look is in all the uranium-bearing ore bodies throughout the world that are at present known or plausibly estimated ('Reasonably Assured Resources plus Estimated Additional Resources'). Taking the figures given by the industry, on the World Nuclear Association (WNA) website for example, it is straightforward to work out how long the deposits would last. This calculation has been done by van Leeuwen and Smith,[23] at the Centre for Energy Conservation, Delft, the Netherlands, using the best figures available for 'burnup' — the heat energy actually

22. *The Guardian*, 12 December 2004.
23. See Table 10, in J. W. S. van Leeuwen and P. Smith, *Can Nuclear Power Provide Energy for the Future: Would it Solve the CO2 Emission Problem?'*, downloadable from <www.oprit.rug.nl/deenen/>. (Cited hereafter as VLS site.)

obtainable from a tonne of uranium ore. Two burnup figures occur in the literature; van Leeuwen and Smith use the higher one, based on extracting energy more efficiently from the uranium fuel. So, if the present global output of electricity were obtained entirely from nuclear reactors, and as efficiently as best practice allowed, for how long could all the uranium of all the known ore bodies in the world keep them going? The answer: just under nine years.[24] Thereafter, the world has no nuclear power stations operating and therefore no power stations at all.

With the operating life of a nuclear station at around thirty years or more, this is hardly acceptable — particularly taking into account that the construction and initial fuelling of a reactor requires significant energy input (see below) and associated greenhouse emissions. Obviously, this suggests we abandon the idea of replacing all the fossil-fuel stations. Whether it is possible and advisable to replace a fraction of them will be considered later.

However, since it is the small amount of uranium in known ore bodies that limits the 'nuclear solution' so severely, it should be asked whether reactor fuel can be obtained elsewhere. Note first that the discovery and opening of new mines previously overlooked, even if equivalent in output to the *whole* of those known at present — and it is hard to imagine this — would not greatly alter the finding above: the operating period of the 'replacement' reactors would just be stretched to eighteen years, still well short of a normal lifetime.

The dismantling of nuclear weapon warheads under disarmament treaties creates another uranium source, which 'from 2000 … is displacing about 9000 tonnes of uranium oxide per year from mines, which represents about 14 per cent of the world's reactor requirements'.[25] Recalling that total world electricity output is about six times that of existing reactors, it is easy to see that on total replacement the nuclear stations would, at this rate of supply, obtain from the weapon stocks only about 14 divided by 6 per cent of their fuel requirements each year — that is, a bit over 2 per cent. This would not add even a month to the period over which the 'replacement' reactors could be fuelled — a period still under the nine-year figure quoted above from the van Leeuwen and Smith study.

24. After the WNA site upgraded its figures for uranium resources, the van Leeuwen and Smith calculation was amended (4 March 2005) to base itself on the new data (established through personal communication with van Leeuwen), giving the figure of nine years cited here.
25. WNA site, 'Supply of Uranium', August 2004.

Thus the known or estimated ore bodies and processed warheads could support between them only a few years of all-nuclear generation. However, the WNA site draws attention to other sources, and these further possibilities should be looked at.

Can Market Forces Produce New Sources of Uranium?

The WNA website states that:

> It is now clear that uranium is not scarce and it is known that it averages almost two parts per million of the Earth's crust. There are substantial resources that are not yet fully proven. These so-called speculative resources are likely to be of the order of 10 million tonnes, about three times the known reserves.[26]

It also mentions the enormous stores in granite and sedimentary rock (respectively four and two parts per million) and even in seawater (three parts per billion). These might sound like tiny fractions, but each is part of a colossal whole — the total amount of uranium in seawater alone is estimated at over four billion tonnes. Sketching the market dynamic that makes resource quantity increase with price, the WNA site goes on:

> An orebody is, by definition, an occurrence of mineralisation from which the metal is economically recoverable. It is therefore relative to both costs of extraction and market prices. At present neither the oceans nor any granites are orebodies, but conceivably either could become so if prices were to rise sufficiently.

