WHERE WILL WE GET OUR ENERGY?

A comprehensive quantitative system engineering study of the relationship between climate, science, and technology

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Foreword

I decided to write this book because there is too much misinformation about energy, and the reliable information about energy is scattered.

I have been fascinated by nuclear power for decades. Before the age of the internet, finding information was difficult. Public libraries didn't have much material. University libraries mostly didn't have visiting privileges, except for faculty and staff. It was difficult to find the names of experts, and once one knew the names of experts, it was difficult to contact them.

That changed when I read *Smarter Use of Nuclear Waste* in the December 2005 issue of **Scientific American**. I contacted the authors and struck up correspondence. I found that I could send an e-mail message to these authors, and others working in the area, and they would patiently and carefully answer my questions. I'm not an eminent nuclear scientist. Indeed, I never worked in the area. They didn't know me from Adam. But they helped immensely. Drs. Yoon Chang and the late George Stanford were especially helpful.

I started studying in earnest.

I spent my entire professional career working for one of the world's premier systems engineering institutions. I was trained in computer science and applied mathematics, and especially the applied mathematics of systems engineering. I started looking at energy as a system problem, not an individual generator or individual source problem.

Once I got past the political hyperventilating, I found there are numerous problems with the proposed alternatives to fossil fuels. Many simply cannot provide enough energy to make a difference. Some of the problems of those that can produce enough energy are related to generators, but the most severe problems are system problems.

This has led me to conclude that most of the proposed alternatives to fossil fuels are useful only for applications that tolerate variable supply, such as pumping water. Where reliable supply is important, the traditional sources – coal, gas, hydro, and nuclear – are the only viable sources. Regardless of the outcome of the debates whether global warming is real, or harmful, or caused by human activity, it will eventually be necessary to phase out the use of fossil fuels. That leaves hydro and nuclear. Hydro currently provides 6.2% of American electricity, or about 2.3% of total energy. There aren't many good sites left for hydro expansion, and some environmentalists want to remove dams. It's impossible for hydro to provide sufficient reliable energy. That leaves nuclear power.

Herein, I first explore the current energy landscape, then the arguments that we must *do something!* about climate change, then describe non-nuclear alternatives to fossil fuels, and finally describe the attributes of nuclear power. Some readers might (or might not) be surprised to discover that essentially all of the objections to nuclear power are based upon false premises. Some readers might (or might not) be surprised to discover that there is no “climate crisis,” but if we accept the social inevitability to *do something!* the logical conclusion is that nuclear power is the only viable future for energy production.

The sooner we get (re)started, the better off we will be.

Van Snyder
June 14, 2024

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Chapter 1

Why do we care about energy?

> *I curse my belly for making me work so hard.*
> – Anonymous Babylonian farmer, thousands of years ago

Energy is the lifeblood of the economy

Energy is the lifeblood of our economy, and the economy is the lifeblood of our civilization.

The mechanical grain mill of the twelfth century was as liberating for women as the washing machine of the twentieth century. All of the tedious tasks that did not require the greater strength of the male body fell upon women. Even 2,000 years ago, Antipater of Thessalonika wrote of the benefits of energy for the daily lives of women [2, §9.418, p. 233]:

> Cease from grinding, ye women who toil at the mill; sleep late, even if the crowing cocks announce the dawn. For Demeter has ordered the Nymphs to perform the work of your hands, and they, leaping down on the top of the wheel, turn its axle which, with its revolving spokes, turns the heavy concave Nisyrian mill-stones. We taste again the joys of the primitive life, learning to feast on the products of Demeter without labour.[a]

Water mills played a large part in the economic development of England for half a millennium. The Domesday book commissioned by William the Conqueror in 1086 recorded 5,624 water mills, about one for every fifty households. On the other side of the channel,

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[a] Demeter was the goddess of harvest and agriculture. The vertical-axle water mill was invented in mid fourth century B.C. Mesopotamia. The horizontal-axle overshot water mill was invented in Greece in about 210 B.C.

windmills became so important that Pope Celestine III (1191-98) taxed them [1, pp. 11-12].

Without today's energy sources our lives would be short and miserable. Girls would be waking before dawn to grind grain to make bread. We would be heating our homes and cooking our food using wood, crop residues, and animal dung. Our forests would be rapidly disappearing.

We would have none of the conveniences we have come to require. No automobiles. No televisions. No electric lights. No microwave ovens. No washing machines. No internet. No running water. No sewage treatment. No hospitals as we know them now.

We would have none of the industries that create those conveniences. We would have none of the materials of which those conveniences are composed. No steel. No aluminum. No concrete. No computer chips.

We would have far less food, and use more land to grow it.

Low-energy farming requires more land, and more people to work the land. Forests and wildlands would be disappearing as villages spread and expand.

90% of families would live on subsistence farms, or in villages surrounded by subsistence farms. Men would spend their days tending crops and livestock, or hunting. Women would spend their days collecting wood, crop residues, and animal dung, and chopping wood, for fuel. Cooking would be slow and tedious, with more attention given to the fire than to the food. Cooking and heating would produce unhealthful pollution. To clean laundry, women would beat clothes on rocks in a nearby stream, wring them by hand, and hang them on a tree – even in winter, when they would beat the ice from the clothes. Children would work on the farm instead of attending school. Farmland would be depleted by lack of fertilizers, and erosion.

Transportation would be provided by animals. In 1900, one out of every four acres of American farmland was devoted to growing food for draft animals. New York City, with less than half its present population, had 100,000 horses, which produced more than 2.5 million pounds of manure every day. Horse corpses littered the streets. Horse theft was more common in New York City than in the entire state of Texas.

Every big city had a similar problem.

This is how environmentalists insist that developing countries must continue to live, and how they want developed countries to live in the future. They complain about the loss of forests in Brazil and Congo, but that's what subsistence farming requires – more cropland. When baboons plunder your sweet potatoes, or elephants plunder your corn, your choice is to watch your family starve, or eliminate the competition and face at least criticism from environmentalists, and maybe arrest, fines, or imprisonment.

Major aid organizations, and most developed countries' foreign aid structures, have shifted away from supporting energy development in developing countries, or actively oppose it. Populations are growing. Forests and wildlands in developing countries are shrinking, while they grow in developed nations.

Without energy, life would be difficult and short. We would envy the residents of today's inner-city ghettos, with their electric light, hot and cold running water, sewage treatment, clean transportation, heated and cooled homes, abundant food, cell phones, microwave ovens, color television, internet, and hospitals.

The Club of Rome wrote

> The common enemy of humanity is man. In searching for a new enemy to unite us, we came up with the idea that pollution, the threat of global warming, water shortages, famine and the like would fit the bill. All these dangers are caused by human intervention, and it is only through changed attitudes and behavior that they can be overcome. The real enemy then, is humanity itself.

George Bernard Shaw worried about population. He advocated that every adult should appear before a board every five years, that would decide whether that person's life would continue. He wished for a "painless gas." Adolph Hitler heeded his message.

In developed countries, with abundant energy and infrastructure, populations are stable or shrinking, or would be but for immigration. Last year, twice as any deaths as births occurred in Japan. For the first time in its recorded history, Japan is accepting immigrants, mostly from China and Korea, but on one condition: They must become farmers. Forests are growing. Wildlands are growing. There are environmental protections. Farms are shrinking, but farm output is increasing, and farming produces enormous and growing food surpluses. Even in Africa, obesity is becoming a problem. The conclusion is that prosperity reduces fertility – and prosperity depends upon energy.

That's why we care about energy.

If you want to read a more detailed picture of the energy-starved "utopia" that the opponents of energy envision, read **Apocalypse Never: Why Environmental Alarmism Hurts Us All** [3].

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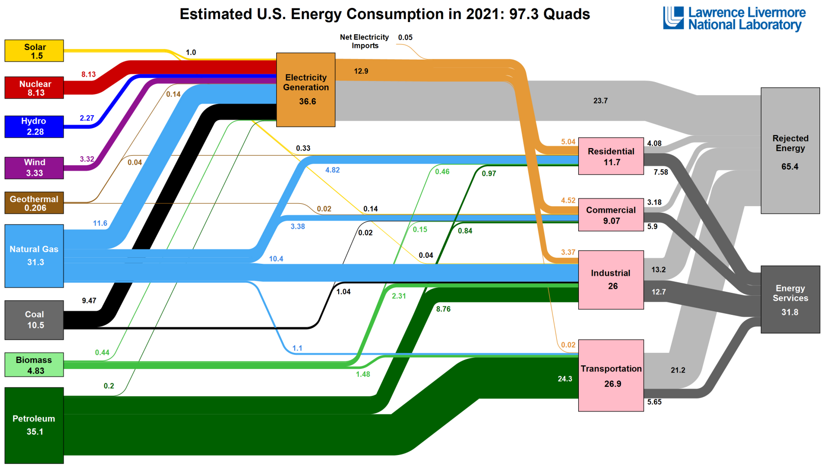
[3] Michael Shellenberger. *Apocalypse Never: Why Environmentalism Hurts Us All*. Harper-Collins, 2020. ISBN 978-0-06-300169-5.

Chapter 2

What are our current energy sources?

2.1 Total energy

According to Lawrence Livermore National Laboratory [2], in 2021 the United States used approximately 97.3 quads[a] = 3.25 TW-yr of energy. 31.8 quads were used for energy services. 65.4 quads were conversion losses, or rejected energy. Overall, the energy efficiency of the U.S. economy was 32.7%.



Source: LLNL March, 2022. Data is based on DOE/EIA MER (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Figure 2.1: Sankey Diagram of Estimated U.S. Energy Consumption in 2021

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[a] Quad = Quadrillion British Thermal Units (BTU). One Quad = 293071.07 gigawatt hours = 33.43 gigawatt years. One BTU is the amount of heat energy required to raise the temperature of one pound of liquid water at a pressure of 1,000 millibars from 39° to 40° Fahrenheit.

2.2 Primary U.S. energy sources

As percentages of the total energy budget, the contributions of primary energy sources were

Geothermal	0.21%	Solar	1.54%	Wind	3.43%
Hydro	2.34%	Biomass	4.97%	Nuclear	8.36%
Coal	10.8%	Gas	32.2%	Petroleum	36.1%

Minor sources such as ocean currents, ocean waves, ocean tides, Amory Lovins's vigorous handwaving, Tinkerbell's pixie dust, and unicorn farts contributed too little to be included in the figures.

Total energy use changes more rapidly than the proportion of energy used in each sector of the economy, and the proportion of energy[b] that each sector gets by way of electricity.

Sector	Input Energy	GWth yr	From Electricity	GWe yr	Useful Energy	Usage Efficiency
Electricity	37.7%	1,223				35.2%
Residential	12.0 %	391.2	43.1%	168.5	23.8%	34.9%
Commercial	9.3%	303.2	49.8%	151.1	18.6%	35.1%
Industrial	26.7%	869.3	13.0%	112.7	39.9%	50.1%
Transport	27.7%	899.3	0.07%	0.669	17.8%	21.0%
Total		3,686		433.0	100%	32.7%

The "total" row of the GWth-yr column is the total primary energy input into the U.S. economy. It is not the sum of the entries in the column because the total energy input to other sectors includes electricity.

The amount of a fuel used depends upon its energy density.

Fuel	Quads	Tonnes used	GWth-hr/T	Quads/T
Natural gas	31.3	616×10^6	1.49×10^{-2}	5.08×10^{-8}
Coal	10.5	463×10^6	6.67×10^{-3}	2.27×10^{-8}
Petroleum	35.1	842×10^6	1.22×10^{-2}	4.17×10^{-8}
Biomass	4.83	128×10^6 to	1.11×10^{-2} to	9.10×10^{-9} to
		531×10^6	2.67×10^{-2}	3.77×10^{-8}
Uranium	8.13	111.4	$21,390$	7.13×10^{-2}

T = tonne = 1000 kg

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[b] GW means "gigawatt," one thousand megawatts or one million kilowatts. GWth-yr means "gigawatt (thermal) year." GWth-hr means "gigawatt (thermal) hour. ‘’GWe-yr means "gigawatt (electric) year." TW means "terawatt," one thousand gigawatts.

2.3 U.S. Electricity

Electricity was produced in 2021 from several sources [3].

	Quads	Fuel	Output		Quads	Thermal
Source	Input	Tonnes	GWe-yr	Fraction	Output	Efficiency
Gas	11.0	216,451,613	169.1	35.5%	5.058	45.98%
Coal	12.1	626,213,000	131.1	27.5%	3.921	32.40%
Nuclear	8.44	115.6	92.07	19.3%	2.754	32.63%
Petroleum	0.24	6,749,477	2.878	0.60%	0.087	36.25%
Hydro	2.69		32.70	6.86%	0.978	
Wind	2.53		31.1	6.53%	0.930	
Solar	0.61		7.28	1.53%	0.218	
Biomass	0.5		7.05	1.48%	0.211	
Geothermal	0.15		1.82	0.38%	0.054	
Other			1.48	0.31%	0.044	
Total			476.58	100%	14.26	

`https://www.eia.gov/electricity/annual/html/epa_01_01.html`
is inconsistent with `https://flowcharts.llnl.gov/`

2.4 Worldwide primary energy sources

Worldwide primary energy sources, TWth-yr, in 2019 were [1]

Oil	6.12	Coal	5.00	Gas	4.48
Traditional Biomass	1.27	Hydro	0.48	Nuclear	0.32
Wind	0.16	Biofuels	0.13	Solar	0.08
Other renewable	0.07				
Total	18.12				

Extrapolating from recent worldwide trends, taking into account decreasing populations and per capita energy usage in developed industrialized economies, and increasing populations and per capita energy usage in developing economies, suggests worldwide primary energy use in 2050 will be about 50 TWth-yr.

In 2008, the World Energy Outlook by the International Energy Agency (IEA) optimistically projected that world energy consumption in 2050 would be about 29 TWth-yr. With an unchanged mixture of energy production technologies, they predicted worldwide production of CO_2 would increase from about 22 billion tonnes in 2003, to about 41 billion tonnes in 2050. But they projected that worldwide CO_2 production will actually *decrease* to about 11 billion tonnes in 2050. According to this projection, "efficiency" can make up the difference. A skeptic might inquire if 75% of total energy use can be made carbon-free by "efficiency," then why not 100%? We need to explore what the nature of this magical "efficiency" might be.

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[3] ______. Table 1.1. Total Electric Industry Summary Statistics. https://www.eia.gov/electricity/annual/html/epa_01_01.html.

Chapter 3

Why do we need to change?

> *This institution will be based on the illimitable freedom of the human mind. For here we are not afraid to follow truth wherever it may lead, nor to tolerate any error so long as reason is left free to combat it.*
> – Thomas Jefferson, commenting to William Roscoe on the founding of the University of Virginia, 27 December 1820
>
> *It doesn't matter what is true; it only matters what people believe is true.*
> – Paul Watson, co-founder of Greenpeace

3.1 Resources are finite

There are two principal reasons to expect the spectrum of sources of energy to change.

Firstly, fossil fuels are a finite and rare resource. Unlike most minerals, which were present in the Earth at its formation, or have been created by tectonic processes from other minerals, fossil fuels were largely created by living things. Because fortuitous combinations of geological and ecological circumstances were required, they were sequestered within the Earth in significant quantities in only a relatively few places. Once those reserves are consumed, it is unlikely any more will be found.

The following is based upon a detailed discussion in Section 4.4 of **Plentiful Energy** by Charles E. Till and Yoon Il Chang [54].

Projections of "peak oil," "peak gas," and "peak coal" vary, but it is likely that production of all of them will begin to decline within 25 years, unless it already has.

Controversy and debate continue about the details of "peak oil." Oil industry people speak (and hope) of a plateau, or a long-duration peak. "Peak oil" people forecast a rapid decline, based upon their examination of past oil field declines. Oil fields have lifetimes measured in decades. The huge ones were discovered decades ago. They were discovered first. There have been few such discoveries since 1980, even with improvements in exploration – those in deep water in the Gulf of Mexico, Brazil, West Africa, and the Caspian Sea are very few compared to the discoveries up until the 1960s. The Prudhoe Bay field in Alaska is in decline. The field in the Alaska National Wildlife Reserve can be exploited responsibly, but can at best produce only a "bump" on the downhill side of the "peak oil" decline. Eighty percent of the world's oil now comes from fields over twenty five years old. Production now outweighs discoveries by a large factor – between three and nine, depending upon whom you ask.

There are some 40,000 oil fields in the world today, but only 360 – aging giant fields discovered before 1960, each of which once held more than five hundred million barrels of recoverable oil – supply 60% of today's low-cost crude oil. Only 120 of them supply nearly 50%. Just fourteen fields, which average close to fifty years old, produce 20%. The super-giant Ghawar field in Saudi Arabia was discovered in 1948, and entered production in 1951. Its peak of production was 5.7 million barrels per day in 1981. Today, it supplies 5% of the world's production.

Liquids associated with natural gas, largely butane and propane, or LPG (liquified petroleum gas), add some production, and the relatively small remainder is "non-conventional oil." Non-conventional oil has higher cost, from hostile locations, deep water, or from heavy oils, tars and bitumens. The resource base of the latter is large – bigger than for conventional oils.

Shale oil is plentiful, but ultimately limited in supply. It is produced using hydraulic fracturing, or "fracking" as it is commonly called, which is controversial. Non-conventional sources will provide a very long, but declining and ultimately limited supply of oil to augment other more ample sources of energy.

Two very different views of the world's future oil production have challenged each other in the last decade or so, but may be coalescing somewhat at present. The so-called "economist's view" of oil production is that as oil prices increase, the amount of oil produced will rise to meet future demand. Forecasts based on this assumption predict continued production growth, with no end in sight. At the other extreme is the "peak oil" view, held by a number of oil exploration geologists, but by no means all of them, that the world's total endowment is now well enough known that a peak in world oil production can now be foreseen; once we're there, decline is inevitable and irreversible.

This oil picture is troubling. The bare facts are enough to raise concern.

It has been suggested that when oil production falls, natural gas will "bridge" the gap between oil scarcity and some new non-fossil source of energy, typically solar or wind. Peak gas, however, is linked to peak oil in a fundamental way. World gas supplies, even today, are not assured, and will decline, loosely linked to oil. World electricity annual growth rates approaching 9 percent or so are forecast. Projections assume, either explicitly or implicitly, that "abundant and cheap," as well as "environmentally friendly" natural gas will take the increasing load. No practical credence can be given to suggestions that wind farms or other new, dilute, and variable "alternative energy sources" will make a meaningful contribution. Without cheap gas, the "gas bridge" to "alternative energy sources" collapses. Like the bridge in the East Fork of the San Gabriel River north of Los Angeles, it is a "bridge to nowhere."

Gas is found in three types of formations: associated gas – the gas occurring in associated oil fields; non-associated gas – the dry gas from conventional gas fields with identifiable boundaries; and unconventional continuous gas – in fields with tight formations, coal bed gas, and shale.

Most natural gas produced worldwide is gas contained in reservoirs along with oil. The world's large reserves of gas are closely associated with oil fields found, as would be expected, in major oil-producing countries. Gas not directly associated with oil has been a mainstay of domestic U.S. production – about two thirds of gas produced in the U.S. during the last hundred years – and is practically all of U.S. production today.

Conventional gas production peaked in the U.S. in 1972, declined by about a third by 1983, then with substantial increases in drilling it increased slowly. Production has leveled out, at about the same level as in 1972, until 2021, when it declined significantly. With all the publicity given to the opening of new gas fields, it remains that, as the Red Queen said to Alice "it takes all the running *you* can do, to keep in the same place."

The difference was made up by gas from shale. This was growing in the United States, largely using hydraulic fracturing, until 2021. There is a lot of it, but even with fracturing the beds remain impermeable, and wells frequently have short lives, with production dropping 50% within the first few months.

Some gas is imported from Canada by pipeline. From 1993 to 2005, the number of wells drilled in Canada quadrupled, but production increased only 10%. Depletion of fields in western Canada means their supplies are less assured than they have been. At current rates of usage, the ranges quoted are between thirty and a hundred years of domestic supply.

Gas has been proposed as an alternative transportation fuel. It is widely used in cities for buses, trucks, and corporate automobile fleets, especially to reduce pollution as compared to diesel fuel. It is difficult to use for long distances because even at high pressure, the energy density is much less than gasoline or diesel fuel. To the extent gas displaces liquid hydrocarbon fuel, the duration of domestic gas supply decreases, and the price increases.

Gas is a much more local fuel than oil. The obvious difficulties in transportation make gas production of little use without pipelines. Pipelines have continental limitations. Without pipelines, gas can only be economically transported as liquid natural gas, or LNG. There is no serious LNG infrastructure in place, and none seriously contemplated.[a] As of 2009, only 3% of North American consumption came from LNG. It has severe limitations due to the cost and acceptability of the infrastructure. For lack of a better alternative, considerable amounts of associated gas are simply flared off because the oil fields from which it is drawn are not connected to pipelines; only their oil output is shipped, using ocean-going tankers.

The coal outlook is less well defined. Although it is mined on every continent except Antarctica, it is by no means distributed uniformly. The biggest deposits are in U.S. and Russia, with China, India, and Australia following in that order. U.S. has 27% of the world's coal, and coal is always thought of as our fuel of last resort. The principal point about coal, however, is that the amounts that will actually be recoverable worldwide are very poorly defined and technology dependent. The resource amounts themselves are poorly defined; some of the numbers date back to the 1970s when the first global estimates were made. Further, for coal particularly, the resource numbers are deceiving. The amount of coal that can be recovered is certainly only a fraction of the resource in the ground. Current guesses are that coal production will peak globally some time between 2025 and 2050, based solely on physical constraints. If constraints due to CO_2 emissions begin to seriously enter the picture, the place of coal will be limited to an even greater degree.

Hydrocarbon availability will inevitably peak and diminish, probably within the next few decades. No practical credence can be given to suggestions that wind, solar or other new, dilute, and variable alternative energy sources will make a meaningful contribution. With this in prospect, it is difficult to understand the complacency with which the stagnation of the nuclear power industry in this country continues to be accepted. Real, practical additions at magnitude must be made, and soon. Yet little is being done.

3.2 Political pressure

> *If it's consensus, it isn't science. If it's science, it isn't consensus. Period.*
> – Michael Crichton[b]

The second principal reason to expect the spectrum of sources of energy to change is that there is significant political pressure to reduce emissions that result from the con-

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[a] After Edmund G. "Pat" Brown lost re-election as California's governor in 1966, he was hired as a lobbyist for the Indonesian state-owned oil company, Pertamina. In return, he got an exclusive contract to import Indonesian LNG into California. As Al Gore, Sr. said when he left the Senate and started working for coal companies, he "went to graze where the grass is taller." In the end, the LNG project never materialized [49, Ch. 10].

[b] *Aliens cause global warming,* Caltech Michelin Lecture 17 January 2003. `https://www.aei.org/carpe-diem/michael-crichton-explains-why-there-is-no-such-thing-as-consensus-science/`

sumption of hydrocarbons – oil, gas, and coal. Some of this pressure is a consequence of concern about pollution, but most results from the politically useful proposition that accumulation of CO_2 in the atmosphere changes the climate significantly, and that the resulting change is harmful.

Another useful proposition for activists is that acidity of oceans increases because of their absorption of CO_2 from the atmosphere, and that this is harmful to the oceans' creatures. This turns out to be a fact-free argument. Yes, the oceans absorb CO_2. When CO_2 is absorbed into fresh water, it does indeed make it more acid. But the oceans are not fresh water. They contain significant amounts of bicarbonate, creating what chemists call a *buffer solution*. When a strong base is mixed with a weak acid, or a strong acid is mixed with a weak base, there is very little change in pH.[c] The carbonic acid that results from absorbing CO_2 into water – $H_2O + CO_2 \rightarrow H_2CO_3$ – is a weak acid. Sodium bicarbonate ($NaHCO_3$) is a strong base – it is strongly alkaline [35] [52].

Activists contend that decreasing pH (increasing acidity) in the oceans, which we've just seen cannot happen to any significant extent, will compromise the ability of shellfish and coral and plankton to make their calcium carbonate (limestone) structures. This too is false: There are shellfish living in estuaries having pH as low as 6.[d] Animals developed the ability to control crystallization of calcium carbonate about 500 million years ago. As will be seen in Figure 3.4 below, the CO_2 concentration in the atmosphere has been much greater than it is now, the oceans were therefore slightly (not vastly) more acidic, and yet those creatures flourished.

Increasing CO_2 in the oceans is, in fact, helpful because it increases phytoplankton growth (they are, after all, plants – see Section 3.3). Phytoplankton are the base of the food chain. Patrick Moore explains this in detail in **Fake Invisible Catastrophes and Threats of Doom** [37, Chapter 10].

In addition to the unrealistic proposals for alternative energy sources, it is proposed that carbon dioxide that results from hydrocarbon combustion can and should be collected and sequestered.

The simplest notion is to pump the collected CO_2 back into the ground. There are several problems with this. Even as a supercritical fluid, it is less dense than the fuel that was burned to produce it, and in a more rarefied state than a liquid or solid. Thus, depleted oil fields, coal mines, and natural gas reservoirs cannot have the capacity to trap the CO_2 that results from burning them. Remembering the recent leak from a natural gas reservoir in Aliso Canyon, near Los Angeles [11], underground storage is questionable.[e] Oil fields in Texas have been proposed, but there are more than a million

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[c] pH is a measure of acidity or alkalinity. Its value is the negative of the base-10 logarithm of the hydrogen ion concentration. pH of 7 is neutral. pH less than 7 is acidic. pH greater than 7 is basic or alkaline.

[d] Water, which is considered to be neutral, neither acidic nor alkaline, has pH = 7.

[e] The Brown family still has extensive gas interests. For example, the Aliso Canyon gas reservoir that

holes in them. Saline formations are another possibility, but their ability to retain CO_2 is unproven. Sequestration beneath the oceans has been proposed, but it is difficult to monitor for leakage. Any leakage would dissolve CO_2 in seawater and eventually release it into the atmosphere.

Apart from the problems of physical feasibility, there is the question of economic viability. At the Petra Nova plant in Texas [60], the only power plant in the United States that captures CO_2, the additional capital cost was about $8 per watt of power plant label capacity. To offset this cost, some of the captured CO_2 is sold to oil and gas wells, to be injected to enhance production. Whether this CO_2 remains sequestered is an open question. It also seems a bit difficult to justify to capture CO_2, and then use it to enhance production of hydrocarbons, which will be burned, and produce CO_2. There are proposals before Congress to provide tax incentives of $20 to $50 per ton of captured CO_2, but this just hides the cost in your tax bill; it doesn't eliminate the cost.

3.3 Is increasing CO_2 concentration a bad thing?

The arguments for the propositions that CO_2 emissions resulting from human activity are causing climate change, and that the resulting change is harmful, are well known and need not be repeated here.

Greenpeace co-founder Dr. Patrick Moore has written an excellent monograph of the history of carbon dioxide on Earth [36]. Here is the executive summary:

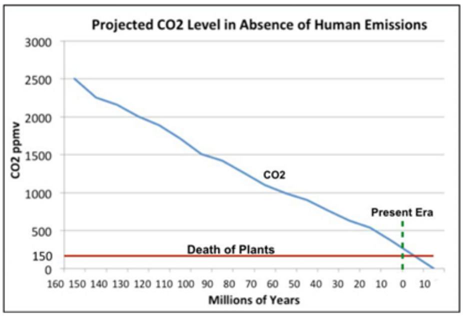

Figure 3.1: CO_2 concentration since its peak at the end of the Jurassic Period.

> This study looks at the positive environmental effects of carbon dioxide (CO_2) emissions, a topic which has been well established in the scientific literature but which is far too often ignored in the current discussions about climate change policy.
>
> All life is carbon based and the primary source of this carbon is the CO_2 in the global atmosphere.
>
> As recently as 18,000 years ago, at the height of the most recent major glaciation, CO_2 dipped to its lowest level in recorded history at 180 ppm,[f]

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leaked in 2015 [11] was under a ranch owned by Edmund G. "Pat" Brown's daughter Kathleen [49].

[f] ppm = parts per million by volume.

> low enough to stunt plant growth. This is only 30 ppm above a level that would result in the death of plants due to CO_2 starvation.
>
> It is calculated that if the decline in CO_2 levels were to continue at the same rate as it has over the past 140 million years, life on Earth would begin to die as soon as seven million years from now and would slowly perish almost entirely as carbon continued to be lost to the deep ocean sediments.
>
> The combustion of fossil fuels for energy to power human civilization has reversed the downward trend in CO_2 and promises to bring it back to levels that are likely to foster a considerable increase in the growth rate and biomass of plants, including food crops and trees.
>
> Human emissions of CO_2 have restored a balance to the global carbon cycle, thereby ensuring the long-term continuation of life on Earth.
>
> This extremely positive aspect of human CO_2 emissions must be weighed against the unproven hypothesis that human CO_2 emissions will cause a catastrophic warming of the climate in coming years (and see Section 3.10).
>
> The one-sided political treatment of CO_2 as a pollutant that should be radically reduced must be corrected in light of the indisputable scientific evidence that it is essential to life on Earth.

Below about 150 ppmv,[g] plants die. When plants die, all higher forms of life also die, because they depend upon plants. The only forms of life remaining on the Earth would be bacteria and viruses, and maybe fungi.

What is the average rate of decline in atmospheric CO_2 concentration between 150 million years ago and 1750, that is, how rapidly have living things in the oceans been removing CO_2 from the atmosphere? That's an easy calculation: (2,500 - 280) / 150 = 2,220 / 150 = 14.8 ppmv per million years. At that rate, when would plants and all higher forms of life have been extinguished from the Earth? That's another easy calculation: (280 - 150) / 14.8 = 130 / 14.8 = 8.8 million years. One of the unchallengeable dogmas of present discourse is that the increase in atmospheric CO_2 concentration from 250 ppmv in 1750 until 415 ppmv now is all due to our Industrial Revolution burning fossil fuels and making cement. From today's CO_2 concentration of 415 ppmv, how long will higher forms of life survive on the Earth? That's another easy calculation: (415 - 150) / 14.8 = 265 / 14.8 = 17.9 million years. Skrable et al have proposed that only a third of the increase in atmospheric CO_2 since 1750 was due to human activity, but the data to support that conclusion have been called into question [51]. In any case, we should congratulate ourselves, and celebrate that the inadvertent experiment, called the Industrial Revolution, has postponed the end of live on Earth by about nine million years. Accepting the proposition that the Industrial Revolution was responsible for the entire increase, we can and should do a lot more to prolong life on Earth, by burning coal

---

[g] ppmv means "parts per million by volume" (not by weight).

as fast as we can (cleanly, of course), and making cement (decomposing limestone and chalk – $CaCO_3$ – to lime – calcium oxide – CaO – and CO_2).

It has been known for a long time that increasing CO_2 concentration increases plant growth. Commercial greenhouse operators buy CO_2 or burn kerosene, gasoline, butane, or propane, to increase the concentration of CO_2 from the ambient 415 ppm to the range of 800-2,000 ppm, depending upon what they're growing (and how much CO_2 they can afford to buy or make). The desirability of this range is the result of measurements of the relationship between CO_2 concentration and plant growth. It's not a vague hand-waving guess.

