2.1 Alternative Means

Some deniers of global warming deny because they know that God, not human beings, controls the climate, and that salvation will prevail over the destruction of the earth. (We'll meet these characters in Chapter 5.) But even among the more agnostic sceptics, who acknowledge that burning fossil fuels may cause problems but insist we can't do anything that would impede economic growth, there are many who believe in salvation—but a secular salvation through cleverer technologies. In the face of dangerous risks we ingenious humans *can* do something after all. There are ways, they say, for us to continue with the fossil fuel burning business *and* at the same time reduce our emissions of greenhouse gases.

To the problem of meeting our 'energy needs' they propose a variety of technological solutions: carbon capture and storage (CCS), hydraulic fracturing for natural gas, expanded nuclear power. (It's significant that there's relatively little talk about what should be the first priority, which is to *reduce* our energy needs.) There are also biofuels, such as ethanol, but in many cases these consume as much energy to produce as they ultimately deliver; and where arable land is converted from needed food crops to biofuel production, the glaring social injustice renders this option difficult to promote. Then there's geo-engineering, and especially carbon *extraction* and storage. Let's consider the viability of these approaches, and then take a look at the unseen drama that's driving them.

First there's the *carbon capture and storage* technique, also known as carbon sequestration. This involves fitting (or retrofitting) fossil fuel power plants with a system that captures the carbon dioxide from the flue gas. Then the CO_2 has to be moved to some other site, preferably by pipeline, where it can be sequestered, stored in some suitable geological formation deep underground—and sealed with a prayer that it won't find its way back to the surface. And none of this in my back yard, please.

For carbon sequestration is a procedure not without its dangers. As the authors of a special IPCC report on the topic warn: 'A sudden and large release of CO_2 would pose immediate dangers to human life and health, if there were exposure to concentrations of CO_2 greater than 7–10% by volume in air.' As for the possibility of leakage of sequestered carbon, and other mishaps when one stores such stuff underground at high pressures:

> Impacts of elevated CO_2 concentrations in the shallow subsurface could include lethal effects on plants and subsoil animals and the contamination of groundwater. High fluxes in conjunction with stable atmospheric conditions could lead to local high CO_2 concentrations in the air that could harm animals or people. Pressure build-up caused by CO_2 injection could trigger small seismic events.

In view of our limited experience with geological storage overall, the authors conclude that 'the effectiveness of the available risk management methods still needs to be demonstrated'.[1]

Since so few CCS systems have been put into operation, there aren't enough data to determine their efficiency and the longer-term costs of building and operating them. In any case a major problem is that the system that 'scrubs' the flue gas consumes a significant proportion of the energy generated by the power plant, so that more fossil fuels are needed to produce the same amount of energy than in a plant without a capture system. The IPCC report estimates that a power plant equipped with a CCS system will use 10–40% more energy, and the capital costs will be 37–76% higher, depending on the type of fuel the plant uses.[2]

If you need to build pipelines to transport the captured carbon, this too will be expensive, and with significant costs to the environment. Then there's the problem of storing the carbon securely, and monitoring it. According to a report by the US Congressional Budget Office: 'Engineers have estimated that, on average, electricity generated by the first CCS-equipped commercial-scale plants would initially be about 75 per cent more costly than electricity generated by conventional coal-fired plants.'[3] Because of the large amount of energy and materials required to build and operate the entire system, the costs are rising steadily—just as the prices of renewable forms of clean energy are falling. Although the costs of CCS would come down as more systems are built, it still looks like an expensive and cumbersome way of allowing us to sustain our fossil fuels habit.

Then there's *induced hydraulic fracturing*, or 'fracking', for natural gas, which has thrilled many people in the US with the prospect of greater energy independence and lower greenhouse gas emissions, as home fracked gas takes over from imported fossil fuels. Such considerations have generated corresponding enthusiasm in many other countries. It's true that a power plant fired by natural gas emits around half as much CO_2 as one powered by coal. But to get the gas out of the ground and into the power plant involves 'fugitive' emissions of methane, a far more effective heat-trapping gas than carbon dioxide. Then there are multiple side-effects and by-products from the fracking process, which involves injecting under heavy pressure millions of gallons of water together with a mixture of toxic chemicals and sand into shale formations deep beneath the earth's surface.[4] Serious and dirty business.

Citing numerous scientific studies of the process, a study by James Hansen and his colleagues emphasises that not enough research has been done to gauge its overall safety and impacts on the environment.

> A large fraction of the injected water returns to the surface as wastewater containing high concentrations of heavy metals, oils, greases and soluble organic compounds. Management of this wastewater is a major technical challenge, especially because the polluted waters can continue to backflow from the wells for many years. Numerous instances of ground water and river contamination have been cited. High levels of methane leakage from fracking have been found, as well as nitrogen oxides and volatile organic compounds.[5]

If this doesn't sound so bad to you, think that whatever gas is extracted through fracking still belongs in our relatively small carbon budget if we're not to risk wrecking the planet.