Measured resources of uranium, the amount known to be economically recoverable from orebodies, are thus also relative to costs and prices. They are also dependent on the intensity of exploration effort. Changes in costs or prices, or further exploration, may alter measured resource figures markedly. Thus, any predictions of the future availability of any mineral, including uranium, which are based on current cost and price data and current geological knowledge are likely to be extremely conservative.[27]

The market dynamic acknowledged here by the WNA is important and has not always been allowed for, leading to a figure

26. WNA site, 'Introduction To Nuclear Energy: Uranium Resources'.
27. WNA site, 'Introduction To Nuclear Energy: Uranium Resources'.

for 'current stocks' being wrongly treated as an absolute and eternal constraint. Thus, even if the van Leeuwen and Smith study shows that present supplies ('reasonably assured' plus 'estimated additional') are far too small to permit any large-scale replacement of fossil fuel by nuclear power, can we assume that more intense exploration will find uranium elsewhere if demand makes the price rise?

Unfortunately, no. There is a further and even more fundamental consideration, not mentioned by the WNA, which is crucial and lies entirely outside the control of the market forces mentioned. It arises because the resource in question — uranium — is wanted for only one reason: that it is a source of *available energy* — in other words, that it can be made to do useful work. Inside a reactor, this energy emerges as heat and then flows into circulating water, converting it to steam. The steam then runs a turbine, whose shaft generates electricity as it spins. There would be no interest at all in that uranium, if the effort of obtaining it required more energy than we would ever get from its electrical output.

This is an issue quite independent of how much it costs to produce the uranium and how much it will sell for on the market; such monetary figures are quite irrelevant. What is needed is not a cost analysis, but an energy analysis. This means calculating the energy input at every step in the industrial process that starts with an untouched deposit and a greenfields site, and ends with uranium fuel rods being loaded as needed into a functioning reactor.

The major part of the van Leeuwen and Smith work cited above is precisely such an energy analysis. Of course, many of the 'energy costs' incurred in order to build a functioning reactor differ little from those met with in building a coal-fired station but, to grasp the major conclusions of the study, it is enough to stress the special character of the *fuelling* stage, at which the uranium is obtained and processed into a form suitable for a reactor.

The van Leeuwen and Smith study calculates the quantity of energy expended in the process of building the reactor and preparing its uranium fuel. The electrical output from a nuclear station — or indeed, from any type of source — is never pure gain, and the study needs to itemize fourteen stages at which energy must be expended to create a functioning reactor. (It should be noted that each of these inputs, and therefore the nuclear project they accompany, will inevitably give rise to greenhouse-gas emissions, despite contrary assertions like that in the editorial quoted above.)

The Nett Energy Gain from Uranium

The results can be understood in terms of 'nett gain': the amount of energy created from the uranium in the reactor, after subtracting the amount that had to be expended to build and operate it. It turns out that the 'nett gain' from uranium coming out of a given ore body depends crucially on how rich the ore was — that is to say, how much uranium was in each tonne of ore.

This is not hard to understand. Digging out and processing (milling) a tonne of rock will always require the same energy input, but, if the ore is less rich, that tonne will contain less uranium; practical considerations mean that only a smaller fraction of what is there will actually be extracted. Thus, to win a given quantity of uranium, the energy that must be spent rises steeply as the ore richness falls.

The van Leeuwen and Smith study dramatically illustrates this dependence with their Figure 6b. For a single fuel load, the figure plots the energy used against the richness of the ore. As the ore becomes less rich, the curve soars up to, and then past, the value for the total electrical output from that fuel load. This means, for such poor ores, *the uranium is yielding less energy than was used in obtaining it*.

This general phenomenon had already been noted years before. The researcher Kistemaker stated in 1976 that, with ore grades less than one part in five thousand, over half the energy in the uranium was lost in the extraction process.[28] The van Leeuwen and Smith value confirms this, and gives the grade of total loss (a nett energy return of zero) as just under one part in ten thousand.