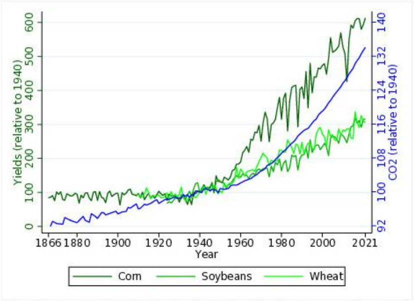

Figure 3.2: Annual yields and CO_2.

This effect has been confirmed by real-world outdoor measurements of plant growth [53]. Figure 3.2 shows the relationship between crop yields and CO_2 concentrations. Other studies have shown corn increases to be less than other crop increases [42].

To metabolize CO_2, to combine it with water to produce glucose, plants need to bring it into their bodies. They have tiny pores in their leaves, called stomata. While stomata allow CO_2 to enter, they also allow water to evaporate. The result is that at low CO_2 levels, plants need large stomata, and therefore more water. When CO_2 levels increase, plants make smaller stomata, and need less water. This is one of the reasons that sub-Saharan forests are inching toward the Sahara.

Satellite observations show a 14% increase in green vegetation since 1981, with about three quarters of that due to increasing CO_2. Total leaf area has been increasing at the rate of 618,000 km^2 per year, or about 2.7 football fields per second. During the last forty years, the increase has been about three times the area of Great Britain [8].

It is clear that increasing CO_2 concentration is not harmful to humans.

- CO_2 concentration in the International Space Station is 4,500-5,000 ppm.
- CO_2 concentration in a submarine is 3,500-4,000 ppm.
- CO_2 concentration in a commercial airliner is 2,000-2,500 ppm.
- CO_2 concentration in a commercial greenhouse is 800-1,500 ppm.
- CO_2 concentration indoors varies between 400 and 800 ppm.

3.4 Are humans really causing climate change?

> *No government has the right to decide the truth of scientific principles.*
> – Nobel Physics Laureate Richard P. Feynman

Every phenomenon observed in a complicated system has many causes. Before looking at whether CO_2 emissions are the only cause of changing climate, consider a short digression. What causes the speed of your automobile to change? The simple answer is manipulation of the accelerator and brake. Does wind velocity have any effect? Does atmospheric pressure or density have any effect? Does rain or snow have any effect? Does the slope or condition of the roadway have any effect? Does the pressure in your tires, or their condition, have any effect? Does a particular position of your accelerator or brake always have the same effect? What if you are using a different grade of fuel? What if your spark plugs are dirty or worn? What if your brake pads are worn…?

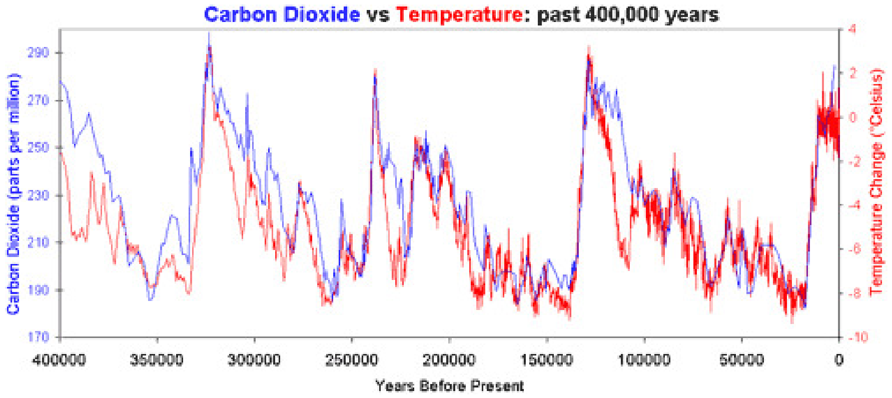

Figure 3.3: Vostok ice core records for carbon dioxide concentration and temperature change [34].

With that short tutorial, now consider whether CO_2 concentration in the atmosphere is the only cause of climate variation. We already know that variations in the Earth's axial tilt and orbit eccentricity cause ice ages with a period of about 100,000 years, as described by the Serbian geophysicist and astronomer Milutin Milanković (see Figure 3.3). What other causes exist?

The climate police insist that "the science is settled." If that were true, why is any disagreement with their position censored, and why are those who disagree abused? Can't their "settled science" stand on its own two feet? Of course, these people aren't real scientists. Real scientists are skeptical. They know that science is never "the truth." Instead, it's a method to develop ever-improving approximations that allow ever-improving computations of observable phenomena. The only thing you can "prove" about a theory is that it's false, or that a better one produces more accurate results. Ask the ghosts of Aristotle, Newton and Einstein. Especially for (most) academic scientists, proving that "science" is *NOT* settled might earn a Nobel Prize. Even a book or journal article about it puts a feather in their cap.

Politicians find the claim that "the science is settled" to be extremely useful to funnel enormous sums of public money to their donors and cronies. They refer to the authority of the United Nations International Panel on Climate Change, or IPCC. The IPCC reports are based upon the work of real scientists, who prepare about 35 volumes of detailed analyses. Ultimately, however, the IPCC reports are not controlled by those scientists; they are controlled by governments. The IPCC itself is composed of two political appointees from each of the 193 members of the United Nations. The scientists whose reports contribute to the climate assessment are chosen and recruited by permanent UN full-time IPCC activists. The content of each 600-page Assessment Report is determined by *Summaries for Policymakers*, which are composed by those government representatives, in meetings behind closed doors [59, §§4.4-4.5]. Two important effects of IPCC rules are:

- *All Summaries for Policymakers (SPMs) are approved line by line by member governments.*
- *Government SPMs override any inconsistent conclusions scientists write for use in the IPCC reports.*

One significant reason to be skeptical about the reports is the list of distinguished scientists who have been disassociated from the IPCC, either voluntarily or not, or have been involved in the process but frustrated in their attempts to be scientifically honest.

Professor Frederick Seitz, former president of the *National Academy of Sciences* wrote "I have never witnessed a more disturbing corruption of the peer-review process than the events which led up to this IPCC report" [48]. Why did he write that? Fifteen passages had been deleted from the document that had been approved by all 28 contributing authors. Here are two of the controversial passages:

> None of the studies cited above has shown clear evidence that we can attribute the observed [climate] changes to the specific cause of increase in greenhouse gases.
>
> No study to date has positively attributed all or part [of the climate change observed] to [man-made] causes.

Under the normal professional journal peer review process, a panel of reviewers is chosen by a journal editor. If reviewers have objections, the author must answer them to the satisfaction of the editor, or change the article to take reviewers' objections into account. Under the IPCC review process, by contrast, the authors are at liberty to ignore criticism.

After his review comments were ignored by the IPCC in 1990, The Alfred P. Sloan Professor of Meteorology at MIT, Richard Lindzen, asked to have his name removed from the list of reviewers. IPCC refused to remove his name; leaving it in the list implied that he agreed with the report. He singled out the 35-page chapter of the underlying technical reports for the 2001 Third Assessment Report (TAR) [25, ch. 7], for which he had been one of the lead authors and that addressed physical processes, and further remarked that the *Summary for Policymakers* did not represent what was reported in the larger volume of technical papers. In particular, the *Summary* says that Chapter 7 shows that "understanding of climate processes and their incorporation in climate models have improved, including water vapor, sea dynamics and ocean heat transport." Lindzen said "that does not summarize the chapter at all" (see Section 3.7). He resigned in 2001, writing:

> It is presented as a consensus that involves hundreds, perhaps thousands, of scientists... and none of them was asked if they agreed with anything in the report except the one or two pages they worked on....
>
> It is no small matter that routine weather service functionaries from New Zealand to Tanzania are referred to as "the world's leading climate scientists." It should come as no surprise that they will be determinedly supportive of the process [21].

Donna Laframboise described a collaborative project involving a worldwide team of "citizen auditors" who checked all the references cited in all 44 chapters of the 2007 scientific reports underlying the *Summary for Policymakers*. The search discovered that of 18,531 references, 5,587 were not peer reviewed. The IPCC recommendations were based on newspaper and magazine articles, unpublished theses, and documents and press releases from organizations such as *Greenpeace* and the *World Wildlife Fund*. After her findings were released, IPCC chairman Rajendra K. Pachauri wrote that there were "approximately 18,000 [not 13,000] peer reviewed publications" and conceded that references included "a limited amount of grey literature." Maybe one third is "a limited amount" for politicians, but not for real scientists [31, p. 48]. It's amazing that "thousands of scientists," 97% of whom agree with each other, were so short of peer reviewed material that they had to rely on material from green activists.

Patrick Brown revealed that peer review has become a less-than-reliable way to convince the reader of an article's accuracy [7].

Dr. Roger J. Pielke resigned after the 1995 report was published. He had recommended texts and papers that were simply ignored. He was appalled that computer models that he pointed out were objectively unable to predict anything accurately were cited as "proof," while others that worked much better but contradicted the politically-desired result were suppressed (see Section 3.7) [40].

One of the world's leading experts on hurricanes has the perfect name for his avocation: Christopher Landsea. He resigned from the IPCC in 2005 after the lead author of the chapter to which he contributed, Dr. Kevin Trenberth, abused his position to turn the research conclusions completely upside down. Landsea (and other contributing authors) had found no long term increasing trend in intensity of hurricanes (and cyclones and typhoons as they're called in various parts of the world). Even their worst-case scenario was a slight increase in rainfall. Trenberth gave exactly the opposite report to a gullible media, who eagerly and unquestioningly claimed hurricanes were increasing in frequency and intensity, and that this is due to human-induced global warming (see Section 3.6). In his resignation letter he wrote "I am withdrawing because I have come to view the part of the IPCC to which my expertise is relevant as having become politicized. In addition, when I have raised my concerns to the IPCC leadership, their response was simply to dismiss my concerns."

Paul Reiter was a contributing author to the chapter of the Working Group II report, dealing with impacts on human health, of the 2001 Third Assessment Report (TAR) [25, ch. 9]. Lead authors, appointed by permanent UN political staffers, insisted there must be a link between climate change and diseases such as malaria. In his resignation report to the House of Lords he wrote "In my opinion, the IPCC has done a disservice to society by relying on 'experts' who have little or no knowledge of the subject, and allowing them to make authoritative pronouncements that are not based on sound science."

Professor of Economics at the University of Sussex Richard S. J. Tol has written extensively about the likely economic impact of warming. He resigned in 2014 stating that self-selection of authors and reviewers caused the *Summary for Policymakers* to over estimate hazards. He wrote that the report

> Omitted improved irrigation and crop yields.
>
> Emphasized heat stress but downplayed reduced cold stress.
>
> Warned about mass climate migrations without any solid evidence.
>
> Overestimated the consequences of climate change.
>
> Could have been written by the Four Horsemen of the Apocalypse.

After his refusal to endorse the report, he was the victim of a smear campaign led by Bob Ward, an editor of the IPCC report and director of policy at the Grantham Research Institute on Climate Change of the London School of Economics. Ward is neither a scientist nor an economist [43].

Jeffrey Grimshaw and Rafe Champion wrote about this scientific malfeasance at length [23, Ch. VII]. It is so egregious that the late physicist Dr. Siegfried Fred Singer formed an independent organization called the Nongovernmental International Panel on Climate Change (NIPCC). They publish their own hefty report, authored by teams of real scientists and economists from across the globe. Their report critiques the IPCC reports, and debunks their most alarmist claims. The IPCC must have failed very badly and obviously if a large group of real scientists and economists found it necessary to develop their own research group and publish their own report, all as volunteers without any government (or corporate) financing.

Here are some reasons to doubt "the science is settled", or, to paraphrase Moore, disprove the hypothesis.

3.4.1 Temperature and CO_2 are unrelated

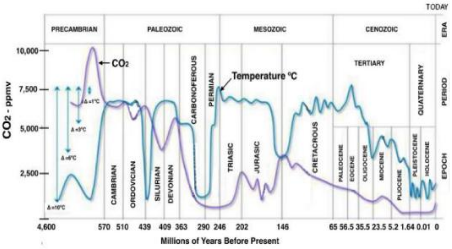

Figure 3.4: Reconstructed atmospheric CO_2 concentration and global mean surface temperature.

Figure 3.3 shows that during the last 400,000 years, changes in the temperature of the atmosphere almost always preceded changes in the content of CO_2 by about 800 years. This is about the length of time required for the oceans to "turn over." The oceans contain about fifty times more CO_2 than the atmosphere. Cold water can dissolve more CO_2 than warm water (or warm beer or warm soda), so as the oceans warm, CO_2 is released. Lawyers like to abuse a logically false Latin phrase: *post hoc ergo propter hoc – after this therefore caused by this*. The Apollo astronauts ate chicken and then went to the moon. I ate chicken. Hooray! I'm going to the moon! To use a corrected phrase *Ante hoc ergo non propter hoc – Before this, therefore* ***not*** *caused by this*.

During the last 600 million years, temperature and CO_2 have been essentially unrelated.

Figure 3.4 is used in essentially all universities that teach geology. It was reconstructed using atmospheric carbon dioxide concentrations reported by Berner and Hothvala [5] and temperatures reported by Scotese et al [47]. The horizontal scale is not uniform. Figure 3.4 shows several important things:

- Scientists caution that correlation is not causation – but anti-coorelation is evidence of absence of causation. CO_2 concentrations and temperatures were uncorrelated during the last 600 million years. If Newton had thrown an apple 1,000 times and if only one of those times it had shot upward, never to be seen again, he would not have written about gravity.

- For hundreds of millions of years, temperatures were low when CO_2 concentrations were high, and temperatures were high when CO_2 concentrations were low. During the Cretaceous period, as CO_2 concentration was declining, temperature was increasing.

- When CO_2 concentrations were at a record high of about 7,000 ppm, temperatures were at a record low. The only time that temperature and CO_2 were both as low as they are today was 250 million years ago.
- Temperatures were much higher about 60 million years ago than they are now, but life flourished.
- Biological and geological processes are gradually emptying the atmosphere of CO_2 (and emptying the oceans of calcium) by production of limestone. Concentrations have therefore been relatively low for the last 300 million years, and have been sharply declining for the last 150 million years, from 2,500 ppm to today's low of 415 ppm (this is also shown in Figure 3.1).

What caused the enormous decline in atmospheric concentration of CO_2 during the Carboniferous Period?

Before the Cambrian Period, most life on Earth was single cell life. During the Cambrian explosion, multicellular life forms developed in the oceans, but they were essentially all jellyfish. It was only during the late Silurian Period, about 410 million years ago, that bones and seashells and calcareous structures in diatoms were developed. Coral reefs came later, about 25 million years ago. These are all made of calcium carbonate, more commonly known as limestone and chalk. The invention of these structures removes CO_2 from the atmosphere and deposits it permanently on the seabed, from which it is eventually subducted under the continents.

Roughly contemporaneously with the invention of seashells, plants worked out how to make lignin, the main structural component of wood, but life had not worked out a way to recycle it. Dead plants piled upon the remains of their ancestors, hundreds of feet thick, and were eventually compressed into coal. Essentially all of the coal was laid down during this period. It was only 100 million years later, after fungi had developed lignase, that land-based carbon sequestration and liberation returned to equilibrium. But ocean-based carbon sequestration continues today.

Levels of CO_2 in the atmosphere recovered slightly due to the Triassic warming (less CO_2 dissolves in warm water than cold – compare how much faster a warm soda "goes flat" than a cold one), then declined until the precipitous cooling at the end of the Jurassic period, which was caused by enormous increases in volcanism, that recycled enormous amounts of CO_2 into the atmosphere. CO_2 levels have been continuously declining since the beginning of the Cretaceous period. Volcanoes now recycle only a small amount of the sequestered CO_2.

3.4.2 Start at the Minimum and Measure Only Increase

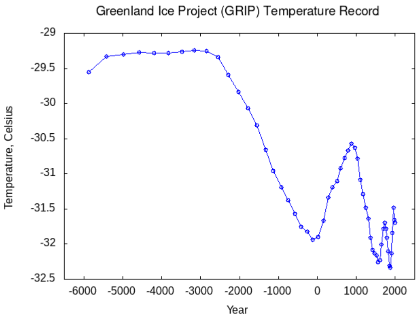

Figure 3.5: Greenland Ice Core Project (GrIP) Temperature Record.

Figure 3.5 shows the results of direct temperature measurements at different depths in ice cores by the Greenland Ice Core Project (GrIP) [13]. The measurements do not have fine vertical resolution, so they show long-term average temperatures. At deeper depths, layers are compressed, so older measurements have less resolution. 1870 was the coldest year in Greenland in more than 8,000 years. Although Daniel Gabriel Fahrenheit had invented the mercury thermometer in 1714 and Anders Celsius began recording temperatures at Uppsala in 1722, 1870 was about the time that accurate widespread temperature records began to be kept. NASA says widespread accurate temperature records do not exist before 1880. If you begin measuring at a minimum, all you record is increase. Bill Maher calls this "presentism," or "nothing actually happened before I was born."

In Greenland:[h]

> The warmth of the climatic optimum during the European stone age 5000 years ago is clearly seen, just as the cool period during the Roman age and the relative warmth of the Viking age (where the Norsemen settled in Iceland and Greenland) and the two cold periods of the "little ice age" at 1600 AD and 1875 AD. *The warming in Greenland in the 20th century only lasts until 1950 AD. After that it has become colder* [my emphasis].

3.4.3 Human activity cannot be responsible for the climate

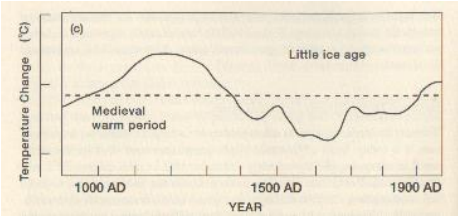

Figure 3.6: Figure 7.1(c) in IPCC *Climate Change 1990* report [27, p. 202].

Most of you have heard of the Sun's eleven-year cycle. But it has several other activity cycles. Many people have noticed climate cycles since the end of the Younger Dryas about 11,500 years ago (see Figure 3.9). Dr. Raymond H. Wheeler was a professor of psychology at the University of Kansas. He spent almost twenty years on a project involving as many as 200 people to compile 2,500 years of records from which he derived many hypotheses. Part of that record showed climate cycles,

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[h] `https://www.iceandclimate.nbi.ku.dk/data/ddjtemp.txt` [57]

using data from tree rings, bog sediments, stalactites, ... He found long-term climate cycles with inexact periods of about 1,000 ± 70 years, and cycles of 500, 170, and 100 years imposed on them [15].

Singer and Avery noticed long-term cycles with a periodicity of about 1,500 ± 70 years and speculated these were caused by a resonance of solar cycles [50]. Wheeler's 1,000 year cycle is close to half the resonance of the solar 11.2 year cycle and his 170 year cycle. The Earth's temperature responds to these cycles, leaving a record in ice cores, stalactites, lake bed and ocean bottom sediments, tree rings, bogs, ..., everywhere throughout the world. This is *not a Northern Hemisphere Phenomenon* as some claim.

These cycles are correlated to the historical record, going back to the pre-Roman Egyptian cooling (during which the Egyptians lost the battle of Carchemish to Nebuchadnezzar II and never recovered), the Roman warming, the Dark Ages, the Medieval warming, and the Little Ice Age, from which we are just now emerging. People didn't write "gee, the climate is cooling" (or warming) but Egyptians wrote about needing to build dams and canals, Romans grew grapes and citrus in northern England and Hannibal crossed the Alps with elephants during winter, 2,000 years ago, Vikings grew barley and raised sheep in Greenland 1,000 years ago, and Slavs moving up the Eastern Alps thought the Germans had abandoned the land because they had become fat and lazy – and then they had to abandon the same land when the glaciers returned during the Little Ice Age.

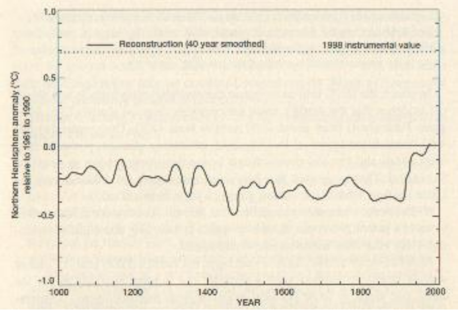

Figure 3.7: Figure 2.20 in IPCC *Climate Change 2001* report [25, p. 134].

The cycles shown in Figure 3.6 appeared in the 1990 IPCC report [27], but as shown in Figure 3.7, they were removed in the 2001 report – at the insistence of the chapter's lead author, Michael Mann, to preserve the illusion that his infamous "Hockey Stick" graph is significant [25].

Singer and Avery describe this in detail in [50].

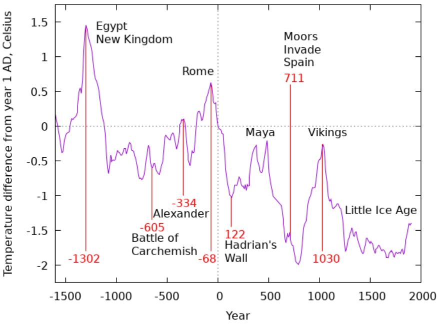

Figure 3.8: Temperature in Greenland from GISP2

The correlation of a few historic events with climate cycles that Wheeler had remarked are noted in Figure 3.8. Notice that the peak temperature in year 1030, the midst of the era when Vikings were growing barley and raising sheep in Greenland, is entirely absent from Figure 3.7. Figure 3.20 in the 1995 IPCC report shows data only from the year 1400 onward

[26, p. 175].

On 1 July 1993, after five years of drilling, the Greenland Ice Sheet Project Two (GISP2,) penetrated the ice sheet and 1.55 meters into bedrock. They analyzed the relationship of the concentration of oxygen-18 compared to other oxygen isotopes in standard median ocean water. The relationship between isotopes of oxygen in water evaporated from the oceans is very sensitive to temperature: $H_2{}^{16}O$, being lighter, evaporates more easily than the 11% heavier $H_2{}^{18}O$.

The atmosphere is well mixed, so that the mixing ratios of the isotopes of oxygen in water vapor are nearly uniform throughout the Earth. The variations in Greenland temperature measured by GISP2, as shown in Figure 3.8, are therefore indicative of worldwide temperature fluctuations, not a northern hemisphere or arctic phenomenon, as the abstract noted [2]:

> Near-simultaneous changes in ice-core paleoclimatic indicators of local, regional, and more-widespread climate conditions demonstrate that much of the Earth experienced abrupt climate changes synchronous with Greenland within thirty years or less.

As shown in Figure 3.9, between 14,500 and 11,500 years ago, the Earth's temperature declined by 18°C, increased rapidly by 14°C, and then more gradually by another 6°C. This period is called the *Younger Dryas*, named for a plant *Dryas Octopetala* that is characteristic of cold climates and found in Scandinavia [1]. Some scientists argue that the rapid increase about 11,750 years ago occured within as little as ten years. It was definitely not caused by humans burning coal and making cement. Life on Earth was not extinguished by the rapid heating, but some anthropologists estimate that the worldwide human population was reduced to 100,000 by the cold at the depth of the period.

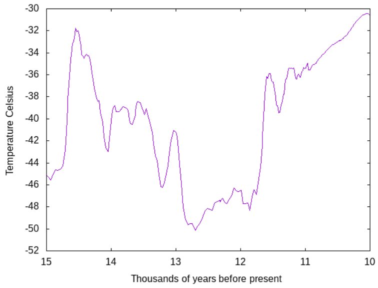

Figure 3.9: Greenland temperatures during the Younger Dryas

3.5 Sea level is not rising at an alarming rate

The sea level is rising, and has been since the end of the Little Ice Age. That its rate is alarming is a tsunami of laughable and failed prophecies. We had not been able to measure worldwide sea levels reliably and accurately until NASA launched SeaSat on 27 June 1978. Its altimeter provided a very short time-series record because the mission failed on 10 October 1978 due to a short-circuit in the Agena-D connection to the solar panels. Lockheed had been requested not to use a slip-ring connection, but they used it anyway.

A more complete time series began when Topex/Poseidon was launched on 10 August 1992. Together with laser measurement of the satellite's position, and precision orbit and attitude determination, the satellite was able to measure the average altitude of 25 km diameter patches of sea surface with a precision of about two centimeters. Topex/Poseidon has been followed by three Jason satellites with even better altimeters, and the Surface Water Ocean Topography mission is now adding to their data set. The El Niño Southern Oscillation and the Pacific Decadal Oscillation are clearly visible in the data.[i] Before Topex/Poseidon and its successors, the only measurements were from tide gauges, which measure local sea levels relative to land at the point of measurement. Measurements by the tide gauge at Fort Denison in Sydney Harbor show that sea level *fell* by five centimeters between 1914 and 2019. Is this because worldwide sea levels fell, or (the eastern part of) Australia rose, or is the distribution of sea levels not static throughout the world?

Alarmists claim that islands will be inundated, and Bangladesh will cease to exist. How can that happen if sea level is rising at the claimed rate of two millimeters per year, but the Ganges Delta is silting up at four millimeters per year? And the "two millimeters per year" estimate is based upon a thirty-year time series.

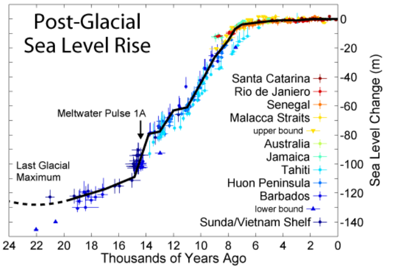

Figure 3.10: Sea levels after the last major glaciation

Figure 3.10 shows that sea levels have been rising at the rate of two millimeters per year for the last 6,000 years, but somehow the invention of the automobile and steam locomotive caused sea levels to rise two millimeters per year during the last two centuries that the previously-occuring natural processes would not have caused.

We are also told that the coral of the Great Barrier Reef will disappear after existing for "millions of years." Competent geologists will tell you that it's actually less than 8,000 years old. Today's barrier reef is the result of a sequence of gradual re-buildings of reefs as sea levels rose 400 feet after the end of the Ice Age. Sea levels must have risen very rapidly due to the 14°C temperature increase at the end of the Younger Dryas (see Figures 3.9 and 3.10). Corals didn't evolve 11,500 years ago. They have been around for 25 million years (but not always in the same place). If they survived the end of the Younger Dryas, how could sea level rising at two millimeters per year doom corals?

Bleaching is another bogeyman. The average sea temperature at the north of Australia is 27°C, and 25°C at the south. Yet coral in the Philippines grow much faster where waters are much warmer – in the range of 28-32°C. Coral eject their symbiotic algae for three reasons: The temperature changes, the salinity changes, or the acidity changes. They don't then die of starvation; they take up a different species of algae that is more

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[i] Full disclosure: I worked on Topex/Poseidon data analysis from 1996 to 2000.

suited to the current conditions.

3.6 Things are not getting more extreme

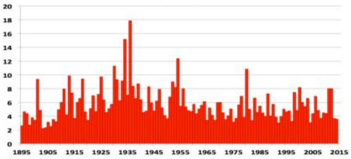

Figure 3.11: Average number of daily high temperatures at 982 USHCN stations exceeding 100°F per year 1895-2014.

Climate activists tell us that the number of extremely hot days per year is increasing. The data from the U.S. Historical Climate Network (USHCN) shown in Figure 3.11 do not bear that out. The greatest temperature change ever recorded in one day in the United States, 103°F from -54°F to +49°F, occurred in Loma, Montana on 15 January 1972. The most extreme temperature difference recorded in the United States is 187°F, between -70°F at Roger's Pass near Helena, Montana in 1954, and +117°F in Glendive, Montana on 20 July 1893, tied with Medicine Lake, Montana on 5 July 1937. The most rapid temperature change recorded in the United States occurred on 11 January 1980 when the temperature rose 47°F from -32°F to +15°F in seven minutes at the Great Falls International Airport. The world did not end.

There has not been any significant change in the frequency of wild fires and forest fires documented for the U.S. As the management practices change, the number changes, but the number of wild fires shown on the left in Figure 3.12 has remained constant since 1985. The average number of forest fires in the U.S. has not changed since 1965, as shown on the right in Figure 3.12 [9, p. 17]. The devastating August 2023 fire that destroyed Lahaina, Maui, was not caused by climate change. The fire was caused by environmentalists' insistence that Hawaii Electric spend funds on solar panels and wind turbines, not on clearing invasive grasses near their power lines or doing maintenance to reduce sparks. More importantly, the Maui County water manager refused for five hours to release water to fight the fires because he was more concerned about "equity" for taro farmers.

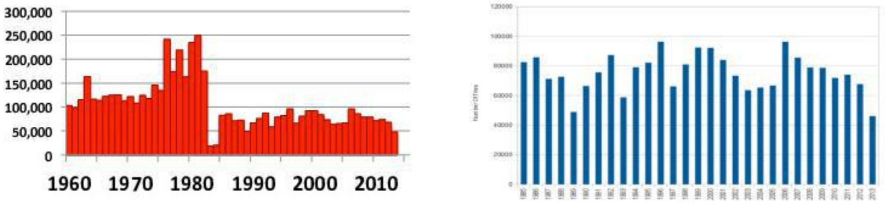

Figure 3.12: Number of U.S. wild fires 1960–2014 – Average number of forest fires 1965–2013. National Interagency Fire Center https://www.nifc.gov/fireInfo/nfn.htm

Droughts are not becoming more frequent or more extreme, either worldwide as shown on the left in Figure 3.13, or within the United States as shown on the right.

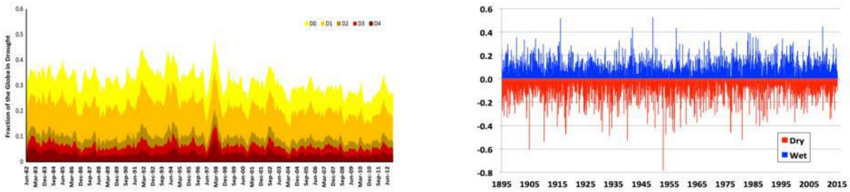

Figure 3.13: Left: Fraction of the global land in D0 (abnormally dry), D1 (moderate), D2 (severe), D3 (extreme), and D4 (exceptional) drought condition (Data: Standardized Precipitation Index data derived from MERRA-Land) [24]. Right: Average fraction of coterminous U.S. under very wet or very dry conditions (NOAA/NCEI).

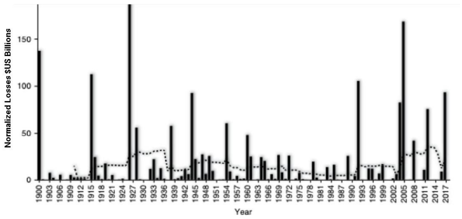

Figure 3.14: Normalized damages from hurricanes 1900-2018.

Hurricanes are not becoming more frequent or more damaging. Figure 3.14 shows total normalized losses over a 118-year study period are about $US 2 trillion, or about $US 16.7 billion per year. The dotted line in the figure is a trailing eleven year average[j] that shows that losses on a decadal scale were larger in the earliest part of the twentieth century, less in the 1970s and 1980s, and then higher again in the first decades of the twenty-first century. Over the entire dataset, there is no significant trend in normalized losses, continental United States (CONUS) landfalls, or CONUS intense hurricanes. The greatest annual normalized loss, $US 244 billion, occurred in 1926, exceeding the second greatest loss in 2005 by about $US 74 billion [63].

After Kevin Trenberth inverted Christopher Landsea's conclusion in the IPCC 2005 report (see Section 3.4), the IPCC finally admitted this in A.R.5:

> Current datasets indicate no significant observed trends in global tropical cyclone frequency over the past century.... No robust trends in annual numbers of tropical storms, hurricanes and major hurricane counts have been identified over the past 100 years in the North Atlantic basin.... In summary, there continues to be a lack of evidence and thus low confidence regarding the sign or trend in the magnitude and/or frequency of floods on a global scale [30].