But it's perfectly safe! spokespersons for the industry assure us. Of course, don't they all say that—the lead paint manufacturers, the tobacco companies, the synthetic chemicals industry, the producers of genetically modified organisms (GMOs), the nanotechnology outfits? It's not *our* product that's responsible for this damage to your health or your genes, or to other species of animals and plants. A familiar story, and one that prompts us to question such invasive forms of technology.

Many technophiles have proposed *geo-engineering* as the solution. Engineering: ever since the Romans invented and deployed the siege engine (*ingenium* in Latin—whence our word 'ingenuity'), engines have been the driving force behind our conquest of the earth. The Industrial Revolution depended on the steam engine, and the internal combustion engine has revolutionised agriculture and transportation.[6] We have already engineered some gigantic projects—so why not the whole earth and its climate?[7]

We can devise means of reducing the natural warming effect of solar radiation: if the sun is too hot because we're generating so much of our own heat, we'll simply 'turn it down' by sowing the stratosphere with sulphate aerosols, as first suggested by Paul Crutzen. The problems with this kind of project are legion (as Crutzen acknowledges): for example, it may reduce precipitation over wide areas, increasing the incidence of droughts; it would deplete the protective layer of ozone in the stratosphere; the reduction of solar radiation would affect crops in ways we can't accurately predict; and it would increase acid deposition and so damage natural ecosystems. To intervene in the climate system so forcefully will no doubt have other unforeseen consequences that are not so favourable.[8]

The increasing enthusiasm for geo-engineering is worrying for several reasons. For one thing it provides an excuse for continued procrastination on coping with global warming: no need to worry if we can't agree to mitigate the problem, because we can always geo-engineer ourselves out of it when we reach the limit. But how many other, worse problems will that create?

It's also disturbing that the technology for distributing sulphate aerosols, or the equivalent in soluble particles for the oceans, isn't so expensive: it's well within the resources of a small state or a large corporation to deploy it. In fact some of it has already been deployed.[9] You can easily imagine a country that's being flooded by rising sea levels becoming so frustrated by other countries' inaction that it decides unilaterally to sow the atmosphere with sulphate aerosols for reasons of self-preservation. And once those particles are up there, if the effects prove disastrous there's no way of bringing them back down.

The technology we most need at this point would extract carbon dioxide from the atmosphere and transmute it into a storable form. This would not only reduce the greenhouse effect but also slow the acidification of the oceans, which is necessary for longer-term stabilisation of the climate. The technology hasn't been developed yet, and the cost projections are prohibitive. A study by the American Physical Society (APS) suggests that the cost of capturing and storing 50 ppm of carbon dioxide would be more than $200 trillion.[10]

If we assigned responsibility for extracting their fair share to nations based on their cumulative CO_2 emissions, the United States would be obliged to achieve a reduction of around 25 ppm, which would cost according to the lowest available projection (which is less than one-quarter the estimate of the APS study) some $28 trillion—or around $90,000 per individual.[11] You would also have to include the costs of secure and reliable disposal of the captured CO_2 which is unusually bulky. For example, the amount of carbon that would need to be extracted from the atmosphere to achieve a reduction of 25 ppm would be equivalent, if made into carbonate bricks, to the volume of around 160,000 Empire State Buildings. In whose back yard are we going to stack all those blocks?

It's no wonder that environmental economists like Nicholas Stern keep telling us it's less expensive to take preventive steps now rather than mitigating measures later—also William Nordhaus, who was awarded a Nobel prize in 2018 for his work on the economics of climate change. Stern and Nordhaus take different approaches to this issue, disagreeing on how to apply 'discount rates' (which estimate the present value of future costs), but they agree that it makes economic sense to spend money on mitigation now rather than later.[12]

Some commentators claim that more nuclear power is the answer to our energy problems, and that a shift to nuclear energy is necessary if we're to reduce our GHG emissions. By the time of the Fukushima Dai-ichi nuclear disaster in 2011, many environmentalists, dismayed by the lack of progress in slowing anthropogenic global warming, had revised their anti-nuclear stance and resigned themselves to the probability that more nuclear energy would be needed to forestall dangerously degrees of climate change. I found myself starting to think the same way at that time.