The grades already being worked in the major uranium mines today are mainly in a range well above this critical value, so that the reactors built to date have benefitted from comparatively rich ores and have thus yielded highly positive nett energy returns. But major sources also include values as low as one part in two thousand (for example, Olympic Dam in South Australia) or one part in five thousand (in South Africa). New sources could well be discovered and tapped if the price of uranium rises high enough,

28. J. Kistemaker, 'Energie-analyse van de Totale Kernenergiecyclus Gebaseerd op Lichtwater Reactoren', LSEO 818, July 1976 (in Dutch). Cited in van Leeuwen and Smith study.

but what is crucial is their grade of ore. They would need to be richer than some of the deposits already included when counting today's 'resources'. Take the South African grade of one part in five thousand, for example; about half the energy to be eventually obtained from it would have to be used in making it into fuel — and this from the van Leeuwen and Smith study, which consistently favours the lower number for energy loss from inputs when there is doubt.[29]

It is important to emphasize that these 'losses' are essentially the energy needed to drive the processing, and that their generation must of course be accompanied by greenhouse gas emissions.

Speculative Resources

The WNA quotation above referring to 'substantial resources that are not yet fully proven … so-called speculative resources', gives their amount as roughly triple known reserves. If indeed these speculative resources proved existent, and their richness was well above the value (about one part in ten thousand) at which the lost input energy becomes significant, they could extend the all-nuclear period from under nine years to nearly thirty years — close to a reactor's lifetime. But in fact we can draw no definite conclusion about their effect, even if they exist, since no indication is given of their likely richness — which determines whether they would be usable. The question is much more clear-cut when it comes to granite (four parts of uranium per million) or sedimentary rock (two!): the van Leeuwen and Smith findings make it obvious that they cannot be 'mined' for nuclear fuel.

Uranium from Seawater: The van Leeuwen and Smith work analyses the mining-milling process, and so is not relevant to the problem of recovering uranium from seawater, on which research still continues. But the Analytical Center for Non-Proliferation Problems, a Russian institute, naming the US Department of Energy as a 'major partner', closely follows progress in this field, for obvious reasons. The Center has summarized where these extraction efforts stood — or stagnated — in 2004:

> Although research and development for recovery of this low-concentration element by inorganic adsorbents such as titanium oxide compounds, etc. has occurred since the 1960s in the United Kingdom, France, Germany, and Japan, the

29. See Figure 6b in the van Leeuwen and Smith study.

> present status of all such research has been subsequent stoppage due to low recovery efficiency.[30]

The Fast Breeder: In the early days of the industry, great hopes were placed in the 'Fast Breeder' reactor, which could in principle produce more fuel than it used up. While there does not appear to be any firm evidence that this hope has been realized in practice, several fast breeders have run long enough to meet with disturbingly severe vicissitudes. The Fermi fast breeder near Detroit was the first to set this pattern, and the accident it suffered in 1966 was the subject of Fuller's gripping book *We Almost Lost Detroit*.[31] Since then, the incidents reported include the not atypical examples below.

In Japan:

> On January 27 [2003] the Kanazawa branch of the Nagoya High Court … handed down a decision favoring local residents who had sued the government seeking to nullify its approval of the prototype Monju fast-breeder nuclear reactor in Tsuruga, Fukui Prefecture … The reactor, which is overseen by the Japan Nuclear Cycle Development Institute (JNC), has been shut down since an accidental leak of sodium in 1995.[32]

In France:

> From its entry into operation, into 1994, the [French fast breeder] Superphénix had operated only the equivalent of 174 days at full power and, in the words of deputy Bataille, in 1996, had 'collected an impressive series of accidents' … On 3 July 1990, the reactor was shut down because of impurities in the sodium in the core … in April [1998] Nersa was asked to begin the permanent shutdown process.[33]