The 1926 hurricane devastated Miami, ended the land boom, and initiated economic depression three years before the stock market crash. Most of the increase in monetary damage was caused by the region's rapid growth, putting more assets at risk. For example, since 1980, inflation has increased prices by a factor of 4 (the analysis in [63] eliminated this effect by normalization), the number of houses in the paths of storms has increased by a factor of 1.7, and the median home value has increased by a factor

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[j] Why eleven years? That's the length of the Sun's shortest activity cycle.

of 6.4. The average monetary value in the path of a storm has increased by a factor of eleven since 1980.

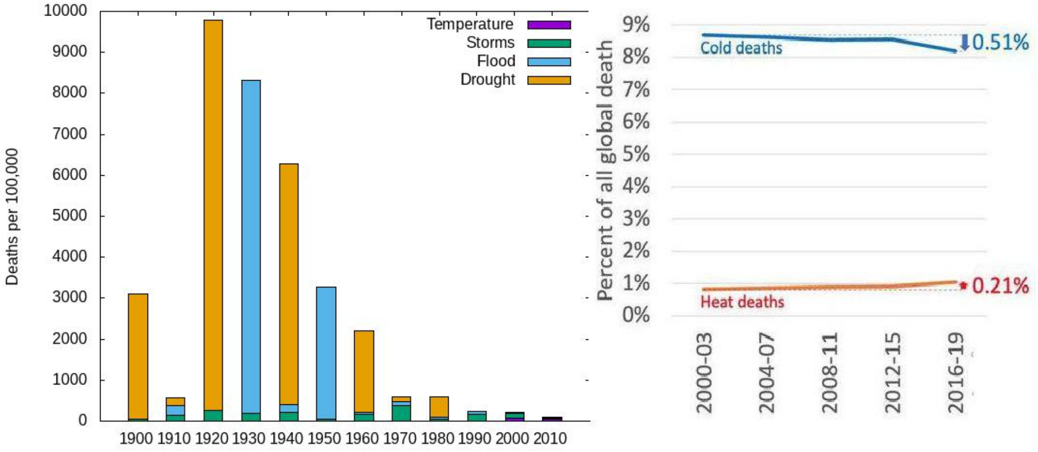

Figure 3.15: Deaths per 100,000 worldwide, and due to extreme temperature (right).

Figure 3.15 shows on the left, using data from *Our World in Data*, that deaths from all environmental causes that might be related to climate are decreasing, largely because we have learned to predict extreme weather (which has not increased) and to cope with floods and droughts (which have not increased). On the right, Figure 3.15 shows that although the number of deaths attributed to extreme heat increased 0.21% between 2000 and 2019, the number of deaths attributed to extreme cold decreased 0.51% [20]. Because deaths due to cold are eight times more frequent than those due to heat, this reduction in death, measured in absolute terms instead of relative terms, is closer to a factor of sixteen than a factor of two: The reduction in the number of deaths due to extreme cold is sixteen times greater than the increase in the number of deaths due to extreme heat.

3.7 Models don't get it right

Nobel Physics Laureate Neils Bohr said "Prediction is very difficult, especially if it is about the future." This is a very old sentiment, even a Danish proverb (Neils Bohr was Danish). Time-series computer models (fine lines in Figure 3.16) ought to be able to "predict" the past, which can be verified against measurements. Most – 101 of 102 – climate models utterly fail when started with 1975 data and are then tasked to "predict" what happened during the last fifty years, especially after 1995 [9, p. 13]. Instead they "predict" that the atmosphere warmed three times faster than measurements show it actually warmed. If the models cannot tell us what happened to the climate, we should not pretend they can tell us why it happened, and in particular we should not use them to make public policy.

The Russian model (INM-CM4) was the only model that produced results close to the observations.

Professor Richard S. Lindzen wrote in 2001 that increasing stratospheric temperature had the effect of reducing cirrus clouds, and that reducing cirrus clouds increased re-radiation (see Section 3.9) [33]. In Senate testimony he said "the effect observed is sufficient such that if current models are absolutely correct [in all other respects], except for missing this, models that predict between 1.5 and 4.5 degrees warming go down to about 0.4 to 1.2 degrees warming." That this was removed from the IPCC *Summary for Policymakers* is one of the reasons that he resigned from the IPCC.

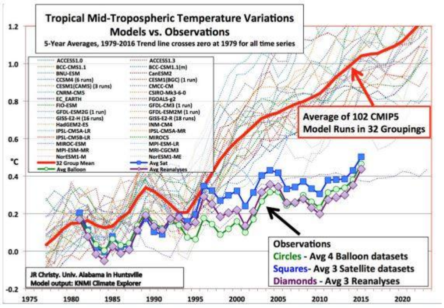

Figure 3.16: Models and measurements

A NASA report [58] wrote

> Even small changes in the abundance or location of clouds could change the climate more than the anticipated changes caused by greenhouse gases, human-produced aerosols, or other factors associated with global change.
> ...
> Another modeling problem is that clouds change almost instantaneously compared to the rest of the climate system.

Appendix A explains, in a superficial way, why climate models are doomed not to work well, especially if they try to incorporate simulations of clouds.

> In climate research modeling, we should recognise that we are dealing with a coupled nonlinear chaotic system, and therefore that the long-term prediction of climate states is not possible.
> – IPCC Third Assessment Report, 2001 [25, § 14.2.2, p. 744].

> The data doesn't (sic) matter. We're not basing our recommendations on the data. We're basing them on the climate models.
> – Professor Chris Folland, Hadley Centre for Climate Prediction and Research.

> The models are convenient fictions that provide something very useful.
> – Dr. David Frame, climate modeler, Oxford University.

3.8 What happens when the atmosphere warms?

The arguments related to the global warming hypothesis are all related to the troposphere, the bottom eleven kilometers or so of the atmosphere. At a particular point on the Earth, the temperature decreases uniformly from the surface to the tropopause, the boundary between the troposphere and stratosphere, at the rate of 6.5°C per kilometer, because the pressure is reduced. Above the tropopause, temperature increases due to ozone absorption of ultraviolet light, which saturates before it reaches the troposphere. The result is a temperature inversion – warm air above cold – that prevents convection between the troposphere and stratosphere. On a smaller scale, the same sort of temperature inversion causes smog in Los Angeles and Denver: Hot desert air coming over mountains to a cooler region. This lack of convection makes the atmosphere above Mount Wilson, near Los Angeles, very stable. This is precisely the reason that George Ellery Hale[k] built his 100-inch telescope on Mount Wilson, where Edwin Hubble discovered in 1929 that the universe is expanding [28].

When the temperature of a gas is increased, it expands. When the temperature of the troposphere increases, it raises the tropopause. As heat within the troposphere is re-radiated as infrared light, it is re-absorbed and scattered until it reaches the tropopause. But because the radiative relaxation time for molecules of CO_2 that are excited by absorption of infrared radiation is seconds, while the mean time between collisions is nanoseconds, most of the heat that molecules of CO_2 absorb is transferred to the far more abundant molecules of oxygen and nitrogen. Because those parcels of the atmosphere are warmed, they rise. Between these two effects, the ultimate re-radiation of heat as infrared light to outer space takes place at the top of the troposphere.

In addition to expansion, another effect of increasing temperature is increasing heat radiation. In 1879, using measurements by Dulong and Petit in 1817 [17] and John Tyndall in 1864 [55][56], a Carinthian Slovenian physicist, mathematician, and poet named Josef Stefan (Jožef Stefan in Slovenian) [12] deduced the relationship that *radiant exitance*[l] is proportional to the fourth power of the absolute temperature [62]. Stefan confirmed his theory by comparing to measurements by de la Provostaye and Dessains [14], Draper [16], and Ericsson [19]. In 1884, Stefan's student Ludwig Boltzmann derived the relationship from theoretical considerations and the laws of thermodynamics [6]. In mathematical form, the *Stefan-Boltzmann* law is written

$$\frac{P}{A} = \epsilon \sigma T^4 \tag{3.1}$$

where P is radiated power in watts, A is the area of the radiating surface in square meters, $0 \le \epsilon \le 1$ is the *emissivity* of the matter, different for each material, σ is a constant of proportionality called the *Stefan-Boltzmann constant*, and T is absolute temperature in Kelvins. The Stefan-Boltzmann constant is derived from other known physical constants as

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[k] My eighth cousin twice removed.

[l] *Radiant exitance* is the amount of radiant energy that escapes from a hot body as electromagnetic radiation.

$$\sigma = \frac{2\pi^5 k^4}{15\, c^2 h^3}$$

where k is Boltzmann's constant, h is Planck's constant, and c is the speed of light in vacuum. The value of σ is known quite precisely: $\sigma = 5.670\ 374\ 419 \times 10^{-8}$ W m^{-2} K^{-4}. The derivation is described in Appendix A.

If the temperature of a body at 20°C = 293.15°K is increased to 21°C = 294.15°K, the ratio of the temperatures is 1.0034. Using Equation (3.1), it is evident that the ratio of the radiated powers is $1.0034^4 \approx 1.014$. That is, a 0.34% increase in temperature results in a 1.4% increase in radiated power. Increasing the temperature increases radiant power more than the increase in temperature, which reduces the temperature. This means that the atmosphere has *negative feedback* – it tends to restore itself to equilibrium. This is called *Le Chatelier's principle*. Systems that have positive feedback are very rare. Explosives are one example. The Stefan-Boltzmann law, along with the logarithmic relationship between CO_2 concentration and atmospheric temperature, described in Section 3.9 and illustrated in Figure 3.18, show that *there can be no runaway greenhouse effect in the Earth's atmosphere*!

3.9 How Much does CO_2 actually warm the earth?

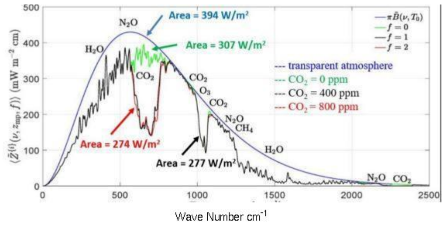

Figure 3.17: Atmospheric Radiation Budget

Figure 3.17, taken from [61], shows the spectrum of the power radiated by the Earth's atmosphere. The area under each curve is the total power radiated back to space. Reducing radiated power increases the temperature of the atmosphere. The smooth blue line shows what the radiated power would be if the Earth had no atmosphere, or an atmosphere transparent at all wavelengths. The jagged green line shows what the radiated power would be if the atmosphere were almost the same as the real atmosphere, but contained no CO_2 (and the Earth would be lifeless). The jagged black line shows the radiated power of the current atmosphere, containing 400 ppm of CO_2. The jagged red line shows what the radiated power would be if CO_2 content were *doubled* to 800 ppm. *DOUBLING* the amount of CO_2 in the atmosphere would change the Earth's radiation budget by 1.08%.[m] Are you actually able to see a difference between the red and black lines? For math nerds, the method to calculate Figure 3.17 is described in Appendix A.

When power retention within the troposphere increases by 1.08%, to bring solar heating back into thermal equilibrium with the atmosphere, the temperature ΔT must in-

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[m] IPCC scientific reports agree with this number.

crease by 0.27%, according to the Stefan-Boltzmann law, Equation (3.1). To see this, substitute $T = T + \Delta T$ and $P = 1.0108 \times P$ in Equation (3.1), and solve for $\frac{\Delta T}{T} = \sqrt[4]{1.0108} - 1 = 0.0027$. The temperature of the Earth is approxiately 15°C, or about 288°K. Therefore the increase in temperature is 0.0027×288°K = 0.78°C.

That is, each *DOUBLING* of CO_2 concentration *ADDS* 0.78°C to the average lower troposphere temperature, not the 3 degrees that the IPCC uses to scare us. Read that again: A *DOUBLING* to 800 ppm, not an *increment* from 400 to 500 ppm.

The spectral forcing shown in Figure 3.17 is defined as the difference between the spectral flux through an atmosphere that contains greenhouse gases, and the spectral flux through a transparent atmosphere. If doubling or halving the column density of CO_2 changes the forcing by a fixed increment, they have a logarithmic relationship, as shown by the curve in Figure 3.18 for an altitude in the atmosphere where the temperature is about 3°C. That is, *multiplying* CO_2 concentration by some amount only *adds* to the spectral forcing. For example, the base-10 logarithms of 10, 100, and 1000 are 1, 2 and 3. The logarithmic relationship between column density of a gas and temperature was first described by Svante Arrhenius in 1896:

> Thus if the quantity of carbonic acid increases in geometric progression, the augmentation of temperature will increase nearly in arithmetic proportion [3, p. 267],

and in terms of incremental spectral forcing in 1906[4]. In 1896, based on extrapolations of some early attempts by Langley to measure the temperature of the Moon [32], Arrhenius had postulated that doubling CO_2 would increase Earth temperatures by 5-10°C [3, p. 267], but that this needed to be confirmed by more direct measurements than Langley's. He believed this would be beneficial and "would warm cooler climates and enhance agricultural production." The IPCC continues to use the temperature change estimate from his early work, but rejects his speculation about the beneficial effects of increasing temperature.

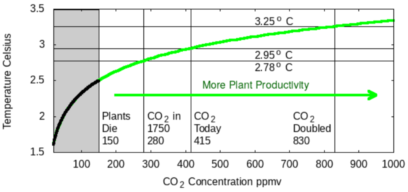

Figure 3.18: Logarithmic heating effect of CO_2.

A significant reason that the red and black lines in Figure 3.17 are indistinguishable is that the radiative relaxation time for a molecule of water vapor or CO_2 that has been excited by long-wave infrared (LWIR) radiation is several seconds. The average collision time anywhere in the troposphere is on the order or nanoseconds. Therefore, heat is transferred from these molecules to the far greater numbers of nitrogen and oxygen molecules almost exclusively by collision. They are hardly cooled at all by re-radiation of LWIR. The re-radiated LWIR is radiated in all directions, not exclusively downward to warm land or oceans. The result is that the downward re-radiated LWIR flux is about 2Wm^{-2}. The total solar flux can be as large as 1000Wm^{-2}, so the 2Wm^{-2} downward flux attributed to LWIR re-radiation from CO_2 is insignificant compared to direct insolation.

The mean free path of LWIR in sea water is on the order of 100 microns, so the 2Wm^{-2} downward flux of re-radiated LWIR cannot warm the oceans. The average sea-surface atmospheric temperature is 2°C colder than the average sea surface temperature. Therefore, the atmosphere cannot warm the oceans by conduction.

Heating nitrogen and oxygen results in convection. Therefore, the troposphere is cooled first by convection, and then by radiation from the top, according to the Stefan-Boltzmann Equation (3.1) [29].

Prof. Happer refers to the radiation spectrum from the top of the atmosphere, as shown in Figure 3.17, as the "Schwarzschild spectrum" (the Schwarzschild equation is described in Appendix A). If the Schwarzschild spectrum is integrated over the range of wave numbers shown in Figure 3.17, the results are indistinguishable from satellite observations.[n]

Most feedbacks in nature are negative. This is called *Le Chatelier's Principle*: If a system in equilibrium is perturbed, it will tend to return to equilibrium. Feedbacks other than radiative forcing are more likely to cause radiative warming to be even less effective than 0.78°C. Both the sign and magnitude of the feedbacks used to construct the IPCC summary report, to scare people that an increase in CO_2 concentration from 400 to 500 ppm will increase the Earth's temperature by 2-3°C, are bizarre and at odds with observations and other natural phenomena. Unsurprisingly, the IPCC wrote

> Climate change takes place when the system responds in order to counteract the flux changes, and *all such responses are explicitly excluded* [my emphasis] from this definition of forcing [38, p. 664].

That is, they explicitly reject Le Chatelier's principle.

3.10 "Coming Ice Age" Scientists are singing a different tune now

> *No matter how beautiful your theory is, if it doesn't agree with reality it's wrong.*
> – Nobel Physics Laureate Richard P. Feynman

The late Stephen Schneider was one of the high priests of "the sky is falling" global warming cult. But in 1976, while he was an acolyte of "the coming ice age" cult, he wrote that the globe would get colder, causing food shortages and famines, leading to

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[n] Private communication 14 October 2023, Prof. William Happer.

the deaths of millions [45]. A *New York Times* review said the book was "reflecting the consensus of the climatological community." His book detailed the Roman and Medieval warmings and their positive impacts on society. Those warmings were erased from the IPCC 2001 report (see Figure 3.7). Look what he wrote, along with S. I. Rasool, in 1971 [41, p. 139]:

> From our calculation, a doubling of CO_2, produces a tropospheric [lower atmosphere] temperature change of 0.8°K. However, as more CO_2 is added to the atmosphere, the rate of temperature increase is proportionally less and less, and the increase eventually levels off.[o] Even for an increase in CO_2 by a factor of 10, the temperature increase does not exceed 2.5°K.
>
> Therefore, *the runaway greenhouse effect does not occur* [my emphasis] because the 15-μm CO_2 band [667 cm^{-1} in Figure 3.17], which is the main source of absorption, "saturates," and the addition of more CO_2 does not substantially increase the infrared opacity of the atmosphere.

Rassool and Schneider wrote these at the time when "scientists"[p] were worrying about the coming ice age. If burning fossil fuels couldn't prevent the coming ice age, how could burning fossil fuels cause catastrophic global warming? If this is still a mystery, re-read section 3.9 above about how much CO_2 warms the Earth.

What does "saturate" mean? Imagine you have a greenhouse in which visible light passes through the glass roof, strikes materials inside, and warms them. Then some of that heat is re-radiated as infrared light – because the plants and soil do not become as hot as the surface of the Sun. Your greenhouse then warms because the glass does not transmit infrared light as well as it transmits visible light. In other words, it holds heat inside. Suppose it retains 90% of the infrared light. If you add another sheet of glass, your greenhouse does not retain 180% of the re-radiated infrared light. That would be absurd; it would require the glass to create heat, not reflect or absorb it. Instead, the second sheet reflects or absorbs 90% of the 10% that got through the first sheet. A third sheet would reflect or absorb 90% of the 1% that got through the first two sheets.... An infinite number of sheets of glass could only reflect or absorb 100% of the re-radiated infrared light. Now re-read this paragraph, mentally substituting "atmospheric carbon dioxide" for "glass." A simpler thought experiment is to imagine a completely soaked sponge floating in your kitchen sink full of dishwater. Adding more water doesn't make the sponge soak up more water.

Study the pronounced dip in the 600-700 cm^{-1} range in Figure 3.17. That dip means CO_2 does not transmit infrared light as well as it transmits visible light.

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[o] This is an imprecise way of saying they have a logarithmic relationship.

[p] Prof. William Happer (physics, Princeton), a real scientist who knows how to compare reality to theory quantitatively, said "climate scientists aren't actually scientists."

After he was instrumental in converting the "coming ice age" cult to the "global warming" cult, Schneider said[q] as paraphrased in the Detroit News [18]:

> We need to get some broad based support, to capture the public's imagination.... So we have to offer up scary scenarios, make simplified, dramatic statements and make little mention of any doubts.... *Each of us has to decide what the right balance is between being effective and being honest* [my emphasis].

He tried to explain this away, claiming that what he said was selectively edited [46]. His more-complete remark in the Discover Magazine interview included a remark about a "double ethical bind." Within one paragraph he said both "we have to include all doubts" and "we have to ... make little mention of any doubts." That proves he wasn't a real scientist.

A few others have said or written similarly interesting things:

> We've got to ride this global warming issue. Even if the theory of global warming is wrong, we will be doing the right thing in terms of economic and environmental policy.
> – Timothy Wirth, president of the UN Foundation. Former U.S. Senator.
>
> No matter if the science of global warming is all phony... climate change provides the greatest opportunity to bring about justice and equality in the world.
> – Christine Stewart, former Canadian Minister of the Environment.

3.11 It's Dangerous to disagree with consensus

> *It is dangerous to be right in matters where established men are wrong.*
> – Voltaire
>
> *The right to criticize can be granted only to the wiser people over the more stupid ones and never the other way around.*
> – Joseph Goebbels, Nazi Minister of Propaganda [22].
>
> *A dictatorship means muzzles all round, and consequently stultification. Science can flourish only in an atmosphere of free speech.*
> – Albert Einstein [39, p. 107].

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[q] Interview published in *Discover Magazine*, October 1989, which is not available from their archive.

If the observational and physical support for the proposition that humans cause global warming, and that it is harmful, is so strong, why is there a need to manipulate and distort data, and invent consensus, especially when consensus has nothing to do with science?

Scientists who disagree with consensus are branded as illegitimate, bullied, ostracized, isolated, sneered at, mocked, deemed as unworthy of remaining in the halls of academia and fired, spat upon, or murdered.

Galileo said "The authority of a thousand is not worth the humble reasoning of a single individual." After philosophers of his time refused to look through his telescope, he was forced on 22 June 1633 to "abjure, curse, and detest" his claims, and then sentenced to house arrest for the remainder of his life. The alternative was the fate of Giordano Bruno, who was burned alive on 17 February 1600.

When Albert Einstein published his *Theory of Relativity*, German newspapers reported "One hundred German scientists claim Einstein's theory of relativity is wrong." Echoing Galileo's words, Einstein said "If I were wrong, it would have taken only one."

Most of professor Peter Ridd's career was at James Cook University (JCU) in Queensland, Australia. He had achieved an international reputation as a careful and honest scientist for his research focused on the Great Barrier Reef. He was dismissed in 2018 when he pointed out that some of his colleagues were misrepresenting the state of the reef, and that their results needed to be checked more thoroughly, and replicated. Another paper revealed that eight studies from JCU could not be replicated: "[W]e comprehensively and transparently show that – in contrast to previous studies – end-of-century ocean acidification levels have negligible effects on important behaviours of coral reef fishes" [10]. One researcher, Oona Lönnstedt, was found to have fabricated data [44]. "The lab simply did not have the materials that Lönnstedt would have needed to perform the experiments…." No action was taken against Lönnstedt, but Ridd was fired for raising concerns.

As an author, speaker, and advisor to governments, the late Professor Bob Carter was upsetting the money-making apple cart at JCU. The university took his office, then his title, then ramped up the spite and took his library card and cancelled his email account.

Many others have had similar experiences.

The atmosphere of fear is understandably rife. Most keep quiet until they retire because they don't want to lose their jobs – they have families to feed, after all. Those who do speak out are either very brave, or tenured, or retired. Being retired might not be enough protection; a spiteful university might strip your Emeritus title, and cancel your library card.

How can "consensus scientists" claim "the science is settled" and "the debate is over" when they have silenced or fired climate realists? In reality, no debate has taken place because they did not wish it to be held. They resorted to devious tactics that only shed shame on their profession. Once you're branded a heretic, there's no reason for your critics to respond, or to justify their vicious attacks.

> *The only reason to silence your critics is to prevent you from being exposed as a moron.*
> – Anonymous online quip

3.12 Conclusion

Geological and historical records show that global temperatures have been much higher than they are now, but life flourished nonetheless. In the words of the Dr. Ian Malcolm character in the *Jurassic Park* movie, "life finds a way." Those records also show that global temperatures and CO_2 concentration are not related, and that, in fact, when they change contemporaneously, the concentration of CO_2 in the atmosphere changes about 800 years *after* temperature changes.

A runaway greenhouse effect *cannot occur* and therefore a climate catastrophe *cannot occur*.

The atmospheric concentration of CO_2 is near the all-time low. It is continuously being removed from the atmosphere by sea creatures and plants in the form of bones and seashells and coccolithophores and coral reefs, which ultimately become compressed to limestone that is then pushed under the continents by geological processes. When CO_2 concentration falls below about one third of the present concentration, life on the Earth will be extinguished. Fortunately, the Industrial Revolution has postponed the end of life on Earth to about eighteen million years in the future – and we could postpone it even more.

Dissolution of CO_2 in the oceans does not significantly increase their acidity, and if it did, that would not be a problem. Molluscs thrive in acidic estuaries. Some corals survive where the concentration of CO_2 in seawater is seven times greater than average. This is not really a surprise because their symbiotic algae are, after all, plants, which thrive on CO_2.

Sea creatures, including coral and molluscs, have clearly coped with sea levels rising at centimeters-per-year rates, so sea levels rising at two millimeters per year are clearly not a threat to them.

It is tempting but intentionally dishonest to believe that when you observe a phenomenon you necessarily know the cause and mechanism. It is especially dishonest when you use this self delusion to convince others.

Environmental extremists rely upon falsehoods and drama. When James Hansen gave a presentation to Congress about climate change in 1988, his team had sabotaged the air conditioning in the building. The press and television had a vision of sweating Congressmen. The team bragged about the sabotage. Remember that Schneider wrote *Each of us has to decide what the right balance is between being effective and being honest*.

The IPCC should immediately have lost credibility, upon its founding, when its first chairman, Sir John Houghton, said in 1995:

> *Unless we announce disasters, no-one will listen.*

The IPCC is fundamentally dishonest, and apparently was intended to be from its beginning. The claim that "climate change" is harmful, and exclusively or even primarily driven by humans burning fossil fuels, is based on five decades of Lysenkoism masquerading as science. Paul Ehrlich, Amory Lovins, Michael Mann, and Al Gore have done more damage to world science than Trofim Lysenko did to Soviet genetics.

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Chapter 4

Never start a vast project with half vast plans

> *Explanations exist; they have existed for all time; there is always a well-known solution to every human problem – neat, plausible, and wrong.*
> – H. L. Mencken, "The Divine Afflatus," *The New York Evening Mail*, 16 November 1917.
>
> *People do not fully understand what needs to be done, or the consequences of not understanding what needs to be done. Master the details to master the risks.*
> – Risk management adage.

4.1 System engineering

If you want to solve the problem, then you have to take in the whole truth.
– Barack Obama

From a skeptical scientist's point of view, the questions whether human activity is causing climate change, whether that climate change is a good or bad thing, and whether increasing concentration of CO_2 in the atmosphere is a good or bad thing, are still not satisfactorily "settled." The answers that humans are causing it, in particular that emissions of CO_2 that result from burning fossil fuels are causing it, and that it is a bad thing, are, however baked into social discourse. Although it is almost certainly not physically necessary to abandon fossil fuels, except in the long run because they'll be depleted, social consensus is that we must do so immediately.

Therefore, numerous proposals for energy sources that do not emit CO_2 are in vogue – primarily solar and wind – but biofuels, biomass, geothermal, tides, ocean currents, ocean waves, ocean thermal gradients, hydroelectric dams, Amory Lovins's vigorous handwaving, Tinkerbell's magic pixie dust, and unicorn farts have all been seriously proposed.

Two of the principles of system engineering are that you cannot do just one thing, and it is almost always impossible to optimize all components of a system simultaneously. The goal must instead be to optimize the system as a whole, even if that means that some components are used in what would be considered to be a sub-optimal way, if they were the only components in some other system, or if their optimality were the only measure.

When one sets out to optimize a system, it is necessary to construct a measure of what to optimize. For example, we want automobiles to have high energy efficiency, and to be safe. Wanting high energy efficiency requires that they be light, and that suggests they ought to be made from toilet paper, but safety suggests they ought to be made from steel. By what measure can one optimize this trade off? One answer is that every customer has a different measure. The spectrum of products is determined by a market. If a central authority determines the balance, it is not obvious whether society's satisfaction would be maximized.

I asked politicians and bureaucrats at all levels – county, state, and federal, including the U. S. Department of Energy – for a report of the comprehensive quantitative life-cycle system engineering study of the transition of the energy economy to use only renewable sources. I received no responses, not even a polite "I'm sorry, we have no such report."

What is meant by *comprehensive life-cycle analysis* is one that includes minerals, metals, concrete, plastic, fiberglass, other materials, transportation, construction, operation, long distance electricity transmission, local electricity distribution, maintenance, safety, decommissioning, destruction, recycling, disposal, energy return on energy invested, energy payback period, financial return on investment, financial payback period, taxation, tax incentives, subsidies, portfolio mandates, and human and environmental effects of each component and step in the process. Operation requires methods for generators to synchronize voltage, frequency, and phase with the grid, and storage for when the weather doesn't cooperate with demand. Increasing penetration of electricity into every energy consumer entails increasing penetration of software.

Electric utilities have typically employed a spectrum of experts, including in areas of budgeting, rates, regulatory compliance, generation, transmission, distribution, maintenance, operating, environmental, planning, construction, marketing, R&D, legal, and strategic planning, as well as sub-areas of these disciplines. One of the reasons for the Electricity Modernization Act of 2005 was an assumption that utilities that owned both generation and transmission resources had an advantage over companies that owned only generation resources. One consequence of the act, as well as regulations by the Federal Electricity Regulatory Commission (FERC) and policies of the North American Electricity Reliability Corporation (NERC), is the creation of "silos" that inhibit rather than promote system engineering. In particular, if generation engineers and transmission engineers and distribution engineers and maintenance engineers work together, a single utility might be subject to fines of as much as $1 million per day. Instead of system engineering, utilities are focused on standards and regulatory compliance [30], and if engineers from generation and transmission utilities communicate, they might be subject to anti-trust violations. The assumption is that regulators, who are largely politicians and attorneys, not engineers, have done the system engineering – which of course they have not because they don't know how to do it – and the real engineers should stick to component engineering alone.

Engineering public policy is important and not obviously possible. The unelected California Air Resources Board is setting the state's 2026, 2030, and 2035 electric vehicle mandates, while assuming that the unelected California Public Utilities Commission will mandate the requisite EV-supporting electrical infrastructure. Yet more silos. It's not obvious that overcoming social obstacles, such as the wished-for changes in personal behavior, is possible.

> *Policymakers often weigh only the benefits [of their policies] and not the other outcomes.*
> – Lee Vinsel, Virginia Tech

Carlos Tavares, CEO of Stellantis, asked at the *Future of the Car 2022* conference in London "Who is looking at the full picture of this transformation?" [11]

Because I received no such report I started doing some research. I haven't put together a comprehensive analysis of my own, but I have found or developed a few pieces.

4.2 Electrify everything

4.2.1 Wishful plan

The goal of climate-inspired activists is to replace all use of fossil fuels (and nuclear power) with electricity produced mostly by generators using hydro, solar, and wind, with smidgens coming from geothermal, tides, ocean currents, ocean thermal gradients, biomass, biofuels, Amory Lovins's vigorous handwaving, Tinkerbell's magic pixie dust, and unicorn farts.

Here is one ambitious timeline for the United States, abbreviated to WWS for wind, water, and sunlight, laid out in 2015 by Mark Z. Jacobson and his colleagues [21]:

- Heating, drying, and cooking in the residential and commercial sectors: by 2020, all new devices and machines are powered by electricity.

- Large-scale waterborne freight transport: by 2020–2025, all new ships are electrified and/or use electrolytic hydrogen, all new port operations are electrified, and port retro-electrification is well underway. One fly in the ointment is that there are no American companies that build large ocean-going commercial ships.

- Rail and bus transport: by 2025, all new trains and buses are electrified. On the weekend after a meeting in Sydney, Australia, I took a ride to Wallongong on a beautiful train pulled by an electric locomotive. I had to change midway at Waterfall (where there is no waterfall). While waiting, a large freight train went by, pulled by several diesel locomotives. There happened to be a rail worker at the station, so I asked him why. He said that using electric locomotives for freight is too expensive. This was before the large 2.9 GWe coal-fired power station at Eraring closed and electricity rates increased 80%. The 1.68 GWe coal-fired Liddell power station closed on 28 April 2023, so expect even higher rates soon.