But then that same year Kristin Shrader-Frechette, a philosopher *and* scientist at the University of Notre Dame, published an unusually comprehensive and intelligent study of the viability of nuclear power, *What Will Work: Fighting Climate Change with Renewable Energy, Not Nuclear Power* (2011). She shows that when you consider the entire nuclear-fuel cycle of *fourteen* stages, you find that only one (the operation of the reactor itself) *doesn't* produce carbon emissions.[13] When you take the other thirteen into account, it turns out that 'average-nuclear-fuel-cycle GHG emissions are *higher* than average-fuel-cycle GHG emissions from natural-gas-fired plants.'[14]

2.2 Drawbacks of Nuclear Power

The first nuclear power plants for generating electricity came online in the early 1950s, and as of early 2019 there were 450 nuclear reactors in operation world-wide, and another 55 under construction.[15] Development of nuclear power has been slowed, understandably, after three major accidents: Three Mile Island (US, 1979); Chernobyl (Soviet Union, 1986), and Fukushima (Japan, 2011).

Nuclear fission and atomic power have always elicited heavy emotional reactions in some quarters. There were powerful fantasies at work in the modern psyche long before the process of nuclear fission was understood and then replicated. As the author of an excellent history, *Nuclear Fear*, explains:

> Radioactive monsters, utopian atom-powered cities, exploding planets, weird ray devices, and many other images have crept into the way everyone thinks about nuclear energy, whether that energy is used in weapons or in civilian reactors. The images, by connecting up with major social and psychological forces, have exerted a strange and powerful pressure within history.[16]

The scientific revolution introduced a new turn to old stories: now, thanks to the power of modern science and technology, humans for the first time acquired the ability to create a utopia or destroy the planet—or at least an elite priesthood of humans did: the scientists.

It was several years after the discovery of radioactivity in 1896 that Ernest Rutherford and Frederick Soddy discovered that radioactive decay often involved the process of nuclear 'transmutation' of one element into another. While Albert Einstein was working out the special theory of relativity, Soddy was thinking about matter and energy in the context of experiments with radioactivity. In a book called *Radio-Activity: An Elementary Treatise* (1904) he emphasised the novelty of nuclear transmutation as being totally different from other kinds of physical or chemical change: 'The process which proceeds spontaneously in Nature, and gives rise to the phenomenon of radio-activity, is entirely beyond the range of ordinary molecular forces.'

The experiments he conducted with his mentor Rutherford confirmed that 'the energy of radio-active change is of the order of a million times greater than is ever manifested in ordinary chemical change'. The powers of nature had hitherto impressed people through phenomena like earthquakes and volcanoes, typhoons and floods, but Soddy sensed a whole new dimension of power *within* matter itself. 'These considerations force us to the conclusion that there is associated with the internal structure of the atom an enormous store of energy which, in the majority of cases, remains latent and unknowable.'[17]

Further reflection on the radioactive properties of radium and the even more powerful element uranium convinced Soddy that the enormous energy contained in radioactive elements 'is possessed to greater or lesser degree by all elements in common and is part and parcel of their internal structure'. This led him to a more general view of the universe as a field of energies behind mere appearances of substantiality—a prescient anticipation of the picture we would later get from quantum physics.

He advocated trying to intervene in the process of nuclear transmutation for human benefit, since the practical consequences could transform the world.

> The energy which we require for our very existence, and which Nature supplies us with but grudgingly and in none too generous measure for our needs, is in reality locked up in immense stores in the matter all around us, but the power to control and use it is not yet ours.

The possibility of humanity's finding the key to unlock this energy through modern technology gave rise to utopian phantasies—cultivated by Soddy but soon widespread among science journalists and the general public—of powering civilisation safely and cleanly.

> A race which could transmute matter would have little need to earn its bread by the sweat of its brow. If we can judge from what our engineers accomplish with their comparatively restricted supplies of energy, such a race could

> transform a desert continent, thaw the frozen poles, and make the whole world one smiling Garden of Eden.[18]

But Soddy was also aware of the dangers of transmutation: a race capable of that feat could come to a sudden end.

> By a single mistake, the relative positions of Nature and man as servant and master would, as now, become reversed, but with infinitely more disastrous consequences, so that even the whole world might be plunged back again under the undisputed sway of Nature.[19]

Our planet, he wrote, can be regarded as 'a storehouse stuffed with explosives, inconceivably more powerful than any we know of, and possibly only awaiting a suitable detonator to cause the earth to revert to chaos.' Visions of apocalypse invaded the public mind—but now brought about not by God or nature, but by scientists possessed of mysterious, almost superhuman powers.[20]

Given the prevalence of such striking visions and archetypal imaginings long before the first nuclear reactor was built in the 1940s, it's no wonder that reactions to radioactivity resulting from human interventions have been more visceral than rational. Since the nuclear explosions from the atomic bombs dropped on Hiroshima and Nagasaki, which made it clear that humankind had come into possession of a horrendous new weapon of warfare, some fear is surely justified.