Russia operated a large breeder for years, but I have found no actual breeding of new fuel reported. India intends to build a fast breeder at the Indira Gandhi Centre for Atomic Research, Mamallapuram, and hopes to avoid the succession of troubles that have plagued the fast breeder prototypes of nation after nation. 'If our ancestors could build temples that last 13 centuries, it should

30. Analytical Center for Non-Proliferation Problems, Review, iss. 13, Annex 8. Download from <npc.sarov.ru/english/digest/132004/appendix8.html>.
31. J. G. Fuller, *We Almost Lost Detroit*, New York, Ballantine, 1976.
32. From <www.fpcj.jp/e/shiryo/jb/0308.html>.
33. From <www.francenuc.org/en_sites/rhone_crey_e.htm>.

not be beyond us to build a reactor that lasts 60 years', says Baldev Raj, director of the IGCAR.[34]

Of course, unlike the fast breeder, the Mamallapuram temples were not cooled by liquid sodium, an element that is highly toxic and flames spontaneously if exposed to the air.

As will appear below, the failure to tame the fast breeder into a reliable supplier of fuel has been a crucial barrier to the expansion of nuclear power.

The Thorium Cycle: the WNA website, on its 'Supply of Uranium' page, also points out:

> Today uranium is the only fuel supplied for nuclear reactors. However, thorium can also be utilised as a fuel … Thorium is about three times as abundant in the earth's crust as uranium.[35]

It is worth noting that experience with reactors based on the thorium cycle is minute compared to the history of uranium's usage, that the use of thorium involves complications not encountered with uranium, and that it is hard to imagine less than a few decades as necessary for any move to the thorium cycle. However, for present purposes it is enough to recall that being 'abundant' is not necessarily the same thing as being usable, as we saw above with the massive but useless quantities of poor-grade uranium. How rich then are the thorium ores? From an Oak Ridge National Laboratory paper:

> While natural thorium is more abundant than uranium in the very long term, most of the thorium reserves are present as very low grade ores; the amounts of low-cost reserves are about the same for uranium and thorium.[36]

This suggests that resort to the thorium cycle, even if it were satisfactorily achieved, would not allow any significant expansion of nuclear power beyond the limits set by uranium stocks.

What Nuclear Can Do

It has been straightforward, though requiring the detailed analysis of the van Leeuwen and Smith study, to show that ore bodies already under exploitation — that is, mines existing or ready to

34. J. Webb, 'Bold Plans for the Nuclear Future', *New Scientis*t, 19 February 2005.
35. WNA website, 'Supply of Uranium', August 2004.
36. P. R. Kasten, 'Review of the Radkowsky Thorium Reactor Concept', *Science and Global Security*, vol. 7, 1998, pp. 237–69. The paper's footnote number 14 is: P. R. Kasten, F. J. Homan, et al., 'Assessment of the Thorium Fuel Cycle in Power Reactors', ORNl./rM-5565, Oak Ridge National Laboratory, Oak Ridge, TN, January, 1977.

open — are unable to provide the uranium that would be needed for all-nuclear electrical generation or anything approaching it. Examining the various proposed alternative supplies (poorer deposits, granite, sedimentary rocks, seawater, weapon warheads, breeders) has been more complicated, because these other industry-cited sources needed individual attention, and, to be properly studied, required the van Leeuwen and Smith energy analysis — necessarily much more complex than a cost analysis.

These other sources do not seem able to alter the general picture, unless some surprising developments occur — for example, a scientific breakthrough in the process of extracting uranium from seawater; or the conversion to peaceful purposes of a much greater number of warheads than envisaged up to now; or the discovery of new deposits about as rich as those known now but with about three times the tonnage of uranium. The issue would then have to be rethought, since alleviating the climate-change crisis through nuclear energy could no longer be seen as a simple impossibility.