- Off-road transport, small-scale marine: by 2025 to 2030, all new production is electrified.

- Heavy-duty truck transport: by 2025 to 2030, all new vehicles are electrified or use electrolytic hydrogen.

- Light-duty on-road transport: by 2025–2030, all new vehicles are electrified.

- Short-haul aircraft: by 2035, all new small, short-range planes are battery- or electrolytic-hydrogen powered.

- Long-haul aircraft: by 2040, all remaining new aircraft use electrolytic cryogenic hydrogen with electricity for idling, taxiing, and internal power.

- Power plants: By 2020, no more construction of new coal, natural gas, or nuclear power plants. The WWS proposal also excludes biomass-fired power plants.

There has not been much progress toward these goals, but some states, such as California, and local governments, are imposing mandates intended to advance them. The California Air Resources Board (not the legislature) has approved a rule that sets California on a path toward requiring that all new on-road vehicles will be electric by 2035 [6].

Another California plan addresses stationary sources such as space and water heaters, off-road vehicles and equipment, and locomotives [5]. The city of Berkeley, California, banned gas connections in all new construction starting 1 January 2020 [29]. That was struck down on 17 April 2023 when the Ninth Circuit Court of Appeals concluded that Federal law pre-empts that ordinance [26]. Activists were briefly floating a plan to ban new gas stoves, until enormous backlash convinced them to wait – but of course they have not abandoned the plan.

The WWS plan envisions a $15.2 trillion 1,591 GWe all-electric energy system with no fuel backup and next to no storage. An analysis [13] and summary [14] of the description found numerous shortcomings.

- **One half million 5 megawatt wind turbines**, on land equal to New York, Pennsylvania, Vermont, and New Hampshire, and in open sea regions equal to West Virginia. Assuming optimistically that wind turbines last 25 years, to maintain one half million 5 megawatt wind turbines will require to remove, recycle or dispose, fabricate, transport, and install 25,000 turbines every year, forever. With proper maintenance, they might last 25 years, but when subsidies expire after ten years, maintenance is typically abandoned, and the machine fails completely a few years later. The average lifetime at sea, even with proper maintenance is closer to twelve years. The replacement requirement is probably closer to 50,000 per year. As of 2020, after about four decades of construction, a total of 24,000 are in service on shore [36], and 8,400 offshore, 6.5% of the demanded number, or 130% of the most optimistically expected yearly replacement [25].

- **18 billion square meters of solar panels**, in industrial scale solar parks, on land equal to Maryland and Rhode Island. Assuming optimistically that solar panels last forty years, to maintain 18 billion square meters will require to remove, recycle or dispose, fabricate, transport, and install 1.23 million square meters of panels every day, forever.

- **Concentrated solar power** (CSP) with molten salt thermal energy storage, on land equal to Connecticut. California has produced almost no new CSP capacity since 2015 [12]. The Energy Information Administration plans no increase at all in new CSP capacity through 2050 [2].

- **Rooftop solar on 75 million homes**, and nearly three million businesses. The average rooftop solar system is about 40 square meters, and the average industrial one is about 1,000 square meters, so these amount to about 6 billion more square meters. Between industrial scale solar parks, and domestic and industrial rooftop solar systems, with a forty year replacement schedule, it will be necessary to replace about 1.6 million square meters of panels every day, forever.

An important figure of merit for any generation method is its *capacity factor*, which is the amount of energy it actually produces during a period of time, such as a year or the lifetime of the device, divided by the amount of energy it would produce if it operated continuously at label capacity.

The capacity factor for rooftop solar is substantially less than for industrial solar installations for a variety of reasons: Solar panels are aimed where the roof is aimed – sometimes even on the north side! (which is OK in Australia, but not California) – the panels' tilts are frequently the same as the roof, which might not be optimal for the latitude, and there might be shade from nearby trees (see Section 7.3).

There are discrepancies in the description of the WWS plan. The numbers don't add up.

Solar PV produces direct current (DC), with the voltage varying depending upon insolation conditions. The distribution grids, most transmission grids, and essentially all electrical equipment use alternating current (AC). To power a building, or connect to the grid, conversion to AC and voltage regulation are necessary, with about 85% efficiency.

Table 4.1: Label capacities from Table 2 in [21]

	Label Capacity GWe	Capacity Factor	DC → AC efficiency	Net Yearly GWe-yr	Claimed by WWS GWe-yr
Onshore wind	1,701	29.7%	N/A	505.2	491.9
Offshore wind	780.9	40.0%	N/A	312.4	303.6
Residential PV	379.5	14.4%	85%	46.5	63.3
Comm/govt PV	276.5	14.4%	85%	33.8	51.5
Industrial PV	2,326	21.9%	85%	433.0	488.9
Utility CSP	227.3	21.9%	N/A	49.8	116.1
Total	5691.2	24.3%		1380.6	1515.4

The capacity factor used for onshore wind in Table 4.1 was for projects built between 2004 and 2015, the time when the WWS report was written. The capacity factor in 2021 was closer to 40% because newer turbines are higher and have longer blades [36]. The capacity factor for offshore wind has been about 40% since 2011 [34].

Table 4.1 doesn't include waves, geothermal, hydro, or tides, which the WWS study proposed would provide 74.3 GWe, or about 4.67% of the total.

Figure 2.1 shows that in 2021, the United States got 40.6% of useful energy, and 13.3% of total energy, from electricity. Average demand was 431 GWe. U.S. label generating capacity was 1,242 GWe [4]. Seasonal maximum power demand is about 768 GWe, so label generating capacity is about 2.88 times average demand, and about 1.62 times peak demand. Label capacity is increasing faster than demand because of increasing use of renewable sources with low capacity factors. Excess capacity is needed to allow for maintenance or unplanned outages of generators with high capacity factors, such as coal, gas or nuclear, or the unplanned but expected erratic output from low capacity-factor solar and wind generators.

The WWS proposal does not envision any excess capacity, or storage other than small amounts of pumped hydro. As will be shown in Chapter 8, even with only twelve hours' storage, California's average renewables' generation (not label capacity) would need to be three times average demand to provide firm power – and 355% of average demand would be dumped. Taking their small capacity factors into account, label capacity of an all-renewable all-electric energy system would need to be about twelve times average demand. The analyses of storage requirements in Chapter 8 are optimistic, in that they do not take storage efficiency, or transmission, distribution, and other losses, into account.

Building the generators envisioned in the WWS proposal is problematic, especially assuming a linear build-out. The proposal has a 35 year time frame. It envisions 484,200 turbines, each of 5 MWe label capacity. Building 1/35th of them each year would require to build 13,800 every year. The best all-time year for turbine deployment was 2012, when 13.1 GWe of label capacity was deployed. If all those generators had been 5 MWe generators, 2,620 would have been deployed, or 18.9% of the number required in that year to meet the linear build-out goal.

The situation for solar is even less promising. The best-ever year was 2015, when 6,200 MWe of new label capacity was installed. The WWS report envisions 2,982,000 MWe label capacity at the end of 35 years. Building 1/35th of that capacity would require to build 85,200 MWe of new label capacity every year, or 13.75 times the production in the best-ever year.

Proponents of the transition to all-renewable energy envision exponential, rather than linear construction with the same relative capacity growth every year. The idea is similar to compound interest. In 2015, actual U.S. production from wind was 21.8 GWe-yr. The WWS proposal envisioned 817.6 GWe-yr per year in 2050 (the sum of the first two rows in the last column of Table 4.1). Assuming that the relationship between label capacity and average output remains constant, the rate of growth required to reach that goal can be computed by solving

$$817.6 = 21.8 \times (1 + r)^n \,, \tag{4.1}$$

for r, where r is the annual growth rate and n = 35 years. The solution for Equation (4.1) is

$$r = 100 \times \left[\left(\frac{817.6}{21.8} \right)^{\frac{1}{35}} - 1 \right] \% = 10.91\% \text{ per year,}$$

that is, $817.6 = 21.8 \times 1.1091^{35}$. Table 6.7b in [3] shows that nationwide WWS label capacity grew from 152 GWe in 2013 to 282 GWe in 2022. Assuming exponential growth as above the rate was 7.9% per year. Solving Equation (4.1) for n with r = 7.9% shows that at the current growth rate, 48 years would be required to reach Jacobson's goal for wind production. Figure 8.3 shows that label capacity for wind generation has not changed in California since 2013.[a]

4.2.2 Significant problems in operating the system

Ben Heard and his colleagues wrote [20]

> While many modeled scenarios have been published claiming to show that a 100% renewable electricity system is achievable, there is no empirical or historical evidence that demonstrates that such systems are in fact feasible. Of the studies published to date, 24 have forecast regional, national or global energy requirements at sufficient detail to be considered potentially credible.

They evaluated those proposals using four criteria:

1. consistency with mainstream energy demand forecasts;
2. simulating supply to meet demand reliably at hourly, half-hourly, or five-minute timescales, with resilience to extreme climate events;
3. identifying necessary transmission and distribution requirements; and
4. maintaining the provision of essential ancillary services.

Ancillary services are the variety of operations of electricity networks that are required to balance supply and demand over all time scales, maintain grid stability, voltage, frequency, and phase within safe limits, maintain efficiency and security, and prevent overload of grid infrastructure.

Electricity transmission and distribution grids, and electricity consumption, use alternating-current electricity. The term "alternating current" or AC means that the voltage varies between positive and negative values, and the current reverses direction, at the rate determined by the frequency.

Many devices that consume electricity, especially motors, depend upon the frequency being constant, at 60 hertz (cycles per second) in the Americas and some parts of Asia, and 50 hertz elsewhere. If the frequency is wrong, their speed changes, internal losses increase, they might not work, or they might be damaged.

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[a] It decreased 164 MWe in 2022. See `https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/electric-generation-capacity-and-energy`.

Because of the alternation of current and voltage, it is necessary also to consider its *phase*, that is, “when do the voltage and current begin to rise?” (which might not necessarily be at the same time).

In 1831 and 1832, Michael Faraday and Joseph Henry independently observed that when a magnetic field changes near a wire, as for example when a magnet is moved near a wire, a current is induced in the wire. This is called *Faraday’s principle of induction*.

The generator at a coal, gas, nuclear, or hydro power station, or in a wind turbine, is a rotating machine. The part that rotates is called a *rotor*. It is an electromagnet, with its field provided by a DC supply called the *exciter*. The term DC means “direct current,” which means the direction of energy flow does not reverse periodically. Therefore, with respect to the rotor, the direction of the magnetic field is constant, and its magnitude is proportional to the current. The surrounding part, that is stationary, is called a *stator*. The stator typically consists of six *poles* of windings, spaced equally around the rotor: Each pole is separated from the next by 60°. Directly opposite poles of the stator are connected. When the rotor rotates, the magnetic field rotates, and therefore changes in each pole of the stator, and a current is therefore induced in each pole. Such a generator produces three-phase power, that is, power on three separate circuits with a 120° difference in their phases. If a DC current is applied to the rotor, and three-phase AC power is applied to the stator, the machine is a motor. If a DC current is applied to the rotor, and the shaft of the rotor is driven by a turbine in a hydroelectric dam, or a diesel engine, or a gas turbine, or a steam turbine in a coal-fired or nuclear power plant, or a wind turbine, the machine is a generator, producing three phases of AC power, one for each pair of poles of windings in the stator.

Of course, the roles of rotor and stator can be interchanged: The stator might be a fixed electromagnet, with electric power induced in and drawn from different poles of the rotor.

The frequency of the generated power depends upon the rotational speed of the rotor. To generate 60 Hz AC three-phase power using a generator with three pairs of poles, the rotor must rotate at 3,600 RPM. Slower speeds can be used by having more poles, while still connecting them to produce three-phase power.

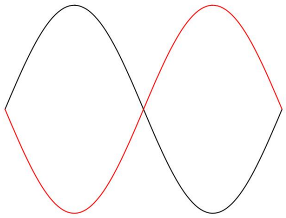

Figure 4.1: One Cycle of Electric Power at Two Phases

When utilities were just starting to put more than one generator in a station, they found (more likely predicted and then verified) that if you close a switch and instantaneously connect corresponding poles of two generators together, and those generators are producing power of randomly different phases, perhaps as much as 180° out of phase, there is a current surge and bad things happen. Fuses and circuit breakers are blown. There are even stories of the shaft of a generator having been broken. The same sort of thing happens if a generator is put onto the grid, and its phase is not matched to the grid. As shown in Figure 4.1, if they are 180° out of phase, their voltage and current sum to zero. But the energy doesn't disappear. At best, it only blows fuses or circuit breakers, but it could damage the grid, the generator, or ancillary systems such as transformers and switches.

If the generator frequency doesn't match the grid frequency, the effect is the same as if it were continuously drifting into and out of phase with the grid. There would be current surges flowing between the generator and grid with a frequency equal to the difference between the frequencies of the grid and generator. These are called *sub-synchronous oscillations*.

It is important that regulating devices on each generator ensure they produce power with voltage, frequency, and phase that match the grid.

The generator's voltage has to match the grid. If it's too low the generator does not supply power to the grid. If it's too high, there are overcurrents in the generator, or the rotational power source is overloaded. The voltage is adjusted by changing the strength of the electromagnet, which depends upon the current supplied to it. When the load becomes greater than the current carrying capacity in the electromagnet, the voltage falls and the generator becomes a consumer. In this case, it is better for the grid as a whole to disconnect the generator.

When your car is driven up a hill, or when you push too hard on an electric drill or saw, it slows down. The same thing happens when the load on an electric generator increases. To maintain your car's speed as you drive up a hill, you can increase the engine's power by increasing the fuel supply using the accelerator pedal.

In a hydroelectric generator, power output is controlled by the water flow rate. In a coal- or gas-fired generator, output is controlled by the steam flow rate, which is controlled by the fuel flow rate. In a nuclear power station, the steam flow rate is controlled by the rate of fuel fission, which is controlled by the positions of control rods. In all of these generators, electricity is ultimately produced by heavy rotating machines, with the voltages, frequencies, and phases of their electrical output controlled to match the grid. In the electric power industry, these are called *synchronous generators*. Their enormous angular momentum, as a consequence of their enormous weight, means that when load increases, their speed, and therefore their voltage, frequency, and phase change gradually and very slightly, giving control systems, which can operate much more rapidly, the opportunity to supply more water, fuel, or heat of fission, just as the cruise control in your car can maintain constant speed regardless of the slope of a hill. That is, energy is stored as rotation of the heavy machines, as it is in a flywheel, "discharged" as needed when loads fluctuate, and "recharged" by increasing fuel flow. The result is that voltage, frequency, and phase change very little, even if loads change rapidly. The output of a wind turbine can be controlled somewhat by adjusting the pitch of its blades. Controlling the output of a solar generator is much more difficult.

In physics, *inertia* is the term used to refer to resistance to change. The international unit of inertia is the kilogram. Grid operators use the term inertia to describe mechanisms to maintain grid stability, voltage, frequency, and phase. From Einstein's famous formula $E = m\,c^2$, mass is equivalent to energy. Inertia, as the term is used in electrical systems, is mostly provided by the energy stored in heavy synchronous rotating generators at hydro, coal, gas, and nuclear power plants, and in wind turbines. These are all essentially flywheels.

The amount of energy in a flywheel of mass m, radius r, and rotational speed ω, is $\frac{1}{2}\,m\,r^2\,\omega^2$. Although a typical wind turbine has less mass, and lower speed, it actually stores more energy per megawatt of label capacity because of its larger radius. When load increases, energy is taken out of the flywheel, and it slows down. We measure this as power, the rate of change of energy. Slowing the rotor in a generator reduces the frequency of AC power it generates.

Batteries can be used, at a manageable scale, entirely different from the scale needed for backup (see Chapter 8), to provide inertia. The critical difference between batteries and wind turbines on one hand, and hydro, coal, gas, or nuclear generators on the other hand, is that there is no valve on a wind turbine or battery to inject energy back into the "flywheel" from another source, whether it be the penstock of a dam, or steam at a thermal power plant, to maintain the rotor's speed. So batteries and wind turbines can provide inertia for only a limited time. And, of course, solar panels have no inertia whatsoever.

While a grid is operating, generators' control systems continuously match voltage, frequency, and phase to the grid. After a grid failure, each generator's voltage and frequency can be controlled independently. To restart the grid, it is necessary to restore phase coherency. Pairs of generators establish connections and synchronize their phases. Then synchronized groups of generators establish connections and synchronize their phases. With a greater number of generators, longer time is required to re-stabilize the grid. A few hundred large generators can be synchronized relatively quickly, in a day or two. Synchronizing millions of small generators is more difficult, unless grid stability is first established using a small number of large heavy synchronous rotating generators to provide a phase reference for small generators.

Heard et al used a weighted scoring system, with a maximum possible score of eight. None of the proposals they studied achieved a score greater than five. For example, of the Jacobson WWS proposal, they wrote that "it depends strongly on extraordinary assumptions relating to electrification, energy storage and flexibility in demand.... The results of such a simulation are likely to be meaningless because the underlying assumptions are unrealistic."

They did not investigate economic viability because they did not consider any of the proposals to be physically feasible.

4.2.3 Preserving poverty

As Shellenberger also observed [31], Heard et al remarked that important progress in living conditions in the developing world would be threatened under most of those scenarios, which apply unrealistic assumptions regarding the scale of energy necessary to raise those people out of poverty. Those assumptions lack any historical precedent, and fall entirely outside all mainstream forecasts. Heard et al continued:

> [O]utcomes in sustainability, social justice and social cohesion will also be threatened by pursuing maximal exploitation of high-impact sources like hydro-electricity and biomass, plus expanded transmission networks.... Our sobering results show that a 100% renewable electricity supply would, at the very least, demand a reinvention of the entire electricity supply-and-demand system to enable renewable supplies to approach the reliability of current systems. This would move humanity away from known, understood and operationally successful systems into uncertain futures with many dependencies for success and unanswered challenges in basic feasibility.... The reality is that 100% renewable electricity systems do not satisfy many of the characteristics of an urgent response to climate change: highest certainty and lowest risk-of-failure pathways, safeguarding human development outcomes, having the potential for high consensus and low resistance, and giving the most benefit at the lowest cost .... It behooves all governments and institutions to seek optimized blends of all available low-carbon technologies, with each technology rationally exploited for its respective strengths.... Anything less is an abrogation of our responsibilities to both the present and the future.

4.2.4 Electric vehicles

The unelected California Air Resources Board has proposed that all new light-duty road vehicles sold in California starting in 2035 must be electric vehicles (EV) [6]. Governor Gavin Newsom has endorsed this proposal. So far, the California legislature has not acted, so (in theory) the “ruling” has no legal effect.

Robert Charette wrote that the transition to electric vehicles is “an intricately tangled web of technological innovation, complexity, and uncertainty, combined with equal amounts of policy optimism and dysfunction” [11]. As with so many other problems related to energy, there is apparently little or no system engineering involved. Systems engineering includes countless interdependencies that are beyond policymakers’ control. Policies rest on optimistic assumptions about technology and wished-for changes in human nature. The transition to EVs works fine in the minds of academics and politicians, but doing the transition at a useful scale is a serious problem. As people said of Microsoft Windows 95, "it runs best on an overhead projector." Accomplishing the transition at the scale, and in the envisioned time frame, is fraught with problems, risks, and unanticipated consequences that need honest and open recognition if they are to be realistically addressed. Shifting a 125 year old auto industry that's optimized for internal combustion engine (ICE) vehicle production to EVs using nascent, and to a certain extent non-existent technology is a monumental challenge. Requiring vehicle manufacturers to complete it in fifteen years is unrealistic.

Nonetheless, with a carrot-and-stick approach from governments, motor vehicle manufacturers worldwide are gearing up to produce electric vehicles. So far, this is definitely aimed at a luxury and virtue-signaling market. The price of an electric vehicle is much greater than an ICE vehicle. Good luck finding a Tesla in the Barrio. Volvo Cars CEO Jim Rowan boldly proclaimed that EVs will reach price parity with ICE vehicles by 2025. Mercedes-Benz's chief technology officer Markus Schäfer and Renault Group CEO Luca de Meo beg to differ [11]. Ford lost $34,000 on every EV it made in 2022, and $66,446 on every EV it sold during the first three months of 2023 – but this might have been less than government penalties would have been if they hadn't made any [8].

Proponents are aiming at more than automobiles. One midwestern farmer has a 10,000 acre farm that spans three counties. His operation is a "partnership" farm that works closely with the John Deere Company, testing new farm vehicles continuously. Deere asked him to switch to electric tractors, trucks, and combine harvesters by 2023. He has five diesel combine harvesters that cost $900,000 each and are traded in every three years. He has ten very large tractors. Farming is an intensely seasonal operation. When the ground has thawed it is important to get seeds implanted as quickly as possible. During the growing season there are important activities, but not as intensely immediate as in the planting and harvest seasons. When harvest season comes, it's important to get the crop in quickly, when it has the optimal mix of moisture, sugars, carbohydrates, and proteins. Too early or too late by a day or two can mean a difference of millions of dollars.

When a diesel-powered harvester, or the truck into which the product is transferred, runs out of fuel, it can be filled in ten minutes, or maybe even without stopping using a tanker running along beside it. Our farmer asked the Deere representative "How do I charge these combines when they are 3 counties away from the shop in the middle of a cornfield, in the middle of nowhere? How do I run them 24 hours a day for 10 or 12 days straight when the harvest is ready, and the weather is coming in? How do I get a 50,000+ lb. combine that takes up the width of an entire road back to the shop 20 miles away when the battery goes dead?" There was dead silence on the other end of the line. When the batteries in an electric harvester or tractor or truck are depleted, several hours are required to recharge them. The fleet of vehicles needs to be about three times the size of a diesel-powered fleet. Farms are capital intensive. In addition to land, they have capital tied up in buildings and stationary equipment and vehicles. Capital has a cost of its own, either interest on loans, or lost opportunity costs. Tripling the size of the vehicle fleet either makes the farm uneconomical or, if every farm does it, increases consumers' costs [16].

An EV is about 25-33% heavier than an ICE vehicle. This causes safety concerns. U.S. National Transportation Safety Board Chair Jennifer Homendy said "I am concerned about the increased risk of severe injury and death to all road users from heavier curb weights" [28]. Being 25-33% heavier, an EV uses more energy to go the same distance as an ICE vehicle. In California, when the sun isn't shining and the wind isn't blowing, that means exporting pollution to coal-fired power plants at the Four Corners region of Arizona, Utah, Colorado and New Mexico. It's nice that the Navaho are getting some prosperity from their coal, but tourists can't see the bottom of the Grand Canyon. The Hopi are not likewise getting some prosperity because the tribal elders are ripping off the peasants.

An EV also puts more stress on the roadway than an ICE vehicle. Being heavier, it makes more tire and brake dust, and stirs up more road dust. Road damage is not proportional to vehicle weight. It is proportional to the fourth power of axle weight. This law was discovered in the course of a series of scientific experiments in the United States in the late 1950s and was decisive for the development of standard methods in road construction [27] [7]. Because of the fourth-power law, a car that has 25-33% greater axle weight produces 2.4 to 3.1 (1.25^4 to 1.33^4) times more road damage. So EVs ought to pay more road tax than ICE vehicles.

EVs don't pay road taxes at the pump like ICE vehicles do, so EVs are a government-sponsored subsidy for people who are wealthy enough to afford them. Britain is addressing this issue: By law, an EV can only be charged using a government-approved charger, which collects road taxes – and can be turned off any time the renewable energy supply doesn't provide sufficient electricity to meet demand. Whether the government-approved charger collects 2.4 to 3.1 times more road tax, to account for the greater axle weight of the vehicle, is an open question. And they can turn the charger around and suck the battery dry, to try to make up for the wind not blowing and the sun not shining, which makes it a bit difficult to get to work in the morning.

Charging EVs is not as easy as activists imagine. The National Association of Home Builders says 31.4% of American households live in multifamily dwellings. Only 40% of households have reliable off-street parking. Where will they charge an EV? A commercial charger with four ports costs $450,000 to $725,000. It needs nine customers per day to break even. This might be difficult in rural areas. Many EV charging stations lose money. Volta is already in trouble. Zoning approval, permits, dealing with the local utility, and other "soft" costs quickly accumulate. Maintenance is expensive. 20% of Tesla superchargers in San Fran Sicko are "non-working."

Installing a residential level-2 charger isn't just a matter of plugging it into a wall outlet. A 115 volt charger charges an EV at about five miles per hour. A 240 volt charger charges at about 18 miles per hour. Wiring in older homes might be entirely unsuitable for installing home chargers. For comparison, if you spend six minutes filling a 400-mile tank in an ICE, you've "charged" it at 4,000 miles per hour.

EVs are proposed as adjuncts to a fixed electricity storage system, to try to help make unreliable solar and wind generators practical (it's impossible; see Chapter 8). But most EV chargers and utilities are not set up for two-way power [11].

All vehicles now contain enormous amounts of software – even more so in EVs. A Ford F-150 has 150 million lines of software. The Ford Lightning has even more. EVs are designed for over-the-air software upgrades. Cell service in rural areas is spotty. So if Ford or GM or … finds a catastrophic bug, when will the driver get the upgrade? Software in public EV charging stations is already a target for hackers. With over-the-air software upgrades, software in vehicles will also be a target, or maybe it already is a target.

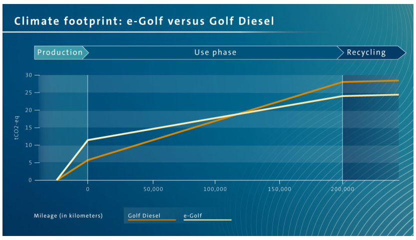

Figure 4.2: Comparison of the carbon footprint of e-Golf and Golf diesel

A system analysis shows that EVs might produce more CO_2 emissions in their lifetimes than ICE vehicles. As shown in Figure 4.2, producing a diesel VW Golf emits 6 tonnes (6,000 kilograms) of CO_2. Producing an electric VW Golf (including its battery) emits 12 tonnes of CO_2. Counting CO_2 emitted to produce the electricity to charge the e-Golf (using the German power mix), if both cars were scrapped before 78,000 miles, the diesel Golf would have emitted less CO_2 in its service life than the e-Golf. Marko Gernuks, Volkswagen's Head of Life Cycle Optimization wrote "compared to a Golf diesel, the e-Golf has a greater carbon footprint in terms of production, but wait: After 125,000 kilometers on the road, it surpasses its brother and has a lower carbon footprint." Using the power mix of China or India, it is unlikely the e-Golf would last long enough to produce less CO_2 in its service life than a diesel Golf. Just to analyze a tire, Gernuks says that Volkswagen takes into account hundreds of factors in 14 processes. The article did not clarify whether the added tire, brake, and road wear due to the 25-33% greater axle weight of the e-Golf were part of the analysis [33].

Activists are pushing to get high-mileage drivers into EVs because that population uses 32% of all gasoline. In heavy-duty long-distance use, the warranty on an EV battery expires in 3.5 years. Replacing a Ford Lightning battery pack costs $28,446 to $35,960. High-mileage drivers are mostly the people who can't afford an electric vehicle, or a new battery for one: Gardeners, carpet installers, electricians, janitors, HVAC technicians, ….

If an EV is involved in a collision, it's impossible to certify the battery is still safe to use, or to repair it [10]. It needs to be entirely replaced. If a damaged battery is left in place, it can catch fire. Battery fires also happen for many other reasons, including overheating during charging and driving. The reasons for some fires are entirely unknown. Many EVs that survived after hurricane Ian battered Florida on 23 September 2022 burst into flames because of salt water damage. Extinguishing a lithium ion battery fire requires about forty times more water than extinguishing a fire in an ICE vehicle – if it can be extinguished at all. It's like trying to quench a rocket engine using a fire hose. You might remember that the Soviet submarine Kursk was damaged and sank because a rocket-propelled torpedo caught fire in a launch tube. A rocket contains both fuel and oxidizer – and so does a lithium ion battery. After a lithium ion battery fire is extinguished (or extinguishing the fire was attempted and failed), all the water that runs off is contaminated with highly toxic materials, and much more of them than after extinguishing an ICE vehicle fire.

EV battery ranges vary but are generally inconveniently short. Actual ranges average 12.5% worse than listed on price stickers, while ICE vehicles average 4% better ranges than their stickers claim. Battery life and range depend very much on temperature and load. If the temperature is hotter or colder than average, mileage reduces significantly. Hotter climates and fast charging can overheat a battery and reduce life expectancy significantly (or it might catch fire). Driving an EV during the winter might unexpectedly leave you stuck in the cold. Using accessories such as an air conditioner, heat, or even a radio, can significantly reduce range. Towing a trailer can reduce mileage by as much as 70% [19].

Part of Jacobson's dream involves electrolytically-separated hydrogen. Generator-to-road end-to-end energy efficiency for battery-powered EVs is about 77% (95% transmission, 90% charge, 90% discharge). Using hydrogen fuel cells in EVs, the end-to-end energy efficiency is reduced to 22%, which means that four times more generating capacity would be required. The capacity factor for wind in 2022 was 36.1% [3, Table 6.7b], so the end-to-end capacity factor for wind-and-hydrogen powered EVs would be 7.9%. As will be shown in Section 6.1, even building a system to supply battery-powered EVs poses an insoluble problem for quantities of materials. Hydrogen has other problems. It's difficult to store because it passes through essentially any metal, embrittling it on the way by damaging the crystal and grain microstructure. The usually proposed way is to compress it to 10,000 PSI, about three times the pressure in scuba tanks. It becomes more viscous at high pressure, which increases distribution cost in pipelines. Jacobson proposes cryogenic (cold liquified) hydrogen for airplanes – the same fuel used in the space shuttles. Hydrogen is more dangerous than natural gas (which is much easier to store). The explosive range in air is 4% to 96%, while for methane the range is 46% to 54%. Hydrogen eventually has a place, but as a component of synthetic hydrocarbon fuels, as will be explained in Chapter 10.

4.2.5 Transmission

Electric power is the product of voltage (denoted by E for *electromotive force* in engineering parlance), and current (denoted by I for *intensity*), that is, $P = EI$. Voltage is like pressure in a water pipe, and current is like flow rate. The difference between high and low electric power is like the difference between the output of a fire hose and a garden hose. The fire hose has both higher pressure, and higher flow rate, than the garden hose. Ohm's law relates voltage, current, and resistance, as $E = IR$, where R is resistance. Substituting Ohm's law into the power relation, the loss during transmission and distribution is seen to be $P = I^2R$, that is, the power loss is proportional to the square of the current. But as is seen from the first relation, the same power can be delivered by increasing the voltage and reducing the current. Resistive loss is decreased in proportion to the square of the increase in voltage. This is the reason that electric power is transmitted and distributed at high voltage.

The electric power system as shown in Figure 4.3 can be broadly divided into four categories: Generation, transmission, distribution, and consumption. The difference between transmission and distribution is that transmission uses much higher voltages, and longer distances. The U.S. transmission system has more than 600,000 circuit miles (960,000 km) of alternating current transmission lines, of which about 240,000 miles (384,000 km) operate at voltages above 230,000 volts (230 kV). It moves electricity from large generators to consumer centers, and provides redundancy. The distribution system comprises about 5.5 million circuit miles (8.8 million km) [22].