It's true that nuclear power was developed out of the weapons programme, by modifying the reactors that were used for the bombs, and it thus got off to a less than blameless start. As one radiation safety expert describes the situation, because of the perceived urgency following the Second World War,

> Regulation in the UK was, shall we say, limited. Irradiated fuel was reprocessed quickly, so, for example, iodine-131, which normally would have decayed by the time the fuel was being reprocessed, was released to the environment, and the liquid discharges were substantially higher than considered appropriate now. It took Windscale, now Sellafield, quite a while to get its house in order, and to change from being a plant with military objectives to one appropriate for treatment of spent fuel from a nuclear power programme.

In an appropriate reaction, nuclear power in the UK is now 'extremely well regulated'.[21]

Nowadays the technological processes involved in generating energy and producing atomic bombs are different. It's impossible for a current-generation nuclear reactor to explode like a bomb, though it can take decades for a damaged reactor to be made safe. In any case, we can think more rationally about the dangers of nuclear energy if we dissociate it from the weapons.

The development of nuclear power has been checked three times: by the accidents at Three Mile Island, Chernobyl, and Fukushima. The Fukushima Dai-ichi catastrophe was especially significant, coming as it did at a time when many environmentalists, dismayed by the lack of progress in slowing anthropogenic global warming, had revised their anti-nuclear stance and resigned themselves to the probability that more nuclear energy will be needed to forestall dangerously degrees of climate change.

When a bad accident occurs, as at Chernobyl and Fukushima, the consequences are formidable and long lasting. (Years after the Fukushima disaster they are still struggling to find satisfactory ways of dealing with the enormous amount of contaminated water coming from areas around the melted fuel in the reactors.) The Chernobyl plant was badly designed and poorly maintained, and the reaction to the explosion of one of its reactors incompetent. The Soviet authorities at first denied that a dangerous incident had taken place and maintained a cover-up for as long as they could. The KGB later sabotaged an assessment by the International Atomic Agency (IAEA) in Vienna by stealing a large registry of data from a computer in Belarus.[22]

These disasters galvanised public opinion against nuclear power, even though the opposition is often based on visceral reaction rather than rational consideration.[23] For example: a search for ‘Chernobyl’ on the website of the Helen Caldicott Foundation, which displays the banner ‘Nuclear Free Planet’, turns up an article with the title ‘Chernobyl Deaths Top a Million Based on Real Evidence’.[24] The mainstay of this real evidence is a study published in 2009 by three scientists from Belarus and Russia, *Chernobyl: Consequences of the Catastrophe for People and the Environment*, which according to Caldicott estimates the number of deaths attributable to the meltdown at around 980,000.[25]

By contrast, according to the third report on the effects of the Chernobyl catastrophe issued by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in 2011, among the 134 plant staff and emergency workers who suffered acute radiation syndrome (ARS) from the accident, the condition proved fatal for 28 of them. By 2006 a further 19 ARS survivors died, though their deaths were not directly attributable to the effects of ionizing radiation. Although the report attributes ‘a substantial fraction’ of the 6000 cases of thyroid cancer in people who were children at the time of the accident to their consumption of milk contaminated with iodine-131, only 15 cases had proved fatal by 2005, some twenty years later.[26] A death toll, then, of under 50.

The figure for fatalities given by Caldicott on the basis of *Chernobyl: Consequences of the Catastrophe* is almost 20,000 times greater than the estimate by the UN scientific committee in its third report—hardly the kind of discrepancy attributable to differences in methodology. What are we to make of this? It's all the more puzzling since the UNSCEAR report 'was prepared in close cooperation with scientists from Belarus, the Russian Federation and Ukraine, who worked with the Committee to scrutinize relevant information'. [27] (Presumably the authors of *Chernobyl: Consequences of the Catastrophe* were not among them.)

A hundred members of national delegations from more than twenty countries attended the fifty-sixth (!) session of the Committee in 2008, with eighteen from the Russian Federation. As the sixth major report on Chernobyl from UNSCEAR since 1988, the document they produced compares favourably with the reports of the IPCC in terms of broad scientific consensus from numerous scientists from many different cultures.[28] What appears to be the most reliable assessment of the situation is a 2019 review of the three most recent books on Chernobyl:

> The official toll is now between thirty-one and fifty-four deaths from acute radiation poisoning (among plant workers and firefighters), doubled leukemia rates among those exposed to exceptionally high radiation levels during the disaster response, and several thousand cases of thyroid cancer—highly treatable, very rarely fatal—among children.[29]

By contrast with the UNSCEAR reports, *Consequences of the Catastrophe* was written by three scientists from Belarus and Russia. Their work wasn't peer-reviewed, and the New York Academy of Sciences, which published the book, has since declined to endorse its contents and conclusions.[30] The similarity to the contrarian fringe in the field of climate science makes you wonder whether their conclusions may have been motivated by factors other than pure science. I've presented the accounts of the aftermath of Chernobyl at some length because they show the importance of considering the results of scientific studies in the broadest relevant context, and with attention to their sources of funding.