But at present each of these eventualities seems quite improbable. More realistically, the role that nuclear power could play in the crisis may be summarized as follows:

- Like any other change in electricity generation procedures, an all-nuclear replacement, even if it were possible, would have no effect on the bulk of the greenhouse gases emitted, which come from outside the electrical power industry.
- The construction of new nuclear stations, and especially of their fuel supply, cannot be done without expending significant amounts of energy and creating its associated emissions.
- The long period it takes to construct a nuclear station, which can exceed ten years, plus the years needed before its output repays the energy taken to build it, means that new nuclear stations must initially worsen the situation.
- The present supply of relatively rich uranium ores is too small to fuel the lifetime operation of even a third of the reactors needed to supply the world. But as poorer ores are mined, the energy loss incurred will cancel out between a half and all of the energy the uranium fuel holds to be created.

As will be discussed below, these are far from being the only sources of concern surrounding nuclear power when seen in the light of climate change. Perhaps the most serious is the peril it creates for opportunities for alternative action — what is sometimes called its 'opportunity cost'. But before taking up this aspect, it is worth asking whether old objections to nuclear power still apply; after all, the world has moved on and perhaps nuclear power has moved with it.

The Nuclear Dream

The opposition to nuclear power goes back about as far as the industry itself, and it is not the place here to repeat these arguments at length. But some recent evidence might be used to show that at least some of the 'traditional' criticisms are still cogent. These are, first, that the spread of 'peaceful' nuclear power is in practice inseparable from the spread of nuclear weapons; second, that nuclear power cannot make its way in the marketplace, and instead depends on subsidies and state financing to cover up its expensiveness; and third, that we should not generate more radioactive waste without having permanent storage for what already exists.

There is no need to show the topicality of the first objection; it is enough to mention Iran and North Korea.

On the second: the industry is now hoping for a new source of subsidy through the 'Clean Development Mechanism' (CDM) provided for in the Kyoto treaty. If a nuclear station export were accepted under the CDM, the exporting country would be credited with the carbon dioxide emissions allegedly avoided by the country accepting the station. Under the scheme, these credits would have a cash value and so draw, the industry hopes, a corresponding grant from the exporter government. China showed years ago that it appreciates and will press for this subsidy:

> Its 10th five-year plan is currently being finalised by Beijing, and may include plans for up to 6 new nuclear reactors. According to a report in the industry journal *Nucleonics Week* China is waiting to see if it will get CDM credits for new nuclear plant before it finalises a decision on how many additional units to build … China said that to meet its current targets it 'will need financial support through the CDM or some other mechanism'.[37]

However else they might see climate change, it seems quite clear that for both the buyer and seller of a reactor, nuclear energy represents welcome excuse for a new subsidy.

37. L. Deshun et al, 'China — Nuclear Power for GHG Mitigation and Sustainable Energy Development', IAEA General Conference, September, 2000.

On the third: lack of safe storage for the poisonous wastes has, from an early stage, been one of the sharpest spurs provoking the public's suspicion of nuclear power. Well aware of this, and after many abandoned projects, the US Department of Energy began as long ago as 1978 to study Yucca Mountain in Nevada and have concluded that its interior could be a suitable waste site. The industry cites this as 'solving' the problem that is now a half-century old. But the *Las Vegas Sun* of 10 February 2005 tells us what some twenty-seven years' effort have so far achieved in disposing of US nuclear waste:

> CARSON CITY — The head of the state agency fighting federal efforts to open a high-level nuclear waste repository at Yucca Mountain told legislators Tuesday that the facility faces so many obstacles it already might be dead. 'The project is limping along', said Bob Loux, executive director of the state Agency for Nuclear Projects. 'We believe the project is dead.' Loux cited the 50 per cent reduction in the Energy Department's latest budget request for the nuclear waste project, 100 miles northwest of Las Vegas, as evidence that the government lacks confidence in the project … The Energy Department's top manager for nuclear waste disposal said Monday that Yucca Mountain will come on line at least two years later than its planned 2010 opening.