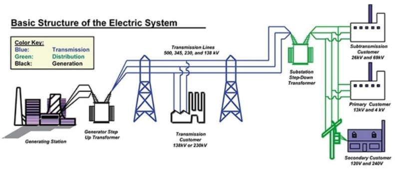

Figure 4.3: Electric Power System

The National Transmission Needs Study [1] used an obscure unit, the gigawatt-mile (GW-mi), a product of the length of a transmission line and the power it can deliver, to describe new transmission needs.[b] They admit it "is a convenient unit for capacity expansion models but is not a common practice in industry." The study says the median new requirement by 2035 is 48,840 GW-mi. This would expand the length of the existing long-distance transmission grid by 57%. For complete electrification, one result quoted in the study was 813,000 GW-mi.

Because the report did not specify the voltages and line lengths of each new proposed GW-mi of transmission capability, it is difficult to estimate the total amount of new transmission lines advocated, so the estimate of a 57% increase is used. The current U.S. high-voltage transmission system comprises about 240,000 miles (384,000 km). A 57% increase would require 138,000 new miles (221,000 km). The recent rate of ex-

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[b] From [1, p. v]: "Gigawatt-mile (GW-mi) is not a commonly used unit in the industry, but is the unit used by capacity expansion modeling results. For comparison, a 100-mile 345kV rated transmission line has an estimated carrying capacity of 860 MW, equivalent to 86 GW-mi (NRRI 1987). And a 200-mi 500kV line has a carrying capacity of 1,320 MW, equivalent to 264 GW-mi (NRRI 1987)."

pansion has been about 1,700 new miles (2,720 km) per year. So the projected increase would require eighty years. It is not going to occur by 2035. If the necessary increase is really 813,000 GW-mi, the line-length increase is 2.3 million miles (3.7 million km), assuming the same relationship between line length and GW-mi increase. At today's construction rate, this would be completed in 1,350 years.

A significant difficulty in building new transmission lines is that permits are required from about 30 different federal, state, and local agencies, and getting most of those permits requires public hearings. There is frequent local opposition, including from rural property owners who do not want power lines and their access roads to cross their property. Senators Sheldon Whitehouse (D-RI) and Mike Quigley (D-IL) have proposed to create a new siting authority within FERC that would "ease" the regulatory process of building new transmission and ease and increase the use of imminent domain, that is, that would transfer more power from local and state governments to unelected bureaucrats who work for the federal government.

There are also physical limits and supply chain constraints. For example, 2.3 million miles (3,680,800 km) of new transmission lines, a 767% increase of the 240,000 kV transmission grid, would require 1.5 million tonnes of copper (assuming 400 kg per km). If the part of the high voltage transmission grid that operates below 240,000 kV needs to be similarly increased, 4.4 million kilometers are needed. If the 8.8 million kilometer distribution grid needs to be similarly increased, 67.5 million kilometers are needed, requiring 27 million tonnes of copper. 67.5 million kilometers is 177 times the distance from the Earth to the Moon.

Table 4.2: Transmission line capacities (MW)

Miles	138 kV	161 kV	230 kV	345 kV	500 kV	765 kV
50	145	195	390	1,260	3,040	6,820
100	100	130	265	860	2,080	4,660
200	60	85	170	545	1,320	2,950
300	50	65	130	420	1,010	2,270
400	NA	NA	105	335	810	1,820
500	NA	NA	NA	280	680	1,520
600	NA	NA	NA	250	600	1,340

The amount of power that can be transmitted using a high-voltage AC transmission line decreases as the distance increases. Table 4.2 from [1, p. 88] shows the relationship between line voltage, line length, and power carrying capacity.

There are several criteria that utilities use to determine the limits of the lengths of their lines. Thermal effects limit the power that can be delivered over short lines. Voltage can increase along a line by a phenomenon called the Ferranti effect. This is more pronounced in underground lines because of the larger shunt capacitance due to conductors being closer together. It becomes a maximum when the line approaches one quarter of the wavelength of the AC voltage, 60 Hz in the United States, about 1250 km (780 miles). If the voltage increases too much, the grid becomes unstable. Voltage stability limits line length to 588 km (367 miles) [18]. Voltage quality and angular stability (the phase difference between voltage and current due to the reactance of the line) effectively limit line lengths to 480 km (300 miles) [15]. Most of these limitations are independent of line voltage.

High-voltage DC lines can transmit power over much longer distances, being limited primarily by thermal (resistive) losses because the Ferranti effect does not occur. Voltage and current are not alternating, so there is no "phase" and therefore no angular stability limit, except during rapid power transients.

DC voltage levels cannot be changed by transformers. Therefore, the voltage of the power produced by a generator must be AC, then stepped up to the transmission voltage by a transformer, then converted to DC. At the receiving end, it must be converted back to AC, and then stepped down to the voltage of a different transmission line, or a local distribution grid, by a transformer.

When high voltage DC transmission lines were first built, power was converted from AC to DC by expensive and reliable motor-generator sets that required a lot of maintenance. Later, AC was converted to DC by less expensive mercury vapor arc valves. These are very robust and reliable, but also required high maintenance. When they wear out, they are toxic waste. At the other end of the line, DC to AC conversion also originally used motor-generators sets, but these were replaced by thyratrons, which are also robust and reliable, but even more expensive then mercury vapor arc valves. They also contain mercury. In newer systems, or as replacements in older systems, insulated-gate transistors (IGTs) are used. Unlike mercury vapor arc valves and thyratrons, the breakdown voltages of IGTs are much less than the system voltage, so hundreds of them are used in series. In both the old and new systems, switching produces a square wave, which would induce significant losses in transformers and produce high-frequency electromagnetic (radio and TV and cell phone and…) noise, so expensive filters to convert to sinusoidal variation must be included. There are also losses in the filters.

Both the old and new devices to convert AC to DC, and DC to AC, are expensive, but their cost can be overcome for longer transmission distances because the cost of a DC transmission line is less than an AC transmission line with the same power capacity. The primary reason for this is the *skin effect* described in every electric power system engineering textbook (and [17, §32-7], [23, p. 27]). An important figure of merit for an electrical conductor is *resistivity*, which is an intrinsic property of the material. The units are ohms times meters. The resistance of a fixed length of a conductor is the resistivity divided by the cross sectional area through which current flows. If power is conducted throughout the entire volume of the conductor, resistance decreases as the square of the radius. AC power travels only along the surface of a wire, penetrating only a small fixed distance, which depends upon frequency and material but not voltage or current. That is, the resistance decreases as the radius of the conductor, not as the square of the radius. The interior of the wire is not used and is essentially wasted. In some systems, tubes are used. Tubes are usually steel-reinforced aluminum because copper tubes are not as strong. But the resistivity of aluminum and steel are significantly greater than copper, so resistive heating loss is greater for conductors of the same size. With DC, the entire wire transmits power. The cost of AC-DC and DC-AC conversion can also be overcome if the generator produces power at a lower cost than is available at the consuming end of the line. For example, the Pacific Intertie is 1,361 km (850 miles). It connects Celilo, WA, where Grand Coulee, Chief Joseph, and Bonneville dams – and the Washington Nuclear Generating Station – provide low-cost electricity, to Sylmar, CA, where more expensive combined-cycle gas turbines would be needed.

4.2.6 Electromagnetic pulse vulnerability

Every eleven years, or so, the Sun belches out several trillion cubic miles of intensely hot plasma. Every sixty six years, or so, it hits the Earth. When it hits the Earth's magnetic field, it produces an enormous electromagnetic pulse (EMP).

The "Carrington Event" in 1859 was caused by a solar EMP. Aurora were seen in Cuba. Telegraph operators discovered that their sets worked without the batteries attached. A few operators were electrocuted. In 1859, the only infrastructure that was affected was the telegraph network.

There was a similar event in 1969. Instead of only the telegraph, telephone and electricity transmission and distribution systems were affected. Wiring was melted. Circuit breakers were tripped, and many were damaged. Switch gear was damaged. Transmission, substation, and distribution transformers were damaged. Recovery from blackouts took more than a week in some areas.

As we saw in Section 4.2.5, converting to an all-electric energy economy will require enormous expansion of the transmission and distribution networks. That will make for a much larger EMP antenna, collecting energy more broadly, and spreading damage more intensely and broadly. All the tiny wires in solar panels will become tiny blown fuses. Damage will be immense. Recovery will take decades. Most of the wiring to connect wind turbines is necessarily underground, until it gets to a collection point, where it is connected to the transmission system, so it might not be directly affected – but individual wind turbines are vulnerable, and an EMP collected in the transmission grid can be transmitted into the underground cables.

4.2.7 Distribution

Replacing ICE vehicles with EVs, and converting domestic heating to heat pumps, will put enormous stress on electricity distribution. Transformers are designed to cool passively at night. After a transition to EVs, people will arrive home from work and plug in the EV, so transformers, from the "pole peg" in your back yard to the pad-mounted behemoth in the substation down the street, don't get a chance to cool. This will reduce the current average lifetime of distribution transformers from thirty or forty years to three or four.

The average 37.5 kVA[c] distribution transformer supports 15 households, assuming each draws 2 kVA, on average. A level-2 EV charger draws 12-19 kVA. Activists also want to switch domestic space and water heating from gas, propane, and fuel oil to heat pumps, which draw 4-6 kVA. Heat pumps contain motors, which shift the phase relationship between load voltage and load current. To compensate for this, the distribution system must increase investment in *power factor* correction. Instead of an average per-home load of 2 kVA, it will become 6-8 kVA, surging to 27 kVA when the EV gets plugged in. Assuming the EV is charging for eight hours, instead of 2 kVA, the average load would be 10-14 kVA. With an average load of 14 kVA per household, a 37.5 kVA distribution transformer could serve 2.7 households. But most of them would have an EV plugged in simultaneously with its neighbors. So instead of serving fifteen homes, a 37.5 kVA distribution transformer could serve 1.4 homes. Put another way, power companies would need to install 13.5 times more distribution transformers, or much bigger ones. Either way, about 150 million power poles would need to be replaced with bigger and stronger ones.

All of this assumes, of course, that the high voltage local distribution network, and the very high voltage long distance transmission network, can transmit and distribute the necessary power. The local distribution network would need to be converted to higher voltage, or be upgraded to carry much higher currents. As seen in Section 4.2.5, the power loss due to resistive heating increases as the square of current, so higher distribution voltage is desirable. But higher voltage distribution lines have higher cost per ampere, which is not entirely offset by less resistive loss.

ERMCO Distribution Transformers, a division of Arkansas Electric Cooperative Corporation that is based in Dyersburg, Tennessee, one of America's biggest manufacturers of distribution transformers, makes about 25% of all utility transformers sold in the United States. They can't hire enough workers to keep up with demand. They made more transformers in 2020 than in any other year, and almost as many, 425,000, in 2020. They had to work so much overtime in 2021 that 700 workers quit. They hired 1,000 more, but would like to hire 600 or 700 more than that. Buddy Hasten, the ERMCO CEO, said "Getting the labor to make these things is everybody's challenge. This is not

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[c] kVA means *kilo volt ampere*. If voltage and current are in phase, one watt is one volt times one ampere. So "kVA" is roughly equivalent to kilowatt.

transitory."

A utility transformer requires a special kind of steel, called *grain-oriented electrical steel* or GOES, a paper-thin product containing about 3% silicon. The silicon improves its "soft magnetic" properties, and reduces losses. The supply is not meeting the demand [32]. 80% of GOES is made in China, Japan, and South Korea. One American company, Cleveland-Cliffs, makes GOES. U.S. Steel is tooling up to make GOES. The same steel is used in EVs, the motors in heat pumps, and wind generators, putting further stress on the supply. Multiplying the problem, the U.S. Department of Energy has mandated increasing the efficiency of utility transformers from 95% to 96% [35]. This requires a new kind of steel, called amorphous steel. There are no American companies that make amorphous steel. Of the new regulation, Theresa Pugh, head of Virginia-based Pugh Consulting, wrote [9]

> Distribution transformers are already regulated to meet energy efficiency. Seeking the additional de minimis 1% is an incredible waste of private sector money, investment, re-design of transformer manufacturing, resulting in reliance upon ONE steel company. Most of all it is a waste of time and makes supply chain problems worse.

Further multiplying the problem, no American company makes the large substation-size transformers. Transformers aren't the only problem. The cost of everything involved in electricity transmission and distribution is increasing, as shown in Table 4.3 [9].

Table 4.3: Cost Increases for Specific Utility Products

	2021	2022
Anchors, rods, nuts	57%	58%
Copper, tie, strand wire	44%	45%
Pad-mounted transformers	28%	47%
Pole-mounted transformers	17%	15%
Wood poles	25%	46%
Insulators	3%	77%

When EVs and heat pumps increase the local electric power load, that load gets pushed upstream to the local substation, which will need to transmit more power. Transmitting that power will require more and larger substations, and either higher local distribution voltage, or higher current. Either way, about 5.5 million miles of local power lines will need to be upgraded, one million miles of new long distance high voltage transmission mines will be needed, and 140,000 miles of aging lines will need to be replaced by 2050. To put that in perspective, between 2010 and 2020, only 18,000 miles of new transmission lines were added to the U.S. grid [11]. A detailed investigation of materials appears in Section 6.1. Just a preview of that analysis is that 400 kilograms of copper are needed per kilometer of high voltage transmission line. 640,000 tonnes of new copper will be needed for new lines. The amount needed for upgrades depends upon the goals to transmit additional power. Higher currents require thicker wires, or more of them running in parallel. Look carefully at high voltage transmission lines. You will frequently see two, three, or four wires in parallel for each branch of the circuit, where only a few years ago there was only one. It will be difficult to produce 640,000 tonnes of new copper because the Biden administration has denied essentially all new permits for mines, only about one or two of every thousand "strikes" turn out to be economically exploitable, bringing a strike into production typically takes about twenty years, and 20-30% of operating mines lose money and shut down [24].

Utility commissioners and their staffs are now dealing with rising workloads with limited staff, limited resources, and growing gaps in internal expertise due to the increasingly specialized needs of today's energy system, and dysfunction of American education. The lack of relevant legal or industry expertise is increasingly worrisome, and may become a major operational and legal problem.

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Chapter 5

Minor players

Round up the usual suspects
– Captain Louis Renault, *Casablanca*

Geothermal

It is remotely possibile that geothermal generation can produce significant amounts of energy, but as of 2022, the U.S. Energy Information Administration (EIA) has projected a growth of only 4 GWe between 2022 and 2050 [12]. The assertion that it is useful everywhere is based upon a false generalization. It is useful in Iceland because it is available at shallow depths and the population is small. This combination is not true in other places such as New York or Hong Kong. It might be useful below Yellowstone National Park, but read Section 4.2.5 again. The 15 November 2017 magnitude 5.5 earthquake in Pohang, South Korea, was blamed on a geothermal power plant. Earthquakes are very rare in Korea [13].

Biofuel

Corn ethanol provides 1% of American surface transportation motor fuels using 10% of currently harvested American cropland, or 1.8% of the land area of the contiguous 48 states. Providing all surface transportation motor fuels from corn ethanol would require 180% of the land area of the coterminous United States. Somehow, I do not envision amber waves of grain from Salt Lake City to Phoenix – of from Fairbanks to Barrow.

J. Craig Venter, a member of the first team to sequence the human genome, has teamed up with ExxonMobil to investigate using algae to make biofuels. The research team has modified *Nanochloropsis gaditana* to increase the lipid (fat and oil) content from 20% to more than 40%. They are careful to stress that this is deep research and a "proof of concept approach.” Vijay Swarup, a vice president at ExxonMobil, was quoted as saying “There’s still a long way to go in making an algae that can produce even more fat, live comfortably in saltwater pools outside, and be processed into fuel for cars, planes and trains” [5]. Articles that hype algae do not provide any estimates of the land area required, or explain how algae could be contained and harvested if grown at sea, or the environmental consequences if the algae escaped.

Between 2005 and 2012, dozens of companies managed to extract hundreds of millions of dollars from venture capitalists to pursue fuels from algae. The promise of algae is tantalizing, but today, most algae companies have switched to more expensive algae byproducts such as cosmetic supplements, nutraceuticals, pet food additives, animal feed, pigments, and specialty oils. The rest have gone bankrupt or moved on to other businesses. In 2017, while he was Secretary of State, Rex Tillotson, who formerly had been president of ExxonMobil, said that commercializing significant quantities of motor fuels from algae was at least 25 years in the future. Six years later, it still is.

Biomass

Biomass fuels consist of solids such as wood, crops grown for the purpose, crop residues such as bagasse from sugar production, animal dung, and indirect residues such as municipal waste. After EU approved the use of wood for electricity generation, as a renewable fuel, coal-fired power plants, especially in Britain, began using wood pellets. This would be a reasonable carbon-neutral energy source, if the wood pellets were consumed at the same rate as they are produced. But they’re being consumed much faster. Southeastern American forests, from the Carolinas to Louisiana, are disappearing into European power plants. The “renewable” argument is that the carbon dioxide produced by burning wood will be taken up by other trees. The defect in this argument is that a large power plant can burn more wood in a week than a forest can produce in twenty years – if the forest ever recovers. Burning wood isn’t really “green” because, per kilowatt hour, it emits more CO_2, more air pollution, and more solid waste, than burning coal.

Hydro

Figure 2.1 shows show that in 2021, hydro provided 6.2% of nationwide electricity, or about 2.3% of total energy. Good sites for hydro generation have already been exploited. Environmentalists want to remove dams, not build new ones. As of 2022, the U.S. Energy Information Administration has projected a label capacity growth of only 200 MWe between 2022 and 2050 [12]. Some growth is projected by adding generators to dams that do not now have them. But growth will be difficult to envision if dams continue to be removed. Four U.S. dams were scheduled to be removed on 237 miles of the Klamath River, one in Southern Oregon and three in Northern California: the Iron Gate, Copco #1, Copco #2, and J. C. Boyle dams make up the Klamath River Hydroelectric Project. This is the largest dam removal project in history. The reason given is to open hundreds of miles of salmon and steelhead spawning habitat. Fish ladders, such as at Bonneville Dam near Portland, Oregon, would work as well on the Klamath River as they do on the Columbia River. An alternative to reservoir dams with fish ladders is run-of-the-river power plants, such as at Grand Coulee on the Columbia River. But even there, activists opposed adding more turbines.

PacifiCorp's 169 MWe (label capacity) Klamath River Hydroelectric Project (FERC No. 2082) is in a predominantly rural area. It consistently generated 716 gigawatt hours per year, or average output of 81.7 MWe – enough for approximately 70,000 households [10]. The capacity factor was 48%

If a dam requiring 400 times more material than Hoover Dam were to be built across the 400-meter-deep Straights of Gibraltar, and the level of the Mediterranean were to be reduced by 100 meters during the next cenury, and then dams were built at the Bosporous and the mouths of Mediterranean tributaries, 36 GWe could be produced, but that it would be difficult to use this electricity beyond Spain, Portugal, and Morocco [11, p. 255]. Total average European electricity consumption in 2022 was 318 GWe, so this project could replace only about 11% of 2022 generation. Hans Thirring estimated that if all economically-exploitable hydroelectric resources were to be harnessed, they would satisfy 80% of electricity demand in 1960. He remarked that electricity demand would increase, which it certainly has, and also that electricity is only a fraction of total energy demand [11, p. 258].

Ocean currents

In notes for a Physics 239 class at the University of California at San Diego [9], the late Professor Frank Hsia-San Shu provided estimates for the amounts of electricity that could be generated by ocean currents, ocean waves, ocean tides, and geothermal generators.

Ocean currents are largely driven by wind (Ekman) drag over the ocean's surface (as pointed out by oceanographer Walter Munk [8]). Ocean waves are created by instabilities that result from friction when wind blows over water. Therefore, they both derive their power from wind, but water is 800 times more dense than wind so one might expect it to be easier to extract energy from ocean currents than from wind.

As one example, Professor Shu computed that where the Kuroshio current flows northward from Taiwan toward Japan, it has a power of about 100 GW. Assuming 50% efficiency of marine turbines to extract this energy in the form of electricity, the maximum extractable power is 50 GWe. Of course, only a tiny fraction of this can be extracted because it would be necessary to suspend generators across the entire depth and width of the current.[a] If more than a tiny fraction were to be extracted from the Kuroshio cur-

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[a] A turbine cannot extract all the energy in a fluid flow because, if it stopped the flow entirely, there

rent as it flows past Taiwan, it would have a profound effect on the climate and marine fisheries of Japan. The same consequence holds for every ocean current. For example, if a significant amount of power were to be extracted from the gulf stream, the climate of Europe would become more like the climate of Canada.

Ocean tides

The differential attraction of the gravity of the Moon on the near and far sides of the Earth lifts the oceans' surfaces relative to the surrounding land by 0.5 meters every 12.5 hours = 45,000 seconds. The surface area of the oceans is 3.8×10^{14} square meters and the density of pure water is 1,000 kilograms per cubic meter (2–3% more for seawater). The total mass of water involved is (0.5 meters) × (3.8×10^{14} square meters) × (1,000 kilograms per cubic meter) = 1.07×10^{17} kilograms. Each element of the mass of the oceans is displaced from its mean position by 0.25 meters every 45,000 seconds against the gravitational field of the Earth, for which the acceleration at the Earth's surface is 9.8 meters per second squared. The total power associated with the oceans' tides is therefore (1.7×10^{17} kilograms) × (9.8 meters per second squared) × (0.25 meters) / 45,000 seconds = 9.3 TW. Most of the energy of this displacement is in deep oceans were it would be difficult to tap. If we assume that we can tap this energy only within 2 kilometers along the four north-south shores of length 20,000 kilometers along the major continents, we then have access to only a fraction, 3.1×10^{-4} of 9.3 TW, or only about 3 GW. The efficiencies to tap this power can be as high as 80%, but only where funnel-shaped bays concentrate the displacement of the tides.

One scheme proposed to put a device across the Bay of Fundy between Nova Scotia and Maine to let the tides flow into and out of the bay through turbines. The scheme was abandoned when analyses showed that the resonant frequency of the entire tidal basin, from Nova Scotia to Cape Cod, would be changed significantly. This would have had serious environmental consequences.

Ocean thermal gradients

Exploiting ocean thermal gradients to produce power was first proposed in 1881 by Jacques Arsène d'Arsonval, a French physicist, engineer, and inventor [4]. One of his students, Georges Claude, built a 22 kWe system in Matanzas, Cuba in 1930. It was destroyed in a storm. He then constructed a plant on a 10,000 ton cargo vessel moored off the coast of Brazil in 1935, but it was destroyed by waves and weather before it generated net power. Tokyo Electric Power Company built a 120 kWe power plant near the island of Nauru, a microstate in Oceania about 300 km from Tuvalu. 90 kWe were required to operate the plant, with the remaining 30 kWe sold to a local village and school.

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would be no fluid motion to operate the turbine. Albert Betz computed the maximum to be 57% [1].

Thermal gradients in the oceans contain enormous amounts of energy because oceans are so vast. The thermal efficiency formula developed by Sadi Carnot is $\epsilon = (T_{\text{out}} - T_{\text{in}})/T_{\text{out}}$ [2]. In the ocean, thermal gradients are small. T_{in} is about 24°C (297°K), and T_{out} is about 4°C (277°K), so the maximum thermal efficiency for ocean thermal gradient machines is about 6.7%. It is not possible that any machine can approach maximum theoretical efficiency. In practice, overall efficiency is unlikely to exceed 3%. This means that enormous devices would be necessary. It is not clear that they would produce more energy in their lifetimes than would be invested in fabricating, deploying, operating, maintaining, removing, destroying, and recycling them.

The U.S. Energy Research and Development Administration (ERDA), predecessor of the Department of Energy, granted contracts for investigation and development in the 1970's, but interest dwindled and the idea was abandoned. Since about 2010, interest has again increased, but there is no prospect that renewed interest, no matter how intense, can make the size of the necessary machines even a little bit smaller.

Newly proposed machines would use the more efficient Kalina cycle or the slightly even more efficient Uehara cycle, both of which use a large amount of ammonia and water, instead of the earlier proposed Rankine cycle machines, which would have used pure ammonia [7]. In either case, damage to the machines would have significant environmental impact.

Ocean waves

The regions of strong wave power are, not surprisingly, where strong east-west winds impinge upon north-south shorelines. Professor Shu estimated that 0.24 TWe could be extracted from the four long north-south shorelines of the Earth, having a combined length of about 20,000 km. A small town in England abandoned a planned wave power project when calculations showed that the train of hinge barges would stretch 32 kilometers out to sea. When the Oceanlinx wave generator at Port Kembla near Wollongong, Australia failed (shown in Figure 5.1), the eyesore was left to rust and rot until taxpayers paid $AU 7 million to remove it [6].

Figure 5.1: Wrecked ocean wave electricity generator at Port Kembla.

Nuclear fusion

The New York Times breathlessly reported that in a December 2022 experiment at Lawrence Livermore National Laboratory, a two megajoule blast from 192 lasers produced three megajoules of heat energy from the fusion of hydrogen atoms[b] [3]. What articles about this breakthrough failed to report, or reported dozens of paragraphs below the lede, is that before the blast, power supplies had slowly put 300 megajoules of energy into a bank of capacitors that were then discharged quickly into the lasers, to produce two megajoules of light energy. In other words, there was no system engineering. They also didn't report that the experiment damaged the apparatus. The heat from hydrogen fusion would be converted to electricity in the usual way, by steam turbines, with about 30% efficiency. So the 300 megajoules of electrical energy put into the capacitors represents 1,000 megajoules of heat energy – to inject two megajoules of heat energy into the fuel, producing three megajoules of heat energy, which would be converted to electricity with the usual 30% efficiency, yielding one megajoule of electric energy. They're still a factor of 300 from "breaking even."

The International Thermonuclear Experimental Reactor, now known as ITER, a pun on *iter* meaning "the way" in Latin, is under development near the Cadarache facility in southern France, between the villages of Saint-Paul-Lez-Durance and Vinon sur Verdon. It will use over 300 MW of electricity to inject 50 MW of heat into a deuterium-tritium plasma, hoping to cause a fusion reaction that will release 500 MW of heat for 400 to 600 seconds. In order to be a net producer of electricity, the subsequent process to exploit the heat would need to exceed 60% efficiency. Needless to say, ITER is not designed as an electricity power plant – rather only as a scientific experiment. The officially projected cost is €18 to €22 billion. Unofficial estimates exceed €65 billion which, of course, the project officially denies.

Regardless of the final price, ITER has been characterized as the most expensive scientific project of all time, the most complicated engineering project in human history, and one of the most ambitious international collaborations since the development of the International Space Station (€100–150 billion) and the Large Hadron Collider (€7.5 billion).

The first planned successor to ITER, called DEMO (DEMOnstration power plant), was planned to produce 2,200 MW of heat and 790 MW of electricity. The timelines for the successors to ITER, first DEMO, then EFDA (European Fusion Development Agreement), now EUROfusion, have slipped from operation in 2040, to 2048, to "some time in the 2050's."

The old quip that controlled thermonuclear fusion is fifty years in the future – and will be for a very long time – appears still to be true.

The only remaining serious proposals for energy sources alternative to coal, gas, and nuclear power plants are solar and wind generators. Before looking at them in detail,

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[b] The fusion was actually between two heavier hydrogen isotopes, deuterium and tritium. Deuterium is found in nature in "heavy water" but it is very rare. Tritium is radioactive with a half life of 12.33 years, so it must be produced continuously, either in the fusion reactors, or in fission reactors, by bombarding lithium with neutrons.

let's start near the beginning of a construction process by looking at estimates of the materials required.

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Chapter 6

Materials and their human and environmental costs

6.1 Quantities

One might envision that machines to extract energy from sunshine and breezes will spring fully formed from the forehead of Zeus, as did his favorite daughter Athena, but that doesn't usually happen. The machines must be constructed from materials, and those materials need to be mined or otherwise extracted from the Earth and then purified, or made from other materials with the same ultimate source (unless a herd of unicorns tows a serendipitous asteroid into Earth orbit and manages to get it down to the surface without destroying 95% of the life on Earth and creating another Chicxulub crater or 500-meter tsunami). A quantitative system engineering analysis must include these materials and their associated processing, including both the energy invested in extraction and processing, and the environmental effects.

Using the details of reports from IEA and others, that urge a spectrum of "technology units" to replace the existing energy generation and consumption infrastructures, Professor Simon Michaux has investigated the amounts of materials that would be necessary to replace all fossil fuel energy sources using renewable sources [12].

One step is to replace all fuel-based (internal combustion engine, or ICE) surface vehicles using electric vehicle technology (see Section 4.2.4). In 2019, it was estimated that 7.2 million electric vehicles (EV) were in use, while at the same time the total number of vehicles (exclusive of railroads) is about 1.416 billion. Only 0.51% of the current fleet are EVs, so 99.49% must be replaced. Unless someone has secret blueprints for electric airplanes and cargo ships, they will need liquid hydrocarbon fuels indefinitely (notwithstanding Jacobson's dream to use cryogenic hydrogen). More on this in Chapter 10. It is also likely that heavy construction, transport of items too heavy or large for railways, farming, and mining, will need hydrocarbon fuels as well.

Turning to the global energy supply system, Professor Michaux estimated that in 2019, fossil fuels provided 84.7% of energy, renewable sources such as biofuels, biomass, hydro, geothermal, solar, and wind provided 4.05% of electricity or about 1.6% of total energy, and nuclear power accounted for 10% of electricity, or about 4% of total energy. The scale of the challenges faced by the Great Green Energy Transition is obvious.

The general strategy is that all ICE vehicles will be replaced by EVs either using lithium ion batteries or powered by hydrogen fuel cells, and that primary energy in all forms will be replaced by electricity produced by biofuels, biomass, hydro, geothermal, nuclear, solar photovoltaic, wind, Amory Lovins's vigorous hand waving, Tinkerbell's magic pixie dust, or unicorn farts.

The mineral resources required to manufacture and service renewable technologies will be truly global in nature. No single nation or geographic region can be entirely self sufficient.

Dr. Michaux is a professor of Mining Engineering at Adelaide University and Geologian Tutkimuskeskus.[a] He obtained the list of "technology units" that the International Energy Agency demands must be emplaced to accomplish the Great Green Energy Transition. This includes generators, transformers, transmission lines and towers, switches, circuit breakers, insulators, batteries, ... For each category of units, he calculated the amounts of materials required.

Table 6.1: Materials for Lithium Ion Batteries for Firm Power in USA

Material	Proportion in batteries (%)	Mass in 8.34 billion tonnes of batteries	Global Reserves (2018)	Required ÷ Reserves
Copper	17.0%	1419	880.0	1.61
Aluminum	8.5%	709	32,000	0.022
Nickel	15.19%	1268	95.0	13.3
Cobalt	2.79%	230	6.9	33.8
Lithium	2.17%	181	22	8.23
Manganese	2.50%	208	1,700	0.123
Graphite	22.0%	1817	320.0	5.74

Professor Michaux estimated that 2,496,845,599 tonnes of lithium ion batteries will be required for electric energy storage, and 282,588,411 tonnes for electric vehicles. As will be shown below, storage to provide firm power from renewable sources in the United States alone, not counting electric vehicles, would require 8.34 billion tonnes of lithium ion batteries. Table 6.1 shows the amounts of materials required to produce those bat-

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[a] Geologian Tutkimuskeskus is in Espoo, Finland, not far from Helsinki. In Suomi, Geologian Tutkimuskeskus means Geological Research Center, but the English title they use is Geological Survey of Finland.

teries, assuming an energy density of 230 watt hours per kilogram [12, pp. 648–650] (amounts are millions of tonnes). Most of the amounts required, for batteries alone, exceed known reserves.