The disaster at Fukushima has demonstrated the enormity and longevity of the problems that arise when things go wrong. Nuclear fission isn't just a super-hot form of combustion, but a quite different and more formidable process. Even large fires eventually burn out, but with nuclear fission it's more complex. When a reactor is damaged and shut down, the fission stops but the decay of the radioactive species produced by fission is slow, and produces lots of heat.

Before the Fukushima Daiichi power plant can be decommissioned, the operator's engineers have to remove the hundreds of tons of melted fuel that sank to (or through) the bottoms of the three reactors that underwent meltdowns. Since it's difficult to tell how deep the fuel has sunk, estimates of how long the clean-up will take are approximate and contested. According to the fourth mission report by the IAEA (2018), preparations are still being made to remove the spent fuel from the damaged reactors over seven years after the catastrophe. The IAEA review team suggests that the clean-up will take another '30 to 40 years', but other estimates are much higher: '70 to 80 years' (a Japanese nuclear regulatory authority commissioner). In any case the costs will be astronomical.[31]

A major lesson to be learned from the catastrophe at Fukushima is that safety procedures need to be observed and enforced meticulously, and that regulation has to be strict and independent (and not performed by friends or servants of the industry, as in Japan and many other countries). It's no surprise that the anti-regulation Trump administration, in a great step backward for humankind, has made safety regulations at nuclear power plants voluntary (!).[32]

At any rate nuclear energy has so far proved much safer than fossil fuels—less destructive of human life and the natural environment—per unit of energy yielded.[33] The nuclear power industry has inflicted far less damage on human lives and the environment since the mid-fifties than the coal industry alone has done over the same period. This is one reason that many people recommend more nuclear power as a (transitional) way of 'meeting our energy needs' without generating too many greenhouse gases. (Though it's surely better to think first about *reducing* our energy needs.)

We need to look into how much 'too many' means in this context, but it's worth noting that the major argument against nuclear power is simply *cost*. The facilities are extremely expensive to build and especially to insure. The costs are so high that governments generally have to subsidise the insurance, which is something they're becoming increasingly reluctant to do.

A much cited and very positive study of the costs is 'The Future of Nuclear Power' (2003), by an interdisciplinary committee at the Massachusetts Institute of Technology. The main purpose was 'to explore and evaluate actions that could be taken to maintain nuclear power as one of the significant options for meeting future world energy needs at low cost and in an environmentally acceptable manner.' Projecting a scenario in which the number of nuclear power plants in the world is increased three-fold, to one thousand or more, the authors calculate that a nuclear program of 1000 GWe (gigawatts of electricity) 'has the potential of displacing 15-25% of the anticipated growth in anthropogenic carbon emissions.

The report concludes that 'The nuclear option should be retained precisely because it is an important carbon-free source of power', although the authors also identify four 'unresolved problems' that limit its expansion:

‘*high relative costs; perceived adverse safety, environmental, and health effects; potential security risks stemming from proliferation; and unresolved challenges in long-term management of nuclear wastes.*’[34] However, the biggest problem with the study itself concerns the issue of ‘an environmentally acceptable manner’: the authors’ focus on the ‘carbon-free’ *operation* of a nuclear power plant—ignoring the substantial carbon emissions from building and then decommissioning the facility.

After a period of six years during which no new nuclear power plants were under construction in the US and little progress was made on the problem of waste management, the MIT team published an ‘Update’ to ‘The Future of Nuclear Power’. In view of this lack of progress the new report issued a ‘sober warning’: namely, ‘if more is not done, nuclear power will diminish as a practical and timely option for deployment at a scale that would constitute a material contribution to climate change risk mitigation.’[35]

Perhaps a peripheral factor behind the lack of progress was the shutdown of the world’s largest nuclear power plant in 2007, following an earthquake. This was the Kashiwazaki-Kariwa plant in Japan, owned and operated by the Tokyo Electric Power Company (TEPCO), which as a result of the closure (for twenty-one months) suffered its first loss in decades. For its ‘Update’ the MIT team added the TEPCO Professor of Nuclear Engineering and Mechanical Engineering, who had been appointed in the context of a collaboration between TEPCO and MIT ‘to develop technological and policy options for nuclear power’.[36]

TEPCO lost even more over the meltdown of its Fukushima Dai-ichi nuclear plant after the earthquake and tsunami of 2011, a disaster that by 2014 had cost some $100 billion. The next TEPCO Professor at MIT was the Co-Chair of another ‘Future of’ study, *The Future of Nuclear Energy in a Carbon Constrained World* (2018). This one frankly declares its aim to be ‘a balanced, fact-based, and analysis-driven guide for stakeholders involved in nuclear energy.’ OK, it’s aimed at the nuclear industry, so the tone is upbeat and the focus is on the costs, with an eye to being competitive.