In the same issue, the *Sun* offers a sample of the reasons behind this hardly believable delay of decades in meeting public concern:

> Concerns over the strength of titanium drip shields that are intended to keep water from leaking into casks deep inside the proposed nuclear waste repository may slow the Energy Department's already delayed licensing process, a Yucca Mountain oversight board said Wednesday … The U.S. Court of Appeals on July 9 threw out the Environmental Protection Agency's 10,000-year standard, saying it did not follow the National Academy of Sciences recommendation of another standard for as many as 300,000 years … Hornberger's comments were the latest criticism of the waste containers, which became a lightning rod after the review board in 2003 said a flaw in their design could increase the likelihood of water corroding the casks.

A keen desire for subsidies was apparent decades ago and the industry today does not seem to have lost this hunger — and presumably this need. Nor is much progress visible on the US waste-disposal front.

The Nuclear Power Station as an Icon

As we have seen above, there is still a great gap between the splendid vista of achievements imagined for nuclear power and what fuel supply would allow it to do. It is in this gap, in its overblown reputation one might say, that there lies a capacity for serious harm which now needs to be looked at.

It may seem extraordinary and well-nigh incredible that a whole industry could simply push aside the fundamental problem of the fuel supply. Indeed, it is extraordinary, and cries out for analysis to lay bare its rationalizations and its lessons. As for the industry's credibility, a glance at the history of the project may soon compel us to believe it.

Looking back, we find the fuel shortage has been no great secret. For instance, the claim that nuclear-generated electricity was competitive with that from conventional fossil fuel drew the comment:

> But it is well known that this competitiveness is based on comparatively cheap fuel costs, using uranium extracted economically from high-grade ore; and the estimated world supplies of this ore fall far short of the fuel needs over the lifetimes of the reactors now planned. Once the reserves of this ore are exhausted, uranium must be mined from the low-grade reserves, containing perhaps 30 or 40 times less metal per ton. This could double the cost of nuclear-generated electricity, and destroy its commercial viability.[38]

This is from a 1976 issue of *Arena*, the precursor to this journal, citing a 1975 source. The industry's dependence on those deposits, so rich and so limited, was recognized by opponents and supporters alike, even if the latter were disinclined to let their visions of the nuclear millennium be spoiled by brutal facts — they foresaw 2000, even 5000 reactors by the year 2000. (The reality is 438.) Even now, after thirty years, the impression is still allowed to circulate that nuclear power is capable of massive deployment and provides the 'technological fix' to overcome climate change.

38. A. Roberts, 'The Politics of Nuclear Power', *Arena*, no. 41, 1976, p. 27.

In fairness to the industry, it should be conceded that, from its very beginnings in the early post-war years, hopes were pinned on the fast breeder, which could in theory 'breed' much more fuel than was ever put into it. But it was back in 1951[39] that EBR-1, the first breeder, started up, and some conclusions should surely have been reached after half a century of experience — years plentiful in unanticipated difficulties, near-disasters and abandoned projects, but altogether lacking in a single new fuel rod.

The nuclear industry has a great advantage over its fossil fuel rivals: its harmful emissions are invisible. The smoky clouds from a coal-burning station manifestly threaten damage (and of course deliver it); but radiation slips by unnoticed. The functionality of a coal-burner thrusts itself into our vision with its grimy chimneys and haphazard brick walls, but a nuclear installation has no huge intake of materials every day to cater for and can be designed to look like a pleasant chemical factory. There is no outward sign of the gigantic energies deep inside, which, from a single human error, can metamorphose into a Chernobyl, making a whole region uninhabitable for generations. Rather, on its green lawns sheep may safely and cleanly graze.

All this helps to shape the nuclear station into an icon of the technological dream. It is a powerful symbol — powerful in its grasp on the imagination, and (supposedly) powerful in what it can accomplish in reality, for who can doubt that power after Hiroshima and Nagasaki? With this genie working for us, surely we need not fear climate change?