Table 6.2: Total Metal Required to Produce One Generation of Technology Units to Phase Out Fossil fuels

Metal	Total Needed (kT)	2019 Global Production (kT))	Years to Produce at 2019 Rate	Global Reserves (MT)	Fraction Possible	Rock ÷ Metal
Aluminum	299 739	63 136	4.7	15 400	5 133%	
Copper	4 364 689	24 200	180.4	880	19%	513
Zinc	35 704	13 524	2.6	210	588%	
Magnesium	500	1 120	0.4	7 072	1 414%	
Manganese	217 581	20 591	10.6	1 700	781%	
Chromium	6 773	37 498	0.2	565	8 341%	
Nickel	899 004	2 350	382.5	95	10%	250
Lithium	899 574	95	9 452.3	22	2.3%	1630
Cobalt	208 328	126	1 653.1	6.9	3.5%	895
Graphite	8 548 146	2 729†	6 778.8	320	3.6%	10
Molybdenum	1 102	277‡	4.0	16	188%	
Silicon*	49 571	8 410	5.9			
Silver	146	26‡	5.5	550		
Platinum	2.682	0.190‡	14.1	0.07	2 610%	
Vanadium	647 929	96‡	6 747.8	24	3.5%	1340
Zirconium	2 614	1 338‡	2.0	64	2 448%	
Rare Earth Metals						
Neodymium	965	24	40.4	8	829%	
Germanium	4 163		29 113	0.038	0.91%	
Lanthanum	5 971	36	166.8	6	101%	
Praseodymium	235	7.5	31.4	4	102%	
Dysprosium	196	1.0	196.2			
Terbium	17	0.280	59.9			
Hafnium	0.216	0.066	3.3			
Yttrium	0.216	14	0.0154			

kT = thousands of tonnes. MT = millions of tonnes. *Metallurgical silicon.
†Natural and synthetic combined. ‡Estimated from mining production.
All others are refined production values.
Rock-to-metal ratio from [13], except graphite from [17].

A summary of a few of the materials needed for the entire Great Green Energy Transition is shown in Table 6.2. The *Years to Produce* column is the number of years necessary to produce the materials necessary to build the demanded "technology units" at the 2019 production rate. The *Fraction Possible* column is the fraction of the demanded "technology units" that could be built if all of the Earth's known reserves were dedicated to building them. Where not shown, or where greater than 100%, the metal is not a "bottleneck" material – but praseodymium will be if there is any other reason for demand of it, and molybdenum is already in demand as an alloying metal in high-performance steels.

For copper alone, if production were to continue at the same rate as in 2019, the required amount could be produced in 189 years. The table shows further, however, that no increase in the production rate can meet the total requirement, in any length of time, because the amount needed is more than five times the total amount known or projected to exist in forms from which it can be extracted (the inverse of the *fraction possible* entry), or about six times the total amount that humans have so far extracted from the Earth. Only about one or two of every thousand "strikes" for copper turns out to be economically exploitable. Bringing a mine into production takes about twenty years, not least because of regulations and local opposition to environmental effects. The Biden administration has denied every new mine in the United States, or stopped development of every already approved one that had not started operation. 20-30% of producing mines lose money and shut down. Because the rock-to-metal ratio for copper averages 513, extracting 4,575.5 million tonnes of copper would require moving 2,347,231 million tonnes of rock and dirt. Professor Michaux did not provide an estimate of the energy required for mining alone, not including purification and fabrication into the forms required for the demanded "technology units."

Essentially all the lithium comes from Tibet and the Argentina-Chile-Peru triangle. Essentially all the cobalt comes from Chinese-owned or -controlled mines in Congo, where four-year-old children work for $2 per day. More than half the nickel comes from Russia. 70% of graphite comes from China.

Professor Michaux's analysis addresses only the construction of the first generation of "technology units." Base metals such as aluminum, copper, and iron are commonly recycled to a high degree of stream recovery using mature and economical processes. Gold, silver, and platinum-group elements can be recovered by more complex and more expensive processes, which are justified because of the greater economic value of those metals. Recycling technology metals is either not done at all, or not done well [11].

Recycling can only be done a limited number of times before it becomes ineffective. Natural laws of physics and thermodynamics determine the maximum achievable recycling rate as a function of the side-stream intermediate products. Recyclability depends not only upon the intrinsic properties of the materials, but also upon the quality of the recycling streams, and their economic value [15]. Material stream quality is determined by the material class (combination of materials, shredding, separation, . . .), particle size distribution, degree of liberation (multi-material particles), and efficiency of physical separation. Waste streams cannot be recycled indefinitely before they need to be valorized by some other means, such as increased prices, new material, or new technology.[b] This realization is not embedded in current thinking or legislation. The conclusion above is that even the first generation of demanded “technology units” cannot be constructed. The conclusion here is that the fraction of the demanded “technology units” that remain in service dwindles with time.

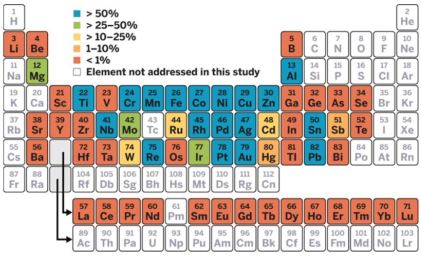

Figure 6.1: Recycling Rates of Metals. Data from [19] and [6]. Graphic from [11] with permission. http://creativecommons.org/licenses/by-nc-sa/4.0/

Figure 6.1 shows recycling rates as of 2011. Current rates would resemble these because recycling technology cannot be improved rapidly. Detailed tables of recycling rates are given in Appendices C, D, and E of [19].

Chapter 8 describes calculations of storage requirements to obtain firm power in California, the United States as a whole, and the European Union. The requirements are 1,216 watt hours per watt of average demand in California, 1,128 watt hours per watt in The United States as a whole, and 953 watt hours per watt in the European Union as a whole. The requirements for Denmark and Germany, taken alone, are not dramatically different. Activists insist an all-electric American energy economy would have average demand of 1.7 TWe (Jacobson estimated 1.6 TWe). Using the 1,128 figure, the storage requirement is 1.92×10^{15} watt hours. Using Professor Michaux’s figure of 230 watt hours per kilogram for lithium ion batteries, the mass of batteries for United States renewable energy storage alone is 8.34 billion tonnes, or almost three times Professor Michaux’s estimate for the entire worldwide economy. He was rather optimistic about the amount of storage that would be required to provide firm power.

“Bottleneck” commodities are not the only ones required. Solar power plants and wind turbines need steel and concrete.

Table 6.3: Lifetime outputs of electrical generators

Method	Lifetime Years	Capacity Factor	Capacity MWe	Total MWh in Lifetime	# to Match One Nuclear	Total MWe
Nuclear	80	93.5%	1,000	655,682,588	1	1,000
Coal	60	47.5%	1,000	249,825,585	2.6	2,625
Gas	40	56.8%	1,000	199,159,203	3.3	3,292
Geothermal	50	90%	1,000	394,461,450	1.66	1,664
Hydro	120	39.1%	1,000	411,291,805	1.6	1,594
Solar PV	25	24.5%	1	53,691	12,212	12,212
Wind	25	34.8%	5	381,313	1,719	8,598

---

[b] Tom Blees has an interesting idea: Vaporize materials, for example from landfills, using plasma torches powered by abundant nuclear power, and separate them by distillation [1].

Table 6.3 uses figures from [5] to compare the amounts of generating capacity that would need to be built to match the output of one contemporary 1,000 MWe pressurized water nuclear power plant during its lifetime. The lifetime estimate for geothermal power plants is 20–50 years; the most optimistic estimate is used here.

The total MWh generated in a plant's lifetime is the product of its lifetime (in hours, 8,765.81 per year), its capacity factor, and its label capacity. The lifetime of a nuclear power plant is given as eighty years. The Nuclear Regulatory Commission (NRC) license review period of 40 years was not changed when licensing authority was moved from the Atomic Energy Commission (AEC) on January 19, 1975. We have learned from the last half century of experience that the usable lifetime of a nuclear power plant is much longer. The number of units built to match one nuclear power plant is the total lifetime production of a nuclear power plant divided by the total lifetime production of another method of the stated capacity. The total label capacity that would need to be built during the lifetime of one nuclear power plant is the number to match the production of a nuclear power plant, times the label capacity of each generator.

Table 6.4: Materials needed for various electricity generation technologies [20, Table 10.4]

	Generation Technology						
Materials (tonne/TWh)	Nuclear PWR	Coal	Gas NGCC	Hydro	Solar PV	Wind †	Geothermal HT Binary
Aluminum	0	3	0	0	680	35	100
Concrete	760	870	400	14,000	350	8,000	1,100
Copper	3	1	0	1	850	23	2
Glass	0	0	0	0	2,700	92	0
Glue	0	0	0	0	3,700	0	750
Iron	5	1	1	0	0	120	9
Lead	2	0	0	0	0	0	0
Plastic	0	0	0	0	210	190	0
Silicon	0	0	0	0	57	0	0
Steel	160	310	170	67	7,900	1,800	3,300

PWR = pressurized water reactor, NGCC = natural gas combined cycle
PV = photovoltaic (silicon), HT = high temperature
† [20, Table 10.4] did not separate onshore and offshore wind.

Table 6.4 shows the total amounts of ten materials that would be needed by generators of each of seven types during their service lives.

Table 6.5: Capital costs for electrical generators

Method	Total MWe	Cost $/MWe	Total Cost $millions
Nuclear	1,000	8	8,000
Gas	3,292	0.8	2,634
Coal	2,625	3.5	9,186
Geothermal†	1,664	4.5	7,488
Hydro	1,594	4.5	7,174
Solar PV	12,212	1	12,212
Wind	8,598	2	17,195

† Geothermal plant cost is for 2020 from [2].

Table 6.5 shows capital costs to build generators to provide the same amount of energy that a nuclear power plant would produce in its lifetime.

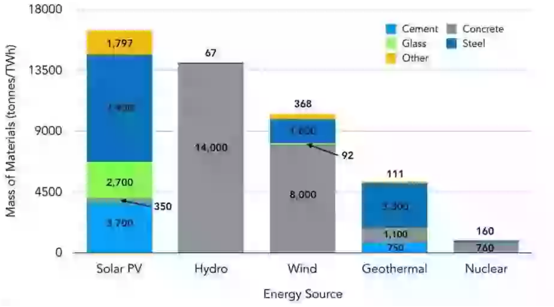

Figure 6.2: Lifetime Materials Requirements for Various Generation Methods (“cement” means “glue”)

Figure 6.2 shows the amounts from Table 6.4 in graphical form. Nuclear and hydro require 10 and 1 tonnes of other materials, respectively, amounts that are too small to show.

The EIA predicts annual generation growth rates of 7.9% for solar photovoltaic, and 1.9% for wind, between 2022 and 2050 in the United States. Only very small growth in outputs of other generation methods are predicted [18]. At these rates, 76 years would be required to produce a 1,700 GWe all electric all solar-and-wind energy system. Using the projected growth rates of 6.9% for solar photovoltaic capacity and 1.5% for wind capacity, after 76 years the label capacity of solar photovoltaic generators will be 8,063 GWe, and the label capacity of wind generators will be 405 GWe. Using the capacity factors from Table 6.3, their combined capacity will be 2.1 TWe, not 1.7 TWe. Capacity factors reported in [5] were taken from EIA publications that are clearly inconsistent with assumptions that the EIA used to compute the outputs predicted in [18].

Combining the figures from Tables 6.3 and 6.4 shows that 5.14 billion tonnes of steel and 152 million tonnes of concrete will be needed to reach and maintain label capacities of 8,063 GWe for solar photovoltaic and 405 GWe for wind. The United States produced 87 million tonnes of steel and 394 million cubic meters (about 800 million tonnes) of concrete in 2021. Concrete and steel are not “bottleneck” commodities – but they also do not have nonzero cost.

Many of the materials necessary for the Great Green Energy Transition come from China. Any country or other entity that the Chinese Communist Party disapproves of will not be eligible to receive these exports. Because China controls 80-90% of rare earth metals, 70% of cobalt, 50% of graphite, and significant amounts of lithium, this becomes a significant national security problem for countries whose decisions have resulted in dependency upon them. It is no secret that China understands this quite well.

If we agree that the energy system must contain only renewable generators, and no nuclear power plants, we could, in principle, end this monograph here because of the obvious physical impossibility of the project. There are some people, however, who believe that the developing world must remain poor (consider the examples that Michael Shellenberger provides in [16]), and who will nonetheless insist that the developed world (except China) must proceed with the Great Green Energy Transition.

6.2 Human and environmental cost of materials production

Most of the resources required to accomplish the Great Green Energy Transition come from poor countries, or from China, where there are no environmental controls, or at best very lax controls.

The "lithium triangle" area where Chile, Argentina, and Peru (and Bolivia) meet is the only place in the world where two species of High Andean Flamingos meet and breed. Copper mining in Chile has already impacted their breeding habitats, and the flamingos have largely abandoned some of them. Lithium is extracted from *salares*, or salt flats, using water. Lithium brines typically contain less than 0.1% lithium, so significant amounts of water must be used – about 580,000 liters of water per kilogram of lithium. Water scarcity has led to conflicts between local communities, local governments, mining companies, and national governments. Some indigenous peoples have been forced from their ancestral lands [17].

The Katanga region of the southeastern corner of the Democratic Republic of Congo (DRC) holds more known reserves of cobalt than the rest of the world combined [9]. In 2020, 74% of worldwide production of cobalt was from the DRC. Australia produced 3%. Other producers include Cuba, the Philippines, Russia, Canada, and Papua New Guinea [3].

Most of the cobalt mines in the DRC are owned, controlled, or operated by Chinese interests. The mining giant China Molybdenum bought one of the world's largest cobalt mines, Tenke Fungurume, located in southeastern Congo, from the U.S. company Freeport-McMoRan in 2016. Today, Chinese companies control 60 percent of global cobalt reserves and 80 percent of the world's cobalt refining capacity [24]. They insist these are all industrial mines, but the "artisanal" share is likely more than 30% [9]. "Artisanal" means that boys as young as four years old are working the mines using picks, hammers, shovels, and baskets, without shoes or safety equipment. The only reason that girls aren't working too is because they're not considered to be strong enough for the heavy work.

Siddharth Kara wrote that the Congo is still being exploited as a "vast subclass of humanity continues to eke out a subhuman existence in slave-live conditions at the bottom of the global economic order. Less has changed since colonial times than we care to admit." The cobalt mines in Katanga are incredibly dangerous:

> Hearing secondhand testimonies was one thing, but when I finally saw the tragic consequences of a tunnel collapse with my own eyes, it was utterly devastating. Sixty-three men and boys were buried alive in a tunnel collapse at Kamilombe on September 21, 2019. Only four of the sixty-three bodies were recovered. The others would remain forever interred in their final poses of horror. No one has ever accepted responsibility for these deaths. The accident has never even been acknowledged. This was the final truth of cobalt mining in Congo: the life of a child buried alive while digging for cobalt counted for nothing. All the dead here counted for nothing. The loot is all....
>
> Our daily lives are powered by a human and environmental catastrophe in the Congo. [9].

Cobus van Staden wrote that

> The dirty secret of the green revolution is its insatiable hunger for resources from Africa and elsewhere that are produced using some of the world's dirtiest technologies. What's more, the accelerated shift to batteries now threatens to replicate one of the most destructive dynamics in global economic history: the systematic extraction of raw commodities from the global south in a way that made developed countries unimaginably rich while leaving a trail of environmental degradation, human rights violations, and underdevelopment all across the developing world.... As battery metals take on a strategic significance in many ways similar to the central role long played by oil, it will be very hard for developing countries with significant resources to keep their development trajectories from being hijacked by geopolitics [24].

Congo has vast mineral resources. Development of those resources could be key to development in all of Africa. But Congo is landlocked. A big problem in Africa is trans-border transportation infrastructure.

Chinese interests are connecting resource-producing regions of central Africa, especially Congo, to seaports, for onward shipment of raw materials to China for processing. A Chinese-built 830-mile rail line recently connected southern Congo to the Angolan port of Lobito on the Atlantic coast.

Several East African countries are jockeying for funding to connect Congo to ports on the Indian ocean. Chinese mining interests promised social infrastructure development such as schools and hospitals as part of major minerals deals, but these promises have so far been slow to appear, if at all. The result is no different from European colonial exploitation in the nineteenth and early twentieth centuries. The Chinese are even worse for Congo than King Leopold II of Belgium was. There is a reason DRC changed the name of their capitol from Leopoldville to Kinshasa.

Li et al estimated that production of rare-earth (RE) metals – largely neodymium, praseodymium, terbium, and dysprosium for production of permanent-magnet electricity generators – must increase 11 to 26 fold to meet wind-power targets [10]. They did not analyze requirements for vehicle targets. Many governments consider REs to be protected and strategic mineral resources. Rare earth magnets are difficult and expensive to recycle, especially ones from offshore wind turbines that have broken and fallen into the sea. There are significant losses during remelting and recasting.

Simon Parry from the Daily Mail traveled to Baotou, China, to see the mines, factories, and dumping grounds associated with China's RE industry [14]. What he found was frightening and disgusting:

> As more factories sprang up, the banks grew higher, the lake grew larger and the stench and fumes grew more overwhelming.
>
> "It turned into a mountain that towered over us," says Mr Su. "Anything we planted just withered, then our animals started to sicken and die."
>
> People too began to suffer. Dalahai villagers say their teeth began to fall out, their hair turned white at unusually young ages, and they suffered from severe skin and respiratory diseases. Children were born with soft bones and cancer rates rocketed.
>
> Official studies carried out five years ago in Dalahai village confirmed there were unusually high rates of cancer along with high rates of osteoporosis and skin and respiratory diseases. The lake's radiation levels are ten times higher than in the surrounding countryside, the studies found.

Stung by this sort of criticism, China has developed more stringent environmental requirements, but this has just moved the problem to other areas.

Si Chen et al described a forest in northern Myanmar that is a source of several rare earth metals as a place where "the birds no longer sing, and the herbs no longer grow. The fish no longer swim in rivers that have turned a murky brown. The animals do not roam, and the cows are sometimes found dead." They drew on dozens of interviews, customs data, corporate records, Chinese academic papers, satellite imagery, and geological analyses gathered by the environmental non-profit Global Witness to tie rare earth metals from Myanmar to 78 companies including Volkswagen, GM, and Tesla. Most did not reply when asked to discuss their supply chains [4].

Worldwide environmental destruction caused by mining materials needed for renewable energy – aggregates (sand, gravel, and crushed stone for concrete), bauxite (aluminum), clay, gypsum, shale, and limestone (cement), iron ore, rare earth metals (magnets and batteries), copper, and zinc – has left many areas barren and worthless for any plants. Played-out mines are restored to pristine condition in the United States, right down to the last dandelion, but this is clearly not in the cards in China or under Chinese colonial exploitation in developing countries.

In addition to the enormous amounts of rare earth metals that wind turbines and electric vehicles need for the magnets in their generators and motors, wind turbine construction is causing deforestation and human exploitation in the Amazon. Balsa wood is light, airy and popular for everything from model airplanes to full-size airplanes. The obsession with green energy has created a massive demand for balsa wood to use in wind turbines. One wind turbine blade can require as much as 5,300 cubic feet of balsa wood. The price of balsa wood shot up, driven by demand from Communist China. Balsa is an ideal forestry crop. It grows quickly and must be harvested before it ages too much. The Chinese have tried to grow their own balsa, but with limited success, so they have turned to deforesting the Amazon. Unscrupulous loggers are using forged permits, promising good pay – $150 per day, a fortune in Ewegona, Ecuador – then taking the logs from the roadside for $1.50 each and not paying the workers [23] [8].

> A power claiming to be generating clean energy is stealing the scaffolding of this small Amazonian country's forests. These paradoxes of the so-called "green economy" ruin the natural stability of the forests and the jungle [21].

In Latin America, green energy has destroyed forests, spread drugs, and also led to the kidnapping and sex trafficking of young girls. The abduction and rape of underage girls has been traced back to the system feeding balsa wood to the wind turbine manufacturers in China and Europe. Logging and mining camps, especially illegal ones, depend on a steady supply of male workers [7]. Once a forest is logged out, the workers are sold to gold miners, where they are confined in unspeakable conditions, often without bathrooms or clean water. If they try to escape, they are murdered. The mines are in such remote locations that the authorities rarely bother to investigate [22].

One reporter noted that "young girls are encouraged by mothers and aunts to exchange sex for diesel so they can watch their favorite soap operas each night and escape the harshness of their lives for a few hours" [22].

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Chapter 7

Solar and wind generators

7.1 Economics

> *It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter, will know of great periodic regional famines in the world only as matters of history, will travel effortlessly over the seas and under them and through the air with a minimum of danger and at great speeds, and will experience a lifespan far longer than ours, as disease yields and man comes to understand what causes him to age.*
>
> – Lewis Lichtenstein Strauss (1896-1974), first chair of the Atomic Energy Commission, in a speech to the National Association of Science Writers in New York City on September 16, 1954.

Strauss wasn't predicting that electricity from "atomic piles" would be free, only that the cost to meter it would be more than the operating cost to produce it, so it ought to be delivered to homes at a fixed fee, primarily to cover capital cost, much like cable TV is now delivered. This was based on the observation that the contribution of the cost of raw uranium, as it comes out of the ground, to the total cost of producing electricity, is about 0.001 cents per kilowatt hour. This doesn't take into account the remainder of the system.

In 1954, the average home's electricity demand was a few hundred watts, mostly lights, a refrigerator, and sporadic use of small appliances such as toasters, radios, vacuum cleaners, and washing machines, with average loads varying between day and night but not much from season to season. With the advent of air conditioning, televisions, computers, electric stoves, water heaters, space heating, clothes dryers – and especially electric vehicles, different homes have sufficiently different loads, at different times of day and in different seasons that fixed-fee delivery doesn't make sense.

Lewis L. Strauss was a shoe salesman, an investment banker, a philanthropist, personal secretary to Herbert Hoover during Hoover's philanthropic efforts in Europe following the first World War, and had risen to the rank of Rear Admiral in the Navy Reserve, administering ordnance during World War II (he had lost an eye at the age of ten years, so he was ineligible for active duty service). By all accounts, he was an able administrator. Because of illness he never attended college, even though he was valedictorian of his high school class in Richmond, Virginia. He did develop an amateur knowledge of physics from reading textbooks. He was not a scientist, and certainly not a systems engineer.

Solar and wind generators share the common attraction that their fuel cost is even less than 0.001 cents per kilowatt hour – it's free! Strauss's "too cheap to meter" remark has been used to reject every estimate of the cost of nuclear power, but it appears to be implicit in every estimate of the costs of power produced by solar and wind generators.

Haar and Haar wrote [43]

> The capital costs of RE [renewable energy] are falling but, because the output is both random and only available less than one-quarter of the time, its costs per unit of output are high. *Without incentives, private investors would not be interested in building it* [emphasis added], putting the nature and size of such subsidies at the heart of the affordability debate. Therefore, it is important to understand how support mechanisms should be designed, their costs calibrated and their impact measured. Using standard financial and economic theory, we evaluate the widely used RE support mechanisms… to address their economic efficiency as manifested in both the returns to investors in RE and negative externalities in the form of social costs.… Although the EU was successful in getting RE built, the direct costs of incentivizing RE, plus the indirect costs to society, have been huge and difficult to justify from the standpoint of economic efficiency.

America's energy supply is increasingly unreliable, and the same is true everywhere that large amounts of solar and wind generators have been installed and mandated. According to Federal data, there were fewer than two dozen major electric power disruptions prior to 2010. In 2020, there were more than 180. Outages are lasting longer. Utility customers experienced just over eight hours of power interruptions in 2020. The average in 2013 was four hours. The utility industry definition for *firm power* is 99.97% availability, about two hours and forty minutes per year without electricity. That was actually the norm in 2020. The U. S. electric power system is faltering just as governments are mandating more reliance on it, from electric vehicles, to converting space and water heating to heat pumps, to converting cooking from gas to electricity (see Section 4.2) [14].

Advocates continue to insist that solar and wind can produce electricity just as reliably and less expensively than coal, gas, or nuclear. What they are talking about is only the cost of building and operating the generators. The rest of the system is never included (see Section 4.1). Everywhere that solar and wind have been mandated and installed extensively, however, consumer prices have increased, and reliability has decreased. Getting the true cost of solar and wind is complicated because governments and utilities have allowed the structure of the wholesale market to be distorted to the advantage of solar and wind generators. Wholesale electricity markets universally, usually by government mandate, give priority of dispatch to output from solar and wind generators. They allow those generators to bid low prices when the sun is shining or the wind is blowing, but the system operator requires utilities to keep their thermal and hydro plants on standby, running but not generating any power or income, wearing out, emitting CO_2, and paying staff and mortgages. They pretend that intermittency is not something that is caused by the addition of solar and wind generators.

One thing that could be done to bring a little bit more reality to the economics of solar and wind dependency is to scrap the idea of grid priority for them. The grid operator should instead seek offers of power that are firm and reliable for some reasonable period, say 24 hours. A longer period, a month or even a year, would be better. If you want to sell power to a grid operator, it's your responsibility, not the grid operator's, actually to do it, and to provide some means to do it when the weather doesn't cooperate (see Chapter 8). Bids must be delivered well in advance, not the day before. For example, a bid for April 1 must be delivered before March 1, so the generator operator can't game the system using short-term weather predictions. A price for increasing penetration of solar and wind generators could be estimated by requiring generators to include in their bids the minimum amount of power that they will provide using solar and wind, say 20% or 30% or more. It's unlikely anybody would bid to provide 70% firm power from solar and wind, or that any sane grid operator would accept such a bid. This would quantify the actual blended cost to the grid operator of each incremental addition of solar and wind generation [62].

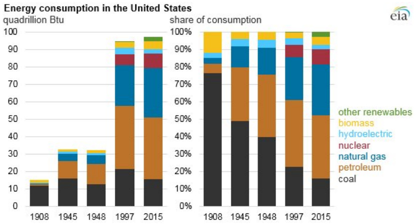

Figure 7.1: Energy source distribution.

In an interview in 2022, Goldman Sachs economist Jeff Currie remarked that as of January 2022, overall fossil fuels represented 81% of U.S. total energy consumption [27]. Ten years ago, fossil fuels represented 82% of energy consumption. In 1908, fossil fuels accounted for 85% of energy consumption. During the decade from from 2011 to 2021, the United States spent \$3.2 trillion on renewable energy, achieving essentially no effect on CO_2 emissions. The only change in the energy system that had an appreciable effect on CO_2 emissions was re-powering coal-fired plants to burn natural gas, which had become cheap and abundant due to fracking. Activists who insist on reducing CO_2 also reject fracking and nuclear power. It's clear that they want the issue, not the solution.

7.2 Energy return on energy invested

The economic health, wealth, and wellbeing of a society depend strongly upon the best choices of energy supply techniques. This involves many parameters of quite different significance. The central question that must be answered is "how much useful energy do we obtain for each unit of effort that we invest to make this energy useful?"

The Energy Return on Energy Invested, abbreviated EROI, is the amount of useful energy a system produces during its service life, compared to the effort – energy – invested in a system, including mining, milling, refining, manufacturing, transportation, construction, operation, maintenance, safety, removal, destruction, and recycling. This is distinct from Energy Money Return on Money Invested (EMROI). In general, discussions that focus on EMROI without also discussing EROI are engaging in obfuscation, not least because it is easy to hide costs in your tax bill by way of subsidies and incentives. There are also frequent distortions or unbalanced procedures used in evaluating both EROI and EMROI. The most common flaws are:

- *Tweaking lifetimes.* Absurdly low lifetimes are assumed for fossil and nuclear power plants, and unrealistically large ones for renewable sources [21].
- *Upgrading output.* The electrical energy output from renewable sources is multiplied by the inverse of average thermal efficiency, about a factor of three, for reasons of "primary energy equivalent." This is equivalent to measuring the energy in coal or gas that would be burned to produce the same amount of electricity. The result is that EMROI is calculated and then compared to EROI.
- *Counting all output*, even if it's not needed. This ignores dumping when output is greater than demand, and the need to provide storage when output is less than demand (see Chapter 8).

Weißbach et al analyzed EROI using several life-cycle assessments. They calculated EROIs using a strictly consistent physical definition and realistic system lifetimes [93].

They also developed a consistent estimate of the EROI required for economic usefulness. Energetically, human labor is insignificant, but financially it dominates and represents the welfare of the society, or the sub-society that works in the energy sector. Calculating the money-to-energy ratio of energy produced is simple: it is simply the market price. Calculating the ratio for energy invested is more complicated, and the ratio is much larger because it contains all the surpluses of the value-added chain. The EROI threshold for economic usefulness can therefore be estimated as the ratio of the GDP to the unweighted final energy consumption (not the primary energy consumption). For the United States in 2015, GDP was $17 trillion and unweighted energy consumption was about 24 trillion kWh, so the "energy value" was about 70¢/kWh. The average price of electricity was about 10¢/kWh. There is therefore a factor of 7 higher money-to-energy ratio on the input side. Weißbach et al calculated a similar ratio for several other countries.

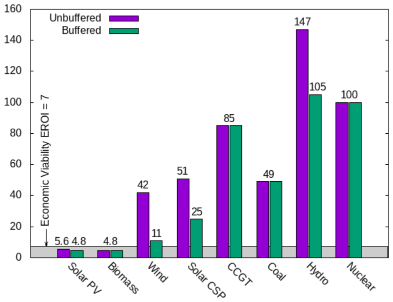

Figure 7.2: Energy Return on Energy Invested.

Figure 7.2, prepared using data from [93, p. 219], shows the EROI for several generating methods. The economic viability level is marked at EROI equal to seven. Solar PV is rooftop solar in Germany. Foundations and other structures might cause EROI to be less for industrial solar. Wind is for the state of Schleswig-Holstein in Northern Germany, where wind resources are quite favorable. Solar CSP means "concentrating solar power" or solar thermal. The quoted values were from a study of an hypothetical 145 GWe system with a 30-year lifetime to be built at Ain Beni Mathar in Morocco (37.14° N, 2.12° W). It must be remarked that, unlike photovoltaics, the output of a concentrated solar thermal plant is not linearly related to solar intensity. This means that they only make sense in "sunbelt" regions such as Nevada or Arizona. If their power is to be used elsewhere, for example in Wisconsin, the energy invested in transmission systems must be included in the analysis. CCGT means "combined cycle gas turbine." "Unbuffered" means there is no storage to accept output that is greater than demand, or to provide power when output is less than demand (see Chapter 8).

For comparison, the EROI during the Roman period was estimated to be about two. Their only energy sources were wood, crop residue, animal dung, draft animals, slaves, and small amounts of hydro, used primarily for grinding grain.