But if the authors acknowledge, as they do, that ‘the main value of nuclear energy lies in its potential contribution to decarbonizing the power sector’, why does the study studiously avoid discussion—or even *mention*—of the carbon emissions produced throughout the life-cycle of a nuclear plant?[37] All the more glaring an omission because it is a finite life: from start to finish only a few decades before the facilities have to be decommissioned, and then you have to start all over again, incurring many more costs and producing more carbon emissions for new construction. It’s hard to avoid the conclusion that funding from TEPCO may have something to do with the emissions omissions.

I mention these MIT studies at length because in the old days you didn't have to worry much about bias in studies undertaken by universities. But now that our institutions of higher learning are becoming more like corporations, with vast infusions of corporate money for research, it's a good idea to investigate the funding sources of academic and scientific studies.

Kristin Shrader-Frechette, a philosopher *and* scientist at the University of Notre Dame, has published an unusually comprehensive and intelligent study of the viability of nuclear power, *What Will Work: Fighting Climate Change with Renewable Energy, Not Nuclear Power* (2011). She points out that the entire nuclear-fuel cycle has at least *fourteen* stages, only one of which doesn't produce carbon emissions.[38] The process up to the end of the construction of the reactor takes around twelve years and is extremely expensive. But the main point is this: 'even under optimum conditions, *only stage (7), reactor operation, is carbon free*. Each of the remaining 13 stages creates high GHG emissions in using mainly fossil fuels'. Hardly a 'carbon free' enterprise. Furthermore, considering that most nuclear power plants use low-grade uranium ore, this in fact means that 'average-nuclear-fuel-cycle GHG emissions are *higher* than average-fuel-cycle GHG emissions from natural-gas-fired plants.'[39]

What Will Work shows in detail that nuclear fission energy doesn't make 'economic sense', nor 'safety sense', nor 'climate sense' (because of its high GHG emissions), not 'ethics sense'—because 'its heaviest, disproportionate health burdens fall on children, developing nations, minorities, and poor people'.[40] What looks to enthusiasts like a magical way to produce vast amounts of energy from a little bit of uranium is in fact not such an efficient or beneficent procedure after all. And because in most countries it takes several years to get approval for the construction of a nuclear power plant, and then several more years to build it, it's unrealistic to regard nuclear power as a feasible 'transitional' energy source while we wean ourselves from burning fossil fuels.[41]

Disposal of the waste poses an especially intractable problem for even a well-functioning nuclear plant. There has been no viable proposal—at least politically—concerning how and where to store the growing amount of radioactive waste from nuclear power plants, which remains toxic for a long time. The prodigious amounts of wasted produced by most of the reactors in the United States is generally stored on the site of the nuclear reactor that generated it, and there's little progress on the preferable alternative of a centralised and secure site (Yucca Mountain in Nevada). But in this case the obstacles are more political than practical.

Politics comes in not only because people don’t want nuclear waste in their back yards, but also because it will be there for many generations. Costly security measures are needed to guard against terrorist attacks and theft of materials usable for nuclear weapons—measures that will remain costly indefinitely.

Notes

[1] *IPCC special report on Carbon Dioxide Capture and Storage*. Prepared by working group III of the Intergovernmental Panel on Climate Change. Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L.A. Meyer (eds.). Cambridge, UK and New York: Cambridge University Press, 2005), 12, 13; available from http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml#2 (23 April 2013).

[2] IPCC, *Carbon Dioxide Capture and Storage*, 4, 343.

[3] Congressional Budget Office, 'Federal Efforts to Reduce the Cost of Capturing and Storing Carbon Dioxide' (2004), 'Summary', para. 4; available from http://www.cbo.gov/publication/43357 (1 August 2014).

[4] See Union of Concerned Scientists, 'Environmental Impacts of Natural Gas', at https://www.ucsusa.org/clean-energy/coal-and-other-fossil-fuels/environmental-impacts-of-natural-gas. Also the informative series by Ian Urbina for the *New York Times*, 'Drilling Down' (Feb 2011 – May 2012); http://www.nytimes.com/interactive/us/DRILLING_DOWN_SERIES.html?_r=0 (7 Mar 2013).

[5] James Hansen *et al.*, 'Assessing Dangerous Climate Change', 9.

[6] For an excellent history (though nothing on Prometheus, in spite of the title), see David H. Landes, *The Unbound Prometheus: Technological change and industrial development in western Europe from 1750 to the present* (Cambridge: Cambridge University Press, 1969).