In causing an ideological trance, the nuclear power prescription carries some danger. It is hardly grounds for celebration when share values in a uranium mining firm soar, or when the beleaguered industry sells a few more reactors. For all their perils, these are minor matters in comparison. What is of real concern is that pushing the nuclear barrow could substitute for effective action of the required scale against greenhouse emissions.

What Should Be Done — and Has Already Started

As a 'solution' to climate change, nuclear power fails in every important respect. But it retains an iconic glitter, far better than the plodding, everyday concerns that have nevertheless crippled its development — questions about how much it costs, where to put

39. Patterson, p. 68.

its waste, what if its operators turn out to be only human and error-prone … To the dazzled eye, such banalities can be simply irritating. ('Tomorrow is already here, and they want us to worry about cents per kilowatt-hour!') Compared to the breathtaking sweep of the nuclear 'solution' that applies a single, ultra-powerful, hypermodern fix, the actual, effective means of combating climate change could be made to seem banal.

Indeed, the very first policy that recommends itself can be put in a banal enough way: 'We should stop wasting energy!'; or, less brusquely: 'Be more efficient in how we use available energy'. Add to this that it is essential in the long term for sustainable energy sources to be developed, and the fundamentals of an effective policy are laid out. Note that what consumers see as their needs is taken to be essentially unchanged; it is a question only of the processes used in satisfying them. (Many of us, perhaps, would like to see a future in which the pattern of these consumer demands has changed to a greater or less extent, but no such developments are being considered here.)

It then becomes a matter of studying whether the threat of 'inadvertent' climate change can be removed simply by using energy more efficiently. What is first involved here is examining whether the improved methods can reduce the amount of energy used — thus reducing harmful emissions — to keep greenhouse gases below danger levels. Then there is the further question of the economic and political plausibility of these methods.

These studies were done many years ago, with a variety of researchers agreeing on overwhelmingly positive conclusions, and were perhaps surprising in their quantitative findings. Schneider has summarized some typical results:

> Numerous studies have evaluated the potential for improving energy efficiency in industrialized countries. In Western European countries the potentials generally range from 30 per cent to 50 per cent. In the US, the utilities' Electric Power Research Institute (EPRI) estimated the technical energy savings potential at 30 per cent of overall electricity consumption. Calculations by Amory Lovins's Rocky Mountain Institute, in Colorado, place the potential for saving energy much higher — at over 70 per cent of current power consumption in the US.[40]

40. M. Schneider, 'Climate Change and Nuclear Power', World Wide Fund for Nature, Gland, Switzerland. Download from <http://www.antenna.nl/wise/cop6/download/climate.pdf>.

For a 'meta-review' of the early work of this sort, see the 1988 paper by Keepin and Kats. Their paper is otherwise relevant for treating exactly the question of particular interest here: a 'comparative analysis of nuclear and efficiency abatement strategies'. Of course they are well aware and take fully into account that in general it takes money to achieve more efficient performance. They ask: if we spend a certain sum on a nuclear station rather than a fossil-fuel one, and thus prevent some weight of carbon dioxide (CO_2) being emitted; how does this weight compare with what could have been eliminated by spending that sum on improving efficiency? This is the question they study, and they summarize their qualitative findings thus, for several scenarios:

> [E]nergy efficiency is the single most important technological factor determining future energy consumption levels, and therefore also future CO_2 emissions. This has been shown repeatedly in a number of sensitivity analyses and uncertainty studies with global models … Opportunities for efficiency gains are so compelling that they suggest that global warming can best be avoided by concentrating on efficiency rather than on a rapid expansion of nuclear power.[41]

This unsurprising but important truism has not escaped the notice of some governments. Within a single week, the media carried two significant items — first, on Canada, which:

> … unveiled a budget last week with some $2.4 billion in new environmental spending. At the center of the eco-money is an $805 million Clean Fund that will dole out cash for private-sector projects that reduce greenhouse-gas emissions, as well as municipal or private initiatives that produce emissions credits under the Kyoto Protocol. There are also tax incentives for private home retrofitting and renewable-energy generation, along with a host of other green incentives, regulations, and infrastructure investments. Ottawa also says it is considering a program of 'feebates,' whereby purchasers of gas-guzzling vehicles would pay a fee and buyers of fuel-efficient cars would

41. B. Keepin and G. Kats, 'Greenhouse Warming: Comparative Analysis of Nuclear and Efficiency Abatement Strategies', *Energy Policy*, vol. 16, no. 6 , December 1988.