Table 7.1: EROI calculation for sodium-cooled fast-neutron reactor

Label capacity	1,340 MWe
Full load hours per year	8000 (capacity factor 91%)
Lifetime	60 years
Total output	**2,315,520 terajoules (TJ)**
Construction energy demand	4,050 TJ
Decommissioning energy demand	1,150 TJ
Maintenance energy demand	6,900 TJ
Initial fuel load	500 TJ
Fuel processing during operation	300 TJ
Total energy demand	**12,900 TJ**
EROI	**179.5**

The analysis by Weißbach et al [93, Table 8] for nuclear power assumed a 1,340 MWe pressurized water reactor with oxide fuel, in service for sixty years. Initial fuel for a 1,340 MWe sodium-cooled fast-neutron reactor with metallic fuel (see Section 9.7) would be obtained by processing about 500 tonnes of spent light-water reactor fuel, not by mining, milling, refining, and enriching new uranium. The reprocessing energy cost would be about 320 terajoules (TJ). Ongoing fuel processing would consume about 5 TJ/yr.[a] As a function of service life in years y, EROI = $38592\,y/(12600 + 5\,y)$. If the plant operates for 100 years, the EROI approaches 300. Table 7.1 summarizes the results.

Space-based solar PV power generators, with microwave transmission to Earth, have been proposed many times. None of the breathlessly enthusiastic proposals have included an analysis of either EROI or EMROI.

7.3 Solar generators

There are two types of solar electricity generators: Solar photovoltaic, and solar thermal. In addition to generating electricity, sunlight can be used for process heat, now almost exclusively domestic water heating.

Because of the low energy density of solar power, in addition to large land area, large amounts of materials are needed, as explained in Section 6.1. For the same reason, industrial solar installations are placed outside cities. As we saw in Section 4.2.5, there are limits on the distance that their output can be transmitted. The dream that the deserts of California, Nevada, and Arizona can provide all of the nation's energy from solar power is much more difficult and much more expensive than dreamers imagine.

Solar photovoltaic

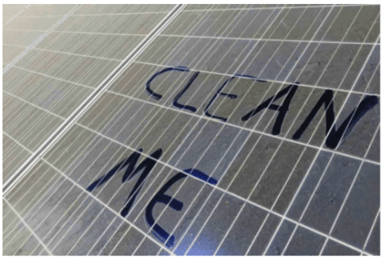

Figure 7.3: Solar panels in the desert.

Solar photovoltaic generators (PV), or solar panels, are composed of semiconductor diodes that convert sunlight to electric power with varying levels of efficiency, ranging from about 15% for amorphous or polycrystalline devices up to about 21% for single-crystal devices, when sunlight is incident perpendicular to the panel. Most photovoltaic installations are on fixed mountings, so they cannot turn toward the sun in different seasons or different times of each day. Output depends upon solar intensity and the cosine of the angle between the Sun and the perpendicular to the panel. Solar intensity varies depending upon weather, upon the time of day because of the longer atmospheric path before and after noon, and upon season and latitude, also because of atmospheric path length differences. Output also depends upon cleanliness of the panels. As little as one gram of fine dust per square meter, such as in Figure 7.3, can reduce output by 50%. In desert installations, water to wash panels might be difficult to obtain. It would be

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[a] Fuel-related energy costs provided by Dr. Yoon Il Chang, private communication, 20 April 2023.

necessary to collect and filter water used to wash panels. In northern latitudes, panels produce nothing when covered with snow, as in Figure 7.4. Their capacity factors are therefore much less than 50%, as one might naively guess by considering only daytime and nighttime. (see Table 4.1).

Figure 7.4: Solar panels in the winter.

It is not possible to convert all of the sunlight that is incident on a solar PV cell into electricity. For a single cell, assuming only radiative recombination,[b] William Shockley and Hans-Joachim Queisser determined that the maximum efficiency for a single-layer silicon device is 44%. They determined that silicon devices would have the highest efficiency [76]. The maximum theoretical efficiency possible using an infinite number of layers and sunlight without concentration is 68%. With concentrated sunlight, which increases the number of photons per square centimeter per second, the maximum is about 86%. There are, of course, sources of loss other than radiant recombination, such as reflection from the front of the cell and shadowing by connecting wires. The record so far, achieved by Green and Ho-Baillie using a five-cell system, is 43.5% [42]. Their device contains lead in a water-soluble form, so there would be some environmental objection to deploying it.

Efficiency also depends upon temperature. For most PV cells, the optimum temperature is 25°C, with output decreasing 0.3–0.5% per degree increase, depending upon the PV materials [32].

Table 7.2 shows capacity-weighted average amounts of land needed by solar photovoltaic and concentrating solar thermal generators. Land use depends upon latitude, micro-climate, the kind of installation, and whether the photovoltaic generators are the exclusive user of the land [71, pp. 18-19] [28].

Table 7.2: Solar Photovoltaic and Thermal Land Use, acres/MWe (AC)

Capacity	> 1 MW < 20 MW	> 20 MW	Concentrating Thermal
Direct area	5.9	7.2	7.7
Total area	8.3	7.9	10

The total area of the United States, exclusive of Alaska, is 3,717,813 square miles, or about 2,380 million acres. At 7.9 acres per MWe, the land required to produce 1.7 TWe average

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[b] When a photon with an appropriate energy strikes a semiconductor junction within the solar cell, it separates an electron from the material, producing a free electron, and a "hole" – an atom that has a net positive charge. The opposite process is, of course also possible: The electron and hole can combine and emit a photon.

power would be 13.5 million acres, less than 0.65% of the total, exclusive of Alaska. Of course, some of the area, such as lakes or mountains, is not suitable for solar power, but the amount is still small.

The cells in solar panels produce direct-current (DC) electricity at low voltage. Their voltage varies depending upon season, weather, and time of day, as explained above. Therefore, the low-voltage DC output from a solar panel needs to be converted to AC with frequency and phase accurately controlled to match the grid, and voltage raised and regulated to match the transmission or distribution voltage. Solar panels provide no electrical power inertia (see Section 4.2.2).

Deer and bighorn sheep grazing areas have been replaced by solar panels, and access to some grazing areas has been restricted by 6-foot fences. Passages between parts of the solar tracts have attracted the attention of coyotes and mountain lions, where they lie in wait, and are now appearing in nearby towns. Birds sometimes mistake the blue-and-silver solar panels for water, and are injured or killed when they try to land, especially when the panels are hot.

Although the total amount of land necessary for industrial-scale solar projects is small, there is frequent local objection to them. In farming communities, neighbors complain that habitat for insects that pollinate their crops is diminished, or simply that they're ugly. In desert communities, neighbors complain about dust, not just during construction but continuously because disturbance of the desert surface recovers only very slowly.

We have already seen in Section 6.1 that producing materials to make solar panels, wind turbines, and batteries is harmful to the environment and oppresses people in Chinese colonies, especially in Africa. Most solar panels are made in China, and most of those are made by slave labor in concentration camps by the mostly-Muslim Uyghur minority in East Turkestan, called Xinjiang province, meaning *New Frontier* – a colonialist term – or more precisely the *Xinjiang Uyghur Autonomous Region* – which is of course far from autonomous. There have been on-again off-again cycles of tariffs and restrictions on Chinese solar panels, both in the United States and Europe. The current condition is that there is essentially no penalty for the human misery their construction imposes.

Hazardous chemicals such as silane (SiH_4), chlorine, hydrochloric acid, trichlorosilane ($SiHCl_3$), nitrogen trifluoride, and hydrogen selenide, are used in solar panel construction. Although these chemicals would be hazardous to society, as of 2011, there were very few reported accidents. But production rates have increased significantly since 2011, and must increase much more to meet Jacobson's targets (see Section 4.2). Overall risk (fatalities per GWe-year) caused by "high frequency" solar PV events, i.e., excluding very rare but very severe accidents, is estimated to be about 24 times the risk from generation III nuclear power, and generation IV nuclear power is significantly safer [18].

Solar panels are also susceptible to damage from an environmental event such as a tornado, hurricane, earthquake, or hail storm. In 2015, a tornado at the Desert Sunlight solar plant destroyed 200,000 panels. When Hurricane Maria struck Puerto Rico in September 2017, the majority of the panels were destroyed at the second-largest solar plant in Puerto Rico at Humacao, which supplied 40% of Puerto Rico's electricity [74].

Solar panels' outputs decline about 1% per year at first, then more rapidly. The usual industry guideline is to plan for a 25 year life. Some have remained in service for forty years because there are no subsidies to remove them. At the end of their life, they become hazardous waste. They are mostly not recycled, as explained in Section 6.1. As a consequence, toxic metals such as cadmium, chromium, lead, selenium, and tellurium can escape into drinking water from landfills or unregulated sites where they are dumped.

Figure 7.5: Damaged Puerto Rico solar plant

Solar panel recycling is mandated by law in Germany, but in an unregulated market, such as in most states in the United States, it will only be done if the value recovered exceeds the cost of the process. A 2016 study found that silicon solar panels consist of about 76% glass, 10% polymer encapsulant and backsheet, 8% aluminum (mostly the frame), 5% silicon, 1% copper, and less than 0.1% silver, tin, and lead. With newer technologies, panels are expected to contain more glass, and less aluminum and polymers [92].

In July 2017, the state of Washington became the first state to pass a solar stewardship bill (ESSB 5939) that requires manufacturers that sell solar panels in Washington to have end-of-life recycling programs for their products. Otherwise, since 1 January 2021, manufacturers are not allowed to sell their products in the state. Washington-based solar panel manufacturer Itek, which helped write the bill, uses a recycling parter in Idaho for damaged panels and manufacturing scrap. Itek also accepts panels from other manufacturers, just to keep them out of landfills.

In 2005, First Solar, which manufactures cadmium-telluride (CdTe) panels, committed to extended producer responsibility. They have recycling plants in Ohio, Malaysia, Vietnam, and Germany. Both cadmium and tellurium are rare and expensive, but even so, recycling CdTe panels is not economically viable on its own. Silicon solar panels have even lower recycling value. First Solar started by including a recycling fee in new panels, but now they expect customers to "do the right thing" and pay to have their panels recycled. Of course, this almost never happens except where it is mandated or subsidized or both.

Solar panel waste management is a cost that is almost never included in quotations of the cost of solar PV electricity – another facet of an absence of system engineering.

The *carbon intensity* of solar PV is often cited as a reason for building it. The carbon intensity for a gas- or coal-fired generator is dominated by the result of burning its fuel. For hydro, nuclear, solar, or wind, which burn no fuel, the calculation is different. But in all cases a common measure can be used: The total amount of CO_2 emitted during the lifetime of the system – mining, manufacturing, transportation, construction, operation, maintenance, destruction, recycling, and disposal – divided by the total amount of energy produced. Table 7.3 shows the carbon intensities listed in the fifth IPCC climate assessment (A.R.5) [53], which is obsolete but still influential because it was the basis for the Paris Agreement. As is the case with too many EROI caluclations (see Section 7.2), it also assumes unrealistically short lifetimes for nuclear, coal and gas generators, and unrealistically long lifetimes for solar and wind generators.

There is only one problem: These estimates are all built on the same small set of studies and cite no independently validated data. They are based on scenarios that are incompatible with reality in the global PV industry. Enrico Mariutti argued that a PV system manufactured in China and installed in Italy might well have a carbon intensity of 200 gCO_2/kWh [58].

Table 7.3: Carbon Intensities of Generation Methods

Method	gCO_2/kWh	Method	gCO_2/kWh
Pulverized Coal	820	CCGT Gas	490
Nuclear	12	Utility Scale PV	48
Onshore Wind	11	Offshore Wind	12

The numbers in A.R.5 were based upon a single review of thirteen studies [47]. Seven of the studies developed their estimates assuming modules are built in Europe with short supply chains and a low-carbon energy mix (hydro, natural gas, the European electricity grid, and waste heat). One of the studies based its estimate on the Swiss energy mix, which is mostly hydro. One was based on the Australian energy mix, which was at the time dominated by coal. The study based on the Australian energy mix found a carbon intensity four times greater than the one based on the Swiss energy mix.

Nonetheless, the IPCC report extrapolated a median figure from the review. This distorts the estimated carbon intensity, and also the expected Energy Return on Energy Invested (EROI – see Section 7.2).

These energy mixes that are used to estimate the carbon intensity of solar PV are far removed from reality. More than 85% of solar panels are made in China. None of the estimates included any ancillary infrastructure (inverters, transformers, transmission systems, …), or transportation, or destruction and recycling. None of the studies discussed grid upgrades. Once again, there was no system engineering, only component engineering.

In the sixth IPCC climate assessment (A.R.6) [1, p. 632] one finds that “GHG LCA [green house gas life cycle assessment] estimates span a considerable range of 9-250 grams of CO2 per kWh,” effectively contradicting estimates in wide circulation, which routinely are in the range of 20–40 grams of CO_2/kWh. Then they waffle when they add "recent studies that reflect higher efficiencies and manufacturing improvements find lower life-cycle emissions, including a range of 18-60 grams of CO_2/kWh and central estimates of 80 grams of CO_2/kWh, 50 gCO_2/kWh, and 20 grams of CO_2/kWh."

They support the revised estimates by citing two analyses (based upon confidential inventories) of lifecycle emissions of modules manufactured in Eurpope. The inventory is the same in both studies because one uses the other as a source. Citing two sources in a review, which appears to magnify credibility, but one cites the other, is considered *predatory journalism*. A third study analyzed emissions from manufacture of a panel made from Upgraded Metallurgical Grade Silicon cells (UMG-Si), despite the fact that there are currently no such cells on the market. A fourth review cited sixteen studies of panels made in Europe.

This is yet another example of the "scientific" chicanery perpetrated by the IPCC (see Section 3.4).

A report from the IEA [36] lists the inventories of materials involved in the construction of a solar PV plant, but estimates neither carbon intensity nor carbon footprint. Mariutti [58] concluded that the carbon intensity and carbon footprint of solar PV systems made in China is clearly much greater than IPCC or IEA reports [4].

Solar thermal

Figure 7.6: Ivanpah solar generator.

There are two main types of solar thermal electricity generators. One is called a *trough* generator, in which a tube carrying a working fluid is at the focus of a parabolic trough. The Solyndra scheme was of this type. In some designs, the trough is fixed; in others, it can tilt, depending upon the season and time of day. The other type consists of a large number of mirrors, mounted on devices that can move them, called heliostats, which together focus sunlight on a central receiver. The Ivanpah solar generating station shown in Figure 7.6 is of this type. It occupies 3,500 acres (about 1,400 hectares) and produces on average 400 MWe (about 8.75 acres/MWe). This does not include roads, storage areas, or temporarily disturbed land. Compare to Tables 7.2 and 7.4.

Both types heat a working fluid to power a turbine, generating electricity with efficiency ranging up to about 25%. Solar thermal generators of the heliostat type frequently include a small amount of molten-salt heat storage, to provide electricity at night. Storage is discussed in more detail in Chapter 8.

When the land was to be cleared to make way for the Ivanpah solar generator, adjacent to Interstate Highway 15 in California, about five miles from the Nevada border and sixty miles south of Las Vegas, animal rights activists walked shoulder to shoulder, with tears streaming down their faces, collecting desert tortoises. The tortoises were taken to shelters, where most of them died. After the facility was started, it has been estimated that as many as 2,500 birds have been killed by intense heat in the convergence zone near the receiver, collisions, or other accidents [79]. Of course, insects are also being fried.

When a 3,000 acre solar project was under development about 10 miles south of Pahrump, Nevada, a team of biologists relocated 139 tortoises. In the span of a few weeks, thirty tortoises were confirmed to have died. Conservationists believe relocation stress made the tortoises more vulnerable, and that drought might have caused badgers to seek seek them out because of a decrease in other prey. Wildlife experts have not determined a specific cause [20].

The Ivanpah solar thermal power station is delivering about one third of the amount of electricity originally contracted, by using sunlight. The remainder required to meet contractual obligations is produced by burning natural gas.

After brief early interest, construction of solar thermal power stations in the United States has essentially ceased. While U.S. solar PV capacity is projected to grow 6.6% between 2021 and 2050, no increase in solar thermal electricity capacity is expected [83].

Solar water heater

A third type of device, a solar water heater, doesn't generate electricity. Rather, it heats water directly, usually for domestic, not industrial use. There are two main types of solar water heaters: Panel systems and passive tank systems. There are two types of panel systems. Active panel systems use panels to absorb sunlight, and control systems and pumps to circulate hot water from panels to storage tanks. Active panel systems are popular in Hawaii, where they do not need protection from freezing temperatures. Protection from freezing temperatures requires either an additional *drain down* system to empty the panels, or a *recirculate* system to pump warmer water from the storage tank to the panels. A recirculate system is vulnerable to freeze damage in the event of power failure. Either method introduces complexity into the system, and therefore active panel systems are less popular outside Hawaii.

Passive panel systems mount a tank above a panel. When water in the panel is hotter and therefore lighter than water in the tank, convection causes it to rise into the tank, and colder heavier water to circulate from the tank into the panel. They are are quite popular in parts of China, Nanjing in particular. Such systems are protected from freezing using *dribble valves* that automatically open at low temperature to allow a slow flow of water from the mains through the panels. Dribble valves can also be used to protect active panel systems from freeze damage. The flow rate varies up to about 3000 gallons per year, according to the relation[c]

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[c] The relation was calculated for two valves, Dole/Eaton FP-35 and Therm-Omega-Tech IC/FP-35.

$$V = 0.0014\,x^2 + 1.7748\,x\,,$$

where V is the flow rate in gallons per year, and x is the *air freezing index* given by

$$x = \sum_{i=1}^{365} \max(0, T_{\text{open}} - T_{\text{day},i})\,,$$

where T_{open} is the valve opening temperature, not much above the freezing temperature of water, $T_{\text{day},i}$ is average air temperature on day i. The "max" function appears because the valve doesn't open for negative values of $T_{\text{open}} - T_{\text{day},i}$. Less water is consumed in warm climates than in cold climates [17].

An alternative freeze protection method for passive panel systems is to fill the panel with antifreeze, and include a heat exchanger within the tank.

Passive tank systems enclose a bare tank within an insulated box and a transparent cover. A sufficiently large passive tank system, say forty gallons, within an insulated box, is immune from sufficient freezing to cause damage at southern latitudes in the continental United States.

Some jurisdictions, notably the Southern California Air Quality Management District, briefly mandated solar water heaters in new construction, but with the end of the mandates, deployment has essentially ceased.

In addition to domestic use, solar collectors are used to heat swimming pools and spas. These are usually made from plastic instead of copper, because they operate at lower temperatures. Because plastic is more flexible than copper, they are less vulnerable to freeze damage in moderate climates such as the American southwest. They usually depend upon recirculation for protection from extreme freezing. A novel application of them in places such as Palm Springs during a scorching hot summer month is to run the pumps at *night* to *cool* the swimming pool. Collectors can also be installed inside of concrete decks. One contractor installed a system under half of a tennis court at a movie star's home. Would you care to guess which half of the court he played on when he had guests over to play tennis? The half from which heat had been pumped into his swimming pool.

7.4 Wind generators

Essentially all wind generators are built on a tower, with a horizontal axle. Although a vertical axle wind turbine is possible, very few have been deployed. Horizontal axle turbines include long blades that essentially double their height. It is difficult to access higher level wind using vertical axle generators.

There are three measures of the amount of land required for a wind project as shown in Figure 7.7:

- permanently disturbed land consisting of turbine pads and permanent roads, with much more land occupied by roads than turbine pads,
- temporarily disturbed land consisting of storage areas and temporary roads, and
- total project area.

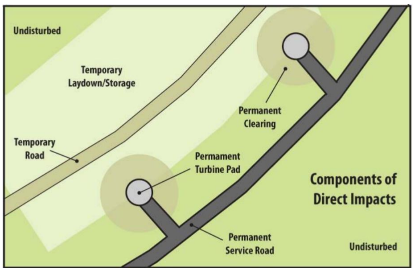

Figure 7.7: Wind Project Land Use [29]

Table 7.4: Land Use for Wind Projects

	Permanently Disturbed	Temporarily Disturbed	Permanent + Temporary	Total Area
Acres/MW	0.75 ± 0.75	1.73 ± 1.48	2.47 ± 1.73	84 ± 54
Hectares/MW	0.3 ± 0.3	0.7 ± 0.6	1 ± 0.7	34 ± 22

A study of the direct impact of 93 proposed or installed projects representing 14 GWe label capacity, and total land area for an additional 161 projects representing 25 GWe label capacity, found the amounts shown in Table 7.4 [29].

The overall summary of the study was a label capacity density of 3.0 ± 1.7 MWe/km^2, about 12 ± 6.9 kWe per acre, or about 82 acres per MWe.

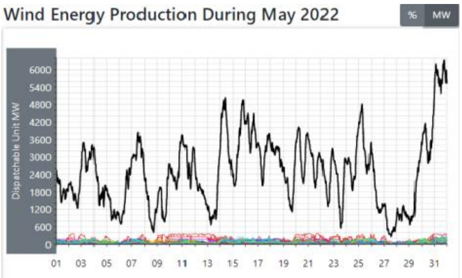

Figure 7.8: Wind power in Australia

Each turbine extracts energy from the wind, leaving less to be extracted by nearby turbines. If the wind were to be stopped completely by the turbines, their blades would stop moving. Albert Betz computed that the maximum fraction that can be extracted by packing turbines more densely is 57% [13].

Wind power is attractive because it works both day and night – of course only when the wind is blowing. But wind is far more erratic than sunlight, as shown for all of Australia for May of 2022 in Figure 7.8.[d]

Prolonged wind droughts are common. On 16-17 February 2021, Texas wind output fell to a paltry 2% of label capacity. The European Dunkelflaute[e] of 2021 shown in Figure 7.9

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[d] Data from Australia Energy Market Operator.

[e] The term "Dunkelflaute" means "dark lull" or "dark doldrums" in German

lasted for several weeks. During the first half of 2021, wind output in Germany declined by more than 25%. Starting in September 2021, and running through mid November, wind power output collapsed throughout Germany and the UK. The energy company SSE reported "32% less power than expected between April and September" [80] [78].

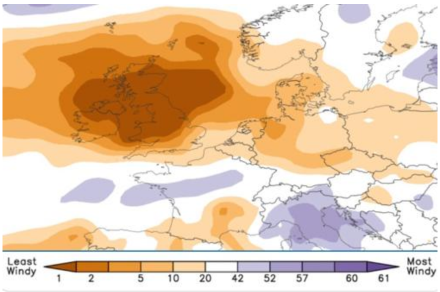

Figure 7.9: Wind in Europe in 2021

Kinetic energy is proportional to the square of velocity v:

$$\mathrm{KE} = \frac{1}{2}\, m\, v^2\,, \tag{7.1}$$

where m is mass. Power is proportional to the rate of change of energy:

$$P = \epsilon \frac{\mathrm{d\,KE}}{\mathrm{d}t} = \epsilon \left(\frac{1}{2} \frac{\mathrm{d}m}{\mathrm{d}t} v^2 + m v \frac{\mathrm{d}v}{\mathrm{d}t} \right)\,, \tag{7.2}$$

where ϵ is the efficiency with which energy is converted to power and "d/dt" means "the rate of change with respect to time." The flow rate of mass is

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \rho\, A\, v\,, \tag{7.3}$$

where ρ is air density and A is the area swept by the turbine's blades. Substituting Equation (7.3) into Equation (7.2) and observing that the second term in Equation (7.2) is zero when wind velocity is constant, shows that wind power at constant wind velocity is proportional to the cube of velocity:

$$P = \frac{1}{2}\, \epsilon\, \rho\, A\, v^3\,. \tag{7.4}$$

This has two effects. When wind speed is reduced by one half, power is reduced to one eighth, and when wind speed is reduced to 2%, power is reduced to 0.0008%. When wind speed is doubled, power is increased by a factor of eight. The latter might seem to be a good thing, but only within bounds. Turbine blades are airfoils, just like wings on an airplane. The blade rotation speed can be adjusted by adjusting the angle of the blades. Because of limits on the ranges of turbine blade rotation speeds that can be accommodated by changing blade pitch, turbines include a gearbox that connects the blades to a generator, and changes the gear ratio so that the generator produces power at the same frequency as the grid (see Section 4.2.2). Above about 55 miles per hour (25 meters per second), even with the blades turned as far as possible, the generator would run too fast to match grid frequency, and the turbine, gearbox, and generator might be damaged, so brakes are applied to stop the turbine – which doesn't always prevent the kind of damage shown in Figure 7.10.

Both solar and wind generators require significant storage or other backup in the form of standby thermal generators to provide firm power, as will be explained in detail in Chapter 8. Without some form of backup, they are utterly useless as reliable energy sources.


Figure 7.10: Wind turbine damaged by high wind speed.

If batteries, pumped hydro, or some other scheme of storage is not included, fast-response thermal generators are necessary to back up solar and wind. A nuclear power station or coal-fired power station cannot change output sufficiently rapidly to cope with the erratic output from wind generators.[f]

The most efficient kind of gas-fired generator is called a *combined cycle gas turbine* or CCGT. The first stage is essentially a giant jet engine. The hot exhaust gas from the turbine is then used to boil water to make steam, which is then used in a second turbine to produce yet more electricity. The thermal efficiency can approach 60%, but output cannot change rapidly. A type of gas-fired generator known as an *open cycle gas turbine* or OCGT consists only of the giant jet engine. It can change output rapidly, but its thermal efficiency is usually about 35%. OCGTs have been combined with coal, nuclear, or CCGTs for decades as "topping" or "peaking" generators for load following. In that application, the necessary capacity is much smaller than "base load" capacity because they only need to cope with variations in load. When used to back up wind generators, the necessary capacity is much larger because they must cope both with load variations and the vagaries of wind production, that is, they must produce about the same output that base-load generators would produce. When wind turbines displace CCGT or nuclear generators, and are then backed up by OCGT generators, CO_2 emissions increase [31].

Neither coal-fired power plants, nor nuclear power plants, nor either kind of gas-fired power plant, can be started rapidly. Therefore, in large-scale (regional, national, or continental) power systems in which significant numbers of wind turbines are included, these thermal power plants must be kept operating, idling at minimum power, wearing out, requiring operating and maintenance staff, emitting CO_2, but producing no power and therefore no income. The cost of backup is never included in quotations of the cost of electricity from solar and wind sources.

The proposition that installing significant amounts of wind generation reduces emissions is primarily supported by models. Measurements show that emissions of sulfur dioxide (SO_2) and oxides of nitrogen (NO_x) increase, especially as a result of coal cy-

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[f] The *Natrium* system proposed by Bill Gates and GE/Hitachi and described in Section 9.7 would couple a PRISM reactor to a molten salt thermal storage to allow more rapid output response.

cling, and that CO_2 emissions are either not measurably decreased, or increase slightly [11]. To the extent that coal-fired generators are replaced or repowered by gas when wind turbines are added to a grid, SO_2 and NO_x emissions can be decreased, and CO_2 emissions decrease, but almost certainly not nearly as much as models suggest they might.

From [12, p. 32]:

> Figure 7.11[g] leads to two overarching conclusions: First, the emissions savings that result from adding an incremental MWh of wind vary depending on the power supply composition of the service territory. Savings are higher in the MISO area where coal constitutes a very large portion of the generation stack (approximately 80%). Conversely, in areas where coal plays a minimal generation role (CAISO and BPA) an increment of wind generates very negligible emissions savings.
>
> The second major conclusion is that savings are relatively small compared to other estimates and accepted policy assumptions. Again, the disparity [between models and measurements] is less pronounced in areas such as MISO where coal is more prevalent, but even in MISO, SO_2 savings are 23% less than estimated by the AWEA approach while CO_2 savings in MISO are slightly higher than expected using the AWEA estimation method.

Nearly a quarter of electricity in California (CAISO) is imported, with a significant amount coming from coal-fired generators at the "Four Corners" area of Colorado, Utah, New Mexico and Arizona. The reports [11] and [12] did not clarify whether their analyses examined only generation in California, or included imports. California in-state coal generating capacity is less than 0.07% of the total [22]. That there is no reduction in CAISO SO_2 emissions shown in Figure 7.11 suggests that the effect of California wind generation on emissions due to imported electricity was not analyzed. The "Four Corners" area is not part of any of the analyzed service territories.

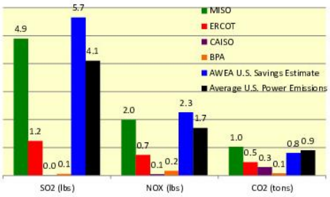

Figure 7.11: Wind generation emission reductions per MWh.

It is quite possible, even with today's small penetration of solar and wind generators, that for short periods of time their combined output can be more than demand. In many jurisdictions, transmission and distribution utilities, many owned by utilities that have significant investment in thermal generators, are required to accept electricity from solar and wind generators, regardless of whether they have demand for it. At these times, the wholesale price of electricity is in fact negative – transmission and distribution utilities are required, by law, to pay solar and wind generators for electricity that they are unable to sell. Solar and wind generator owners are not affected because

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[g] AWEA = American Wind Energy Association; BPA = Bonneville Power Administration; CAISO = California Independent System Operator; ERCOT = Electric Reliability Council of Texas; MISO = Midwest Independent System Operator.

they have direct subsidies and indirect subsidies such as tax incentives as shown in Table 7.5, from all levels of government, and contracts based upon label capacity, not actual moment-to-moment generation. This drives up the cost of output from thermal generators because they need to keep their staff on duty, keep their generators operating at low power, maintain them, and pay their mortgages, while not receiving any income.

Table 7.5: Direct Federal subsidies for electricity generation in 2018 [7]

	Coal	Gas	Hydro	Nuclear	Wind	Solar
¢/kWh†	0.071	−0.066	0.0127	0.020	2.063	3.753
California adds 40% to Federal subsidy for Solar PV						1.501
Total						5.254
per nuclear ¢/kWh	3.55	−3.3	0.635	1.000	**103.15**	**262.71**

Yes, the government made a profit on gas.

†Includes 1.5¢/kWh Production Tax Credit for wind, and 1.3¢/kWh for solar. Investment tax credit, state and local support, and the effect of mandates, are not included.

Reports after 2018, e.g., [8], report energy generation in thermal units, making comparison more difficult

Warren Buffett has said "the only reason to build wind generators is to get the subsidies." T. Boone Pickens owned substantial gas fields in Oklahoma and Texas. He built wind generators on them, partly to get the subsidies, and partly to sell backup electricity produced by open cycle gas turbines.

In 2019 in Britain, wind power operators were given £136 million in so-called "constraint payments." What are these? They're paid *higher sums not to produce* electricity when there is no wind, or when wind is so intense that they need to feather their generators' blades and apply the brakes so they do not destroy themselves. These scams are typically not counted as direct subsidies, and are not included in Table 7.5. Does your employer pay you more *not* to produce anything than to produce what you were hired to do?

In a letter to shareholders, Jamie Dimon, the CEO of J. P. Morgan Chase, the world's largest bank by market capitalization, wants the government to seize private property so that his bank can finance the construction of more solar and wind energy plants. His bank is one of the biggest players in the $20 billion per year tax equity finance business. He wrote [30]:

> Permitting reforms are desperately needed to allow investment to be done in any kind of timely way.... We may even need to evoke (sic) eminent domain – we simply are not getting the adequate investments fast enough for grid, solar, wind, and pipeline initiatives.

About half of all tax equity financing deals in the United States, about $10 billion per year, are being done by just two banks – J. P. Morgan Chase and Bank of America. They find that tax equity financing, with a yield of 6% to 8%, is more attractive than other activities, such as lending. Dimon's letter to shareholders did not reveal that J. P. Morgan Chase, along with two other companies, had bought $2.5 billion of equity units in NextEra, the world's large renewable energy producer [66]. In a recent 10-K filing, NextEra reported nearly $4.3 billion in federal tax credit carry forwards [33]. The shareholder letter did reveal a prediction that J. P. Morgan Chase plans to "finance or facilitate" $2.5 trillion in alt-energy projects over the next decade, with $1 trillion spent on renewables and "clean" technologies. The entire Apollo program cost $150 billion, measured in the 2020 decade's dollars.