[7] For many reasons why not, and an excellent overall assessment of geo-engineering (which also uses the category of the Promethean along the lines of those sketched in the following section), see Clive Hamilton's excellent *Earthmasters: Playing God with the Climate* (New Haven: Yale University Press, 2013).

[8] See Alan Robock, '20 reasons why geoengineering may be a bad idea', *Bulletin of the Atomic Scientists* 64/2: 14-18, DOI: 10.2968/064002006.

[9] Geo-engineering references **. Singapore book*.

[10] Hansen et al., 'Assessing Dangerous Climate Change', 16. 'Direct Air Capture of CO_2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs'; http://www.aps.org/policy/reports/assessments/upload/dac2011.pdf (5 August 2014). For a number of reasons they estimate that the amount actually captured for $200 trillion would be considerably less.

[11] Hansen et al., 'Assessing Dangerous Climate Change', ***.

[12] Nicholas Stern, The Economics of Climate Change: The Stern Review (2007)*, etc. ***; William Nordhaus, A Question of Balance: Weighing the Options on Global Warming Policies (2008), The Climate Casino: Risk, Uncertainty, and Economics for a Warming World (2015). * For an intelligent discussion of these issues, see Jamieson, Reason in a Dark Time, chapter 4, 'The Limits of Economics'.

[13] Here's the list (in slightly abbreviated form):

(1) mining uranium ore—or leaching it out; (2) milling the ore; (3) converting the U_3O_8 to gaseous uranium hexafluoride (UF6); (4) enriching the UF_6 and removing the 85 percent of the UF_6 which are enrichment tails; (5) fabricating the fuel into ceramic pellets of uranium dioxide (UO_2), packing the pellets into zirconium alloy tubes, then bundling the tubes together to form fuel rods for reactors;(6) constructing the reactor; (7) operating the reactor; (8) reprocessing waste fuel or spent fuel; (9) conditioning the spent fuel; (10) storing radioactive waste until it is cool enough for transport and permanent storage; (11) transporting the waste to a secure, permanent, storage facility; (12) storing the waste permanently in a secure facility; (13) decommissioning the reactor; and (14) reclaiming the uranium mines, milling facilities, enrichment facilities, and so on. Kristin Shrader-Frechette, *What Will Work: Fighting Climate Change with Renewable Energy, Not Nuclear Power* (Oxford & New York: Oxford University Press, 2011), 45-46,

[14] Shrader-Frechette, *What Will Work*, 52 (emphasis added). See also J. M. Pearce, 'Thermodynamic limitations to nuclear energy deployment as a greenhouse gas mitigation technology', *International Journal of Nuclear Governance, Economy and Ecology* (2008), vol. 2, no. 1: 113-30.

[15] International Atomic Energy Agency, 'Power Reactor Information System database' (2019); https://www.iaea.org/pris/ (26 Apr 2019).

[16] Spencer R. Weart, *Nuclear Fear* (Cambridge, Mass. & London: Harvard University Press, 1988), xi.

[17] Frederick Soddy, *Radio-Activity: An Elementary Treatise* (1904), 93, 94, 170.

[18] Frederick Soddy, *The Interpretation of Radium* (London and New York: John Murray, and Putnam's Sons, 1909), 232-33, 244.

[19] Soddy, *The Interpretation of Radium*, 243, 244.

[20] Frederick Soddy, 'Some Recent Advances in Radioactivity,' *Contemporary Review* 83 (May 1903):708-720, cited in Weart, *Nuclear Fear*, 17. For the full story, see Weart's second chapter, 'Radioactive Fears'.

[21] A. D. Wrixon (formerly of the IAEA), personal communication, May 2019.

[22] Sophie Pinkham, 'The Chernobyl Syndrome', *New York Review of Books*, 4 April 2019, 23.

[23] An excellent source of information about the dangers of radiation is a booklet produced by A. D. Wrixon *et al.* and published by the International Atomic

Energy Agency, *Radiation, People and the Environment* (Vienna, 2004), which shows among other things that the dangers are nowhere near as great as most people seem to think.

[24] http://www.helencaldicottfoundation.org/articles/chernobyl-deaths-top-a-million-based-on-real-evidence.html (2 August 2014).

[25] Alexey V. Yablokov *et al.*, *Chernobyl: Consequences of the Catastrophe for People and the Environment* (Hoboken: New York Academy of Sciences, 2009). Figure cited in Helen Caldicott, 'How nuclear apologists mislead the world over radiation', *The Guardian*, 11 April 2011: http://www.guardian.co.uk/environment/2011/apr/11/nuclear-apologists-radiation?