> receive rebates — a revenue-neutral program that could spur the sale of more eco-friendly autos.[42]

The second item, with measures to encourage sustainable electrical production, might be doubly surprising — because of its initiator as well as its content. It featured in the *San Francisco Chronicle* on 1 March 2005:

> Gov. Arnold Schwarzenegger announced on Monday his latest effort to cover California rooftops with solar panels, reviving an idea he has touted since taking office. Schwarzenegger and two senators introduced two bills to spur the installation of solar power systems in 1 million homes and businesses within the next 13 years, using a combination of rebates and tax credits … One bill would give home builders and homeowners rebates to install solar panels on new or existing buildings. The rebates would lower the cost of installation from $13,000 to $8,000 but would decrease over time, ending in 2015.
>
> In new housing projects with 50 or more homes, builders would have to offer the option of installing a solar power system … Another bill would extend an existing solar energy tax credit, set to expire this year. Homeowners would receive a 7.5 percent tax credit for every dollar they spent on solar installation, not counting the amount they would get back in rebates.[43]

These are measures to be supported and disseminated, but they should not be overrated. As every climate conference makes increasingly clear, governments are doing too little and may well be too late. Governments were generally irresponsible when the question of nuclear power originally arose, educated only when the public moved to protect generations to come and held those governments to account. To achieve timely action against climate change will probably require a similar public awareness and a similar political pressure.

For a last word, let us return to the work of Keepin and Kats above. A quantitative figure emerges from their analysis when they

42. S. Chase, *The Globe and Mail*, 24 February 2005. Downloaded from <grist.org/cgi-bin/forward.pl?forward_id=4402>.
43. 'Governor Fires Up Solar Plan', *The San Francisco Chronicle*, 1 March 2005, downloaded from <sfgate.com/cgi-bin/article.cgi?file=/c/a/2005/03/01/BUGOPBIF881.DTL>.

consider a sixfold expansion of nuclear power suggested by a nuclear advocate, and ask the question:

To what extent does this sixfold nuclear expansion scenario effectively *contribute* to the greenhouse warming problem, in the sense of diverting funds away from more promising CO_2 abatement strategies?

Their analysis allows them to give, in the case of the United States, a startling figure for this 'opportunity cost':

> *[E]ach dollar invested in efficiency displaces nearly seven times more carbon than a dollar invested in nuclear power … every $100 invested in nuclear power effectively releases an additional tonne of carbon into the atmosphere.*[44]

Over the years since 1988, each of the cost figures involved — for nuclear power and for improving efficiency — will have changed, but if anything, these changes would probably tilt the balance today even more heavily against nuclear expenditure. (The price of uranium has gone up, for instance, while the tendency of technological change is to lower the cost of efficiency improvement.)

Reasons have been given above why a large-scale nuclear program is not possible and, when they consider the prohibitively large capital investment required, Keepin and Kats give their own reasons for this. But to do harm, the program does not have to be extensive; even a single nuclear station 'replacement' would have an effect measurable in tonnes — the tonnes of greenhouse gas that need never have been emitted, if the station had not taken funds away from improving energy efficiency. Rather than ineffective placebos like the opening of a few nuclear stations, we need a far-reaching overhaul of our current practices that squander energy while threatening to make the world seriously unliveable.

44. Keepin and Kats, pp. 551–2. Italics in original. 'An additional tonne of carbon', in the sense that it would not have been emitted if the $100 had instead been spent on improving energy efficiency.