[26] United Nations, UNSCEAR, *Sources and Effects of Ionizing Radiation*, vol. II, *Scientific Annexes C, D and E* (New York: United Nations, 2010), 64-65. (Downloadable from: http://www.unscear.org/unscear/en/publications/2008_2.html)

[27] Peter Rickwood, 'New Report on Health Effects due to Radiation from the Chernobyl Accident' (Vienna: United Nations Information Service, 2011), at http://www.unis.unvienna.org/unis/en/pressrels/2011/unisinf398.html

In addition: 'The fifty-sixth session of the Committee was attended by … the official contact points of Belarus, the Russian Federation and Ukraine, for matters related to the Chernobyl accident; observers for Belarus, Finland, Pakistan, the Republic of Korea, Spain and Ukraine; and observers for the United Nations Environment Programme (UNEP), WHO, IAEA, the International Agency for Research on Cancer, the European Commission, the International Commission on Radiological Protection, the International Commission on Radiation Units and Measurements, the International Organization for Standardization and the International Union of Radioecology.' (UNSCEAR, *Sources and Effects*, 1.)

[28] For a summary, and links to the six major UNSCEAR reports on Chernobyl, see http://www.unscear.org/unscear/en/chernobyl.html (13 April 2013).

[29] Pinkham, 'The Chernobyl Syndrome', 22.

[30] See the reviews of *Chernobyl: Consequences of the Catastrophe* by Ian Fairlie and by Monty Charles in *Radiation Protection Dosimetry* (2010), 141(1): 97-104.

[31] 'IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap toward the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station' (Vienna: IAEA, 2018); available at https://www.iaea.org/newscenter/pressreleases/iaea-issues-final-report-on-fourth-review-of-fukushima-decommissioning (21 March 2019). Justin McCurry, 'Five years on, cleanup of Fukushima's reactors remains a distant goal', *The Guardian*, 11 March 2016, citing a report (12 February 2017) by the International Research Institute for Nuclear Decommissioning, http://irid.or.jp/en/topics.

[32] Emily Atkin, ‘It’s not just Pork: Trump is also Letting Nuclear Plants Regulate their own Safety’, *New Republic*, 5 April 2019, https://newrepublic.com/article/153465/its-not-just-pork-trump-also-letting-nuclear-plants-regulate-safety (8 Apr 2019)

[33] See, for example, A. Markandya and P. Wilkinson (2007), ‘Electricity generation and health’, *Lancet* **370** (9591): 979–990. An excellent source of information about the dangers of radiation is a booklet produced by A. D. Wrixon *et al.* and published by the International Atomic Energy Agency (IAEA), *Radiation, People and the Environment* (Vienna, 2004), which shows among other things that the dangers are nowhere near as great as most people seem to think.

[34] *The Future of Nuclear Power: An Interdisciplinary MIT Study* (2003), 1, 26, 2; http://web.mit.edu/nuclearpower/ (6 Aug 2013).

[35] PDF available at http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf (6 Aug 2013).

[36] *Update of the MIT 2003 Future of Nuclear Power* (2009), 19. ‘Kazimi first to hold TEPCO professorship’, *MIT News*, 3 May 2000, https://news.mit.edu/2000/tepco-0503 (6 Aug 2013).

[37] MIT Energy Initiative, *The Future of Nuclear Energy in a Carbon Constrained World* (2018), Executive Summary, ix, xi, xvii.

[38] Here’s the list (in slightly abbreviated form):

(1) mining uranium ore—or leaching it out; (2) milling the ore; (3) converting the U_3O_8 to gaseous uranium hexafluoride (UF6); (4) enriching the UF_6 and removing the 85 percent of the UF_6 which are enrichment tails; (5) fabricating the fuel into ceramic pellets of uranium dioxide (UO_2), packing the pellets into zirconium alloy tubes, then bundling the tubes together to form fuel rods for reactors;(6) constructing the reactor; (7) operating the reactor; (8) reprocessing waste fuel or spent fuel; (9) conditioning the spent fuel; (10) storing radioactive waste until it is cool enough for transport and permanent storage; (11) transporting the waste to a secure, permanent, storage facility; (12) storing the waste permanently in a secure facility; (13) decommissioning the reactor; and (14) reclaiming the uranium mines, milling facilities, enrichment facilities, and so on. Kristin Shrader-Frechette, *What Will Work: Fighting Climate Change with Renewable Energy, Not Nuclear Power* (Oxford & New York: Oxford University Press, 2011), 45-46,

[39] Shrader-Frechette, *What Will Work*, 52 (emphasis added). See also J. M. Pearce, ‘Thermodynamic limitations to nuclear energy deployment as a greenhouse gas mitigation technology’, *International Journal of Nuclear Governance, Economy and Ecology* (2008), vol. 2, no. 1: 113-30.

[40] Shrader-Frechette, *What Will Work*, 36, 70, 4.

[41] I was persuaded to change my mind on this issue by the arguments of Martin Schönfeld.*