Wind industry advocates claim that turbines have almost zero maintenance, running on the smell of an oily rag and needing only an occasional hug. They are not nearly that reliable. Maintenance costs reported on balance sheets average $24-25 per MWh. Many coal-fired power plants deliver wholesale electricity at about that price – which includes their fuel, capital, and operating expenses, not just maintenance. In 2014, Siemens wrote off a €223 million loss because it had to replace bearings in a fleet of turbines that were less than two years old. They blamed the failures on the supplier. Old-fashioned mechanical wear and tear actually do happen. Generator and gearbox works need lubrication, and contain an oil sump, as in an automobile, but typically much larger – about 250 liters. As in an automobile, the oil needs to be drained and replaced periodically. Gearboxes apparently wear out much faster than manufacturers claim, and warranty service is costing manufacturers millions. Mechanics who must change the oil resort to special efforts to clean out the ground up metal so they can drain the oil/metal mixture.

The Siemens 2014 loss is not a one-off event. They posted a $974 million loss in 2022, blaming increased warranty costs on their Spanish partner Gamesa [77].

Wind industry advocates claim that turbines last 25 years. The reality is that wind turbines' output decreases steadily, and it is not unusual for them to be taken out of service after about twelve years, as shown by a study of almost 3,000 turbines in Britain. The claimed lifetime of 25 years is used to calculate subsidies in Britain. Professor Gordon Hughes of Edinburgh University said "the subsidy regime is extremely generous if investment in new wind parks is profitable despite the decline in performance due to age and over time" [21].

Turbines throw ice off their blades, and throw off their blades. Siting them near schools is not a stroke of brilliance. One threw massive chunks of ice through roofs and windows at a Massachusetts Community College in 2018. Fortunately, no one was killed. In 2013, turbines throughout the Scottish highlands were shut down (and many were removed) after one unshackled its blades and flung one more than 60 meters. In 2009, a turbine at a primary school on the Isle of Skye was quietly removed after it disintegrated and threatened the lives and limbs of youngsters. In April 2023, a turbine in a schoolyard near Petersburg, Illinois started losing its blades after its braking system failed. Fortunately, no school children were harmed in the making of this 2023 wind energy drama [25].

7.5 Environmental effects

Land use

Two papers published by Harvard researchers concluded that the transition to solar and wind power in the United States would require five to 20 times more land than previously thought. Using the locations of 57,636 wind turbines that had been released by the U. S. Geological Survey in 2016, as well as electric power generation statistics from the U. S. Energy Information Agency, they estimated the power densities of 1,150 solar photovoltaic plants and 411 wind facilities. They wrote "for wind, we found that the average power density – meaning the rate of energy generation divided by the encompassing area of the wind plant – was up to 100 times lower than estimates by some leading energy experts." These estimates, based upon observations, are also much lower than estimates used by the U. S. Department of Energy and the Intergovernmental Panel on Climate Change. Most of the earlier estimates had failed to take account of the effect of upstream wind turbines on the efficiency of downstream ones. "Once the wind parks are more than five to 10 kilometers deep, these interactions have a major impact on power density" [65].

Temperature change

The whole point of wind turbines is to limit global warming. Another Harvard study by the same authors concluded that if such large scale wind facilities were to be built, they would warm average surface temperatures over the continental United States by 0.24°C. To estimate the climate effect, the authors hypothetically covered one third of the U. S. continental land area with enough wind turbines to meet present-day demands. Because wind turbines, especially large ones, mix atmosphere near the ground with atmosphere at and above their tops, while simultaneously extracting energy from the atmosphere's motion, the effect is to warm the continent by an average of 0.24°C. The effect is more pronounced at night, causing warming of up to 1.5°C, because temperatures increase with height during the night. The authors admit that although their hypothetical large deployment is extremely unlikely, they found that localized effects were similar. They validated their models by comparing their calculations to satellite observations of North Texas [96]. The warming caused by wind turbine operations was more than the imputed reduction resulting from reduced carbon emissions from fossil fuel power plants displaced by wind turbines. They repeated their calculations for solar power and found the effect was in the same direction but only about one tenth the effect of wind power [64].

Rainfall

Wind facilities not only warm the climate more than the temperature is claimed to be reduced by displacing fossil fuel generators, they also decrease soil moisture and appear to reduce rainfall. Pierre Gosselin [41] summarized an article in German [6] that noticed a correlation between density of wind turbines in Germany and a recent drought. The German study (as translated by Gosselin) concluded

> As a conclusion, it can be said that it is certain that wind parks change the local climate. Very large wind parks or many wind parks also have an effect on the global climate. The results are mostly based on simulation models, whereby the study by Zhou et al. [96], which was able to draw on comparative data, confirms the results found in the simulation models. The new study by Wang et al. [91], which we discussed today, confirms the model calculations using real data obtained from a Chinese wind park and shows for the first time that soil moisture is reduced by wind parks not only downwind but also upwind.
>
> Wind parks thus contribute significantly to the drying out of soils, and to drought.

The Wang study cited by the German study found that (1) the soil moisture within wind parks decreases most significantly, with a decrease of 4.4% observed; (2) in summer and autumn, the declines in soil moisture in the downwind direction are significantly greater than those in the upwind direction, with the opposite occurring in spring. (3) Wind parks aggravate soil drying in grassland areas, which may have impacts on grassland ecosystems [91].

Plant diversity

Other studies show that wind parks reduce plant diversity and productivity. A study of 2,404 wind parks encompassing 108,361 wind turbines and 7,904,352 plant diversity observations during 2000-2022 in China concluded that absorbed photosynthetically active radiation and gross primary productivity decline 0.0094% to 0.0034% and 0.0003 to 0.0002 g/m^2, respectively, within a 1-7 km buffer. The adverse effects last more than three years, magnified during summer and autumn, and are more pronounced at low altitude and in plains. Forest carbon sinks decreased by 12,034 tonnes within a 0–20 km radius, causing $1.81 million economic loss on average [39].

Fiberglass and toxic epoxy pollution

The outer part of most wind turbine blades is made from fiberglass. Fiberglass consists of glass fibers bonded by a plastic, usually epoxy. Normal wear on turbine blades, a phenomenon known as *leading edge erosion*, causes them to shed tiny particles consisting mostly of epoxy. Epoxy typically consists of 40% Bisphenol-A (BPA). BPA is frequently banned because it is an endocrine disrupter and neurotoxin. Academic research has shown the potential for 137 pounds (62 kg) of epoxy microparticles to be shed per turbine per year. According to the United States Geological Survey, there are 72,731 turbines in service in the United States, which could shed almost ten million pounds of epoxy microparticles per year [89]. This estimate might be the number of turbine *blades*, as others estimate 24,000 on land and 8,600 offshore (see Section 4.2) [95].

A special blade coating that contains toxic ingredients from the PFAS[h] family of "forever" chemicals, which are cumulative and not biodegradable, could minimize the erosion. PFAS is also a common ingredient in lubricants and hydraulic fluids that routinely leak from wind turbines.

New York State has banned PFAS from packaging materials and has set a maximum concentration in drinking water of 10 parts per trillion [82]. In March 2023, EPA proposed limits in drinking water of four parts per trillion for two PFAS (PFOA and PFOS), and ten parts per trillion for four others (PFNA, PFHxS, PFBS and HFPA-DA – commonly referred to as *GenX Chemicals*). Public water supply systems would be required to measure and monitor them [88].

When a wind turbine blade breaks, it causes fiberglass to shatter and spread onto the property, and onto nearby properties whose owners didn't even want to have one on their property. Shattered fiberglass ruins crops. Neither people nor cattle can eat fiberglass, so crops cannot be harvested, either for human consumption, or to feed animals. Livestock cannot graze on the grass. If the fiberglass gets into a waterway, it is carried downstream where it cannot be used to water crops or livestock. The owners of one property in Marshall County, Kansas appealed to NextEra, the company that owns a turbine that broke, and to local, state, and federal agencies. There was no remediation, and no apology from NextEra [60].

Blinking lights

Wind turbine towers have red lights on top that blink every three seconds, to warn airplanes. Some are now fitted with an Aircraft Detection Lighting System (ADLS) that only turns on the lights when aircraft are nearby, but that depends upon the aircraft having a transponder. They are required by law to have one. What happens if it's not working? Even if the wind turbine tower has an ADSL-equipped light, it's not autonomous. ADSL systems receive signals from transponders. They attach a time stamp and their location to a message that is sent to a data center, which computes the location of the aircraft using differences in signal arrival times, and then sends signals to certain lights to turn them on. This depends upon the data center and network being in operation, and

---

[h] PFAS is an abbreviation for *per-* or *polyfluoroalkyl substance*.

the receivers' clocks being synchronized. Needless to say, some pilots are unenthusiastic about ADSL. But neighbors of wind turbines are not enthusiastic about red lights blinking every three seconds from dusk to dawn. Some towns in rural communities are entirely surrounded by wind turbines. Some turbines are so close to homes that residents have had to buy black-out curtains. And if you don't have black-out curtains, and your local wind turbines have ADSL, they can still start blinking and wake you up while you're trying to sleep, if an aircraft approaches. Some airports have restrictions on when aircraft are allowed to land or take off, but some people don't respect them. The San José, California airport prohibits them after 11:00 PM. The CEO of Oracle, Larry Ellison, would routinely land at 2:00 AM and happily pay the $10,000 fine.

Noise and shadow flicker

Wind turbines generate a broad spectrum of low-intensity noise. Walls and windows attenuate high frequencies, but have little effect on low frequencies. Low frequency noise is generally not a problem for businesses, public buildings, or outdoors, but it affects people in their homes, especially at night. The most common complaint is annoyance and impact on quality of life caused by sleeplessness and headaches. Some states have low frequency noise standards. For example, the Minnesota nighttime standard in 2009 was that a level of 50 dB(A) was not to be exceeded more than 50% of the time, but this appears to under-weight penetration of low frequency noise into dwellings.

Wind turbine noise depends upon wind velocity. Some wind projects estimate average wind velocity using measurements at a ten meter altitude, and then extrapolate to the turbine height using models. Many studies have found that these models underestimate actual wind velocities when the turbines are erected. Although low frequency noise is generally not perceptible beyond about 1/2 mile, if a turbine is subject to aerodynamic modulation caused by terrain, mountains, buildings, or trees, or different wind conditions through the rotor plane, turbine noise can be heard at greater distances.

Turbine noise that is at a lower frequency than is generally perceptible has many of the same health effects of noise at perceptible frequencies.

Shadow flicker can affect individuals outdoors as well as indoors. It is not limited to daytime; it also occurs on moonlit nights. Shadow flicker appears to exacerbate the effects of low frequency noise.

A report from the Environmental Health Division of the Minnesota Department of Health recommended that wind turbine noise estimates should include cumulative impacts (40-50 dB(A) isopleths[i]) of all nearby wind turbines, that isopleths for dB(C)-dB(A) greater than 10 dB should be determined, to evaluate the low frequency noise component, and that potential impacts of shadow flicker and turbine visibility should

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[i] An *isopleth* is a line on a map connecting points having equal incidence of a specified phenomenon, usually a meteorological feature.

be evaluated [46].

Predatory contracts

Farmers in rural communities are duped into signing one-sided contracts. They are told a lie that they're the only land owner who has not signed a contract to host turbines, while their neighbors had already signed, and that their recalcitrance is holding up millions of dollars of investment, hundreds of jobs, tons of property tax, and oodles of wonderful "free" wind energy. In many cases, the wind turbine company has negotiated a sweetheart deal with a state or county whereby they pay no property tax for ten years, as an indirect subsidy to expand wind energy.

> [W]e were also told that we were the ones holding up the project. That all of our neighbors had signed, and we were the last hold-outs. It persuaded us.
>
> What we didn't know then was the developer was not being truthful. We were not the "last hold-out" at all. In later discussions with our neighbors we found out that in fact we were the very first farmers to sign up. I have since found out this kind of falsehood is a common tactic of wind developers.
>
> By signing that contract, I signed away the control of the family farm, and it's the biggest regret I have ever experienced and will ever experience.
>
> – Gary Steinich, Cambria, Wisconsin. June 2011.

Whales, dolphins, and seals

Whales, dolphins, and seals depend heavily upon sound for essential biological functions, including communication, mating, foraging, predator and ship avoidance, and navigation. Construction and operation of wind turbines creates noise from helicopters, geological and geophysical (G&G) surveys, wind turbine generator (WTG) studies – usually for foundations, pile driving, cable laying, and vessels associated with offshore activities. Such noise might have adverse impacts on marine animals if sound frequencies overlap their hearing ranges. Noise can cause behavioral or physical effects that might interfere with essential biological functions.

G&G surveys for site assessment and characterization can generate high-intensity impulsive noise intermittently over a 2- to 10-year period. This has the potential to affect marine mammals through auditory injuries, stress, disturbance, and behavioral responses. Temporary and permanent threshold shifts in their hearing ability can result.

Operating wind turbine generators produce non-impulsive underwater noise in the frequency range from 10 Hz to 8 kHz that is audible to marine mammals, with intensities from 110 to 125 DB. Sound levels would exceed the behavioral threshold for most marine mammals within 0.9 miles from an operating turbine. That is, about 2.5 square miles of habitat disruption per wind turbine.

The intense impulsive noise caused by impact pile driving can cause behavioral and physiological effects in marine mammals. Behavioral effects include displacement and avoidance. Physiological effects include permanent and temporary shifts in hearing thresholds. Permanent threshold shifts would permanently limit an individual's ability to locate prey, detect predators, navigate, find mates, and avoid ships, and could therefore have long-term effects on individual fitness or survival. Vibratory pile driving produces non-impulsive noise. Similarly to other continuous noise, vibratory pile driving could cause behavioral or physiological effects in marine mammals. Drilling, which may occur during geotechnical surveys and construction, also produces continuous non-impulsive noise.

Dredging for seabed preparation for foundations or cable installation produces noise levels up to 176 dB at one meter using clamshell dredges; hydraulic suction dredges produce noise levels as high as 190 dB at one meter. Although these levels at short distances are unlikely to produce permanent threshold shifts, if they occur in one area for a relatively long time, they might cause temporary threshold shifts.

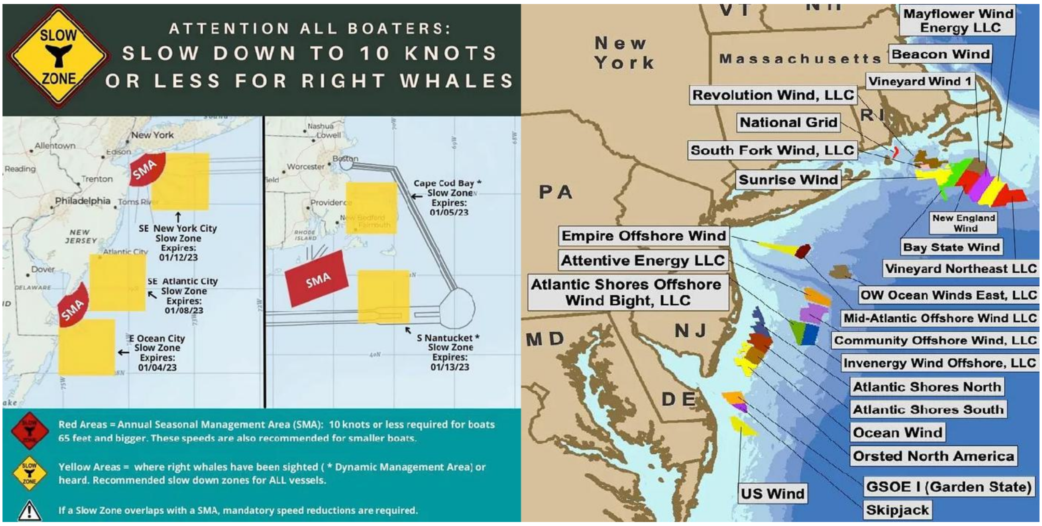
Cable laying noise is less intense, and generally occurs in a small area for only a few hours, which could briefly impact foraging efficiency due to animals devoting more energy to vigilance and avoidance.

Vessels produce low frequency (10 to 100 Hz) non-impulsive noise that could affect marine mammals because the frequency range overlaps their hearing range. Vessel noise propagates long distances because of its low frequency. Potential responses to vessel noise include startle responses, behavioral changes, stress, and avoidance. Vessel noise is known to increase stress hormone levels in critically endangered North Atlantic Right Whales. This might contribute to suppressed immunity and reduced reproductive rates and fecundity. Masking, that is, vessel noise interfering with normal sounds, might affect detection of prey and predators, and affect communication abilities [68, pp. 370-373].

Many people who live in beach communities on the Atlantic coast have concluded that wind turbine operations, construction, and surveying areas in which there are plans to build them, are causing marine mammal deaths.

Since December 2022, at least 30 dead whales have washed up on the East Coast shoreline, including 10 in New Jersey. Many of these are critically endangered North Atlantic Right Whales, of whom only 340 are estimated to be alive. Fishermen have reported dead whales, and pieces of dead whales in their nets. As of September 2023, 71 whale deaths had been documented. This rate is not normal. One fisherman said "in 25 years on the water I had never seen a dead whale; last year I saw three." On 21 March 2023, eight dolphins beached themselves at Sea Isle City. Two of the dolphins died almost

Figure 7.13: NOAA Fisheries and BOEM maps



immediately. Six others were euthanized when their condition deteriorated.

Figure 7.12: Beached whales in New Jersey.

Protect Our Coast NJ, an independent grassroots organization, held a rally at the New Jersey state house to demand that Governor Murphy halt offshore wind development projects. They presented an online petition with more than 500,000 signatures. U. S. Representative Jeff Van Drew, whose district includes shore towns in Atlantic and Cape May counties, introduced a resolution that called for a congressional investigation of the potential negative impacts of offshore wind development. The resolution demands a halt in wind park development and surveying activity pending an investigation into the causes of the whale deaths [38].

As of mid-March 2023, NOAA Fisheries has handed out fifteen marine mammal *incidental take authorizations* to wind projects from North Carolina to Massachusetts. These will allow companies to “take” 111,817 whales, dolphins, and seals. The term “take” refers to harassment, injury, or killing of marine mammals. Included in the 111,817 figure is authorization for 118 “Level A” and 111,699 “Level B” takes. Level A includes permanent hearing loss or other bodily injury. Level B harassment includes behavioral disturbance such as frightening an animal from its normal feeding area, or temporary hearing loss. A deafened whale fleeing into a shipping channel is likely very soon to be a dead whale [40].

A map that is readily available from the Bureau of Ocean Energy Management (BOEM) [87] shows proposed offshore wind turbines precisely where the National Marine Fishery Service has instituted a new *Right Whale Slow Zone* off the coast of Nantucket, Massachusetts [86]. The maps taken together as in Figure 7.13 show that the proposed wind turbine project (30,000 MWe) is in direct conflict with the need to preserve the critically-endangered North Atlantic Right Whale [15]. The Bureau of Ocean Energy Management, under the Department of the Interior, has hijacked fishery management and protection of marine resources from the National Marine Fishery Service (part of NOAA, and under control of the Department of Commerce), and thumbed their nose at any legal restraints that are required by the Endangered Species Act and the National Environmental Policy Act. The cowards at the National Marine Fishery Service stood quietly by and watched while research vessels have been surveying using powerful sonar and seismic devices before even applying for any incidental "take" permits. Sean Hayes, from the National Marine Fisheries Service protected species department fully expects offshore wind development to complete the extinction of the North Atlantic Right Whale [56]. Environmentalists and other anti-humanists have long belabored us about human-caused extinctions. Essentially all of them occurred on islands newly settled or newly discovered by humans. The extinction of the North Atlantic Right Whale would be the first pelagic extinction.

When did environmentalists stop shouting *Save the Whales*! and start shouting *Screw the Whales*!

Crabs

Electromagnetic fields from submarine power cables can affect crabs' physiology and behavior. From the abstract of one study [73]:

> EMF strengths of 250 μT were found to have limited physiological and behavioural impacts. Exposure to 500 μT and 1000 μT were found to disrupt the l-Lactate and d-Glucose circadian rhythm and alter THC [total hematocyte count]. Crabs showed a clear attraction to EMF exposed (500 μT and 1000 μT) shelters with a significant reduction in time spent roaming. Consequently, EMF emitted from MREDs [Marine Renewable Energy Devices] will likely affect crabs in a strength-dependent manner…[j]

Exposure to higher levels of magnetic field strength changed the number of blood cells (hematocytes) in the crabs' bodies, which could have a range of consequences, including making them more vulnerable to bacterial infections. There were changes in sugar metabolism. They store more sugars and produce less lactate. Changes in the species behavior could have significant effects on their population because male crabs migrate up and down the Scottish coast. One of the authors (Lyndon) remarked

---

[j] The Earth's magnetic field flux density is about 50 μT.

> [when the field is] at a strength of 500 microteslas or above, which is about 5 percent of the strength of a fridge door magnet, the crabs seem to be attracted to it and just sit still. That's not a problem in itself. But if they're not moving they're not foraging for food or seeking a mate.... Male brown crabs migrate up the east coast of Scotland. If miles of underwater cabling prove too difficult to resist, they'll stay put. This could mean we have a build-up of male crabs in the south of Scotland, and a paucity of them in the north east and islands, where they are incredibly important for fishermen's livelihoods and local economies.

This particular species of crabs, *Cancer pagurus*, is native to waters off the coastline of Scotland. There is no reason to expect these effects are limited to that species. It is the the most commercially important species of crab in Europe, with 10,000 tonnes harvested yearly from the English channel. It is the UK's second most valuable crustacean catch, and the most valuable inshore catch.

Lobsters

Another study found birth and development defects in lobsters and the same species of crabs. From the abstract of that study [45]:

> Chronic exposure to 2.8 mT EMF [about 28% the strength of a fridge door magnet] throughout embryonic development resulted in significant differences in stage-specific egg volume and resulted in stage I lobster and zoea I crab larvae exhibiting decreased carapace height, total length, and maximum eye diameter. An increased occurrence of larval deformities was observed in addition to reduced swimming test success rate amongst lobster larvae. These traits may ultimately affect larval mortality, recruitment and dispersal.

Lobsters were three times more likely to grow deformed, with bent tail sections most common. The creatures were three times more likely to fail a swimming test, showing that their ability to get to the surface to obtain food would likely be impaired. There were also deformities that disrupted eye development.

One of the authors (Lyndon) told *The Telegraph* "Lobsters were more affected than crabs by the electromagnetic field, at least in the short term.... Both crab and lobster larvae exposed to the electromagnetic field were smaller, which could have an impact on their survival. Underwater, bigger means better able to avoid predators." Lobster species are not yet endangered, but are under sustained pressure because of their commercial value. The studied species of lobster, *Homarus gammarus*, is native to European waters, but there is no reason to expect the effects are limited to that species.

Cooling offshore HVDC converters

Once through cooling systems for power plants, in which cooling water is taken directly from the near-shore ocean or an estuary, cause massive aquatic mortality. According to the NRDC [34]:

> As water is being drawn into a cooling system, full-grown fish and other aquatic life are smashed and trapped against screens at the opening of an intake structure. This is referred to as impingement. In addition, early-life-stage fish, eggs, and larvae are often sucked into the cooling system, where they are harmed by heat, pressure, mechanical stress, and/or chemicals used to clean the cooling system before being dumped back into a water body. This is referred to as entrainment.

New cooling plants are now restricted from using once-through cooling. They build a cooling pond into which water lost by evaporation is replenished much more slowly than it is pumped through the power plant, or they use cooling towers, or both. The Bureau of Ocean Energy Management has apparently not gotten the memo from the Department of Energy. Substations at sea that aggregate power from large wind installations, to transmit the power to shore, will be allowed to use once-through cooling. An official BOEM document contends that the only feasible cooling system for a HVDC Substation is a once through, or open system – the kind that is not allowed for new power plant construction on shore because of its devastating effects on aquatic life. This embarrassing official BOEM document concerning the effects of offshore wind substations admits it knows nothing about how many substations are planned, how big, and where they will be. Before the *Green New Deal*, a National Environmental Policy Act study would have been hundreds of pages. Because conductors in undersea or underground cables are spaced much closer together than overhead lines, the maximum distance for AC transmission is significantly less (see Section 4.2.5). Therefore, power from offshore wind turbines must be converted to DC. Page 1 of the BOEM National Environmental Policy Act study states [63]

> Converting high voltage electricity from AC to DC for long range bulk transmission from offshore wind parks reduces losses of power experienced on AC transmission lines and becomes cost effective within 37 to 60 miles from shore [85]. When electricity is generated offshore, it is converted from AC to DC for transmission from the offshore wind park, then converted back to AC onshore for distribution to consumers. The offshore conversion from AC to DC is accomplished through an HVDC system located in the wind park. The HVDC system converts AC to DC, creating a byproduct of heat in the process. For the system to operate continually, the portion of the conversion equipment that emits heat, called the "thyristor," must be cooled....

> Presently HVDC system structures for an offshore wind park range from about 200 to 400 feet long, 140 to 350 feet wide, 80 to 300 feet high, and weigh several thousand tons [3]....
>
> These structures are likely to get larger as offshore wind parks grow and move further offshore.

How much bigger might they get? How many will be needed? Where will they be? How are they secured in place? How much water will be circulated? What will be the outlet temperature? What species of fish will be impinged, and what will be the effect on fisheries? None of these questions, for which the National Environmental Policy Act requires answers, are answered in the BOEM application [56].

Instead, the report says

> Most filtration systems backflush filters to allow for continuous use, so the collected filtrates will eventually return to the ecosystem; however, larval species will be lost and will not grow to maturity. The number of larval fish and invertebrates lost in the process is difficult to measure. Losses of larval food sources for other species is notable, in addition to the larval species that do not survive to maturity. It is unclear how many marine species do not mature to reproduce and provide fish and shellfish for human and animal consumption.

Birds

Apologists for the wind industry routinely claim that the hundreds of thousands of birds and bats killed by wind turbines aren't a big deal. If you watch a wind turbine operating, you might wonder how it could possibly kill a bird because the blades turn so slowly. But the blades are eighty meters long, and even at a slow rotation rate, the speed at the tip can exceed 350 km/hr (220 mph). No birds or bats can fly that fast. They argue that other forms of energy production, and buildings, and housecats, kill birds too. But housecats are not killing falcons or hawks or eagles or pelicans or vultures or condors.

A 2013 report estimated between 140,000 and 328,000 birds were killed annually by collisions with monopile turbines – both supporting towers and blades. Wind industry secrecy made rigorous analysis difficult, resulting in the large spread of the estimate. Pre-construction assessment of collision risk at proposed sites was unreliable, with no clear link between predicted risk levels and post-construction mortality rates. Predictions frequently considered only total bird populations, but failure to consider species-specific risks resulted in much higher post-construction fatality rates than had been predicted. Mortality rates increase with turbine hub height, and are different in different regions, in particular, somewhat lower in the U. S. midwest. Evaluation of risks to birds is warranted prior to continuing a widespread shift to taller wind turbines. The overall estimate is that five birds are killed per year for each MWe of wind turbine label capacity. The result under Jacobson's plan for 2.5 million MWe (see Section 4.2) would be 12.5 million birds killed every year by wind turbines [55].

Figure 7.14: Golden Eagle

That wind turbines are killing golden eagles was proven in April 2022 when the Department of Justice prosecuted ESI, a wholly-owned subsidiary of Florida-based NextEra, the world's largest renewable energy producer, for the deaths of at least 150 bald and golden eagles (one is shown in Figure 7.14) [69]. The DoJ prosecuted ESI for what it called its "blatant disregard" for Federal wildlife laws. Both bald and golden eagles are protected by the Bald and Golden Eagle Protection act of 1962; it as a Federal crime to kill one, but other threats are increasing. The DoJ said that NextEra rushed to build the Wyoming wind projects known as *Cedar Springs I and II* so that it could meet "deadlines for particular tax credits for renewable energy." That is, they didn't get permits that would have required them to institute mitigation measures to avoid killing eagles because they were racing to get subsidies and tax credits. The DoJ said that NextEra "received hundreds of millions of dollars in federal tax credits for generating electricity from wind power at facilities that it operated, knowing that multiple eagles would be killed and wounded without legal authorization, and without, in most instances, paying restitution or compensatory mitigation" [16]. To whom would the compensatory mitigation be paid? The dead birds' heirs don't care about money. [90].

Figure 7.15: Turkey Vulture

Turkey vultures such as shown in Figure 7.15 are unlikely to win any beauty contests with their more iconic eagle cousins. But they are still apex predators that are critical to a healthy ecosystem. In the wind industry body count, vultures are quickly catching up to eagles. Vultures are heavier than eagles, and rely even more on "coring" thermals to gain altitude. If they are downstream of the blade sweep of a wind turbine, the turbulence can force them downward out of a soaring climb. Turbine blade sweep is part of increasing habitat fragmentation and disruption that is created by increasing wind project construction and operations. Habitat destruction doesn't include just nesting and feeding grounds, but also migratory pathways. Habitat disruption and fragmentation, and avoidance, is equivalent to habitat destruction [2].

The top of a ridge is a favorite place for a wind turbine. It's also where soaring birds go to exploit "ridge lift" – low-altitude winds being forced upward by the ridge – to gain altitude.

Wind turbines don't only kill birds by collisions with their blades. Wind turbines, and associated ship traffic for surveying, construction, and operations, also shift where they choose to fly and land and breed. One large "before and after" study of the German North Sea found that loons (*Gavia* spp.) are particularly vulnerable to anthropogenic activities, including both wind turbines and associated ship traffic. That study found that loons in the German North Sea have been squeezed into a smaller resting area along their spring migratory route, which could make it harder for them to find food. By affecting routes, migratory birds endure longer flights, putting further stress on their individual and population survivability.

There is also indirect evidence that offshore wind turbine facilities reduce food resources for all sea birds. The decrease in loon abundance became significant as far as 16 km from the closest offshore wind facility, as shown in Figure 7.16. Loons belong to the species group that is most sensitive to avoidance of offshore wind facilities. Because they are so sensitive, and because of their concentration in European waters, they have been listed in Annex I of the *EU Birds Directive* and are considered to be particularly threatened by human activities. Because of the hazards to both individuals and populations, they are currently rated as a species group requiring particular consideration with respect to marine turbine spatial planning in Germany and the UK [61].

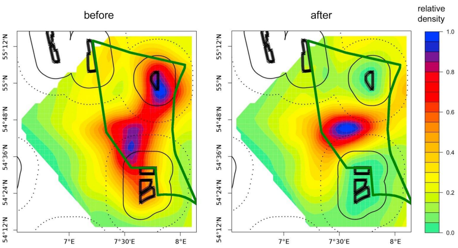


Figure 7.16: Loon distribution in the German Bight

Bats

Bats are also being killed at dangerous rates. The viability of one population of migratory bats, the North American hoary bat (*Lasiurus cinereus*), is threatened. 38% of all bats killed by wind turbines in North America are hoary bats; their population might decline by as much as 90% over the next fifty years. Over 500,000 bats in the United States and Canada, and over 300,000 bats in Germany, are estimated to be killed annually by wind turbines. Risks are difficult to quantify accurately because migratory populations of bats are the ones most frequently killed by wind turbines, but are also the least studied populations. Given the ecology of these populations, the difficulty of empirical measurements of deaths, and reproduction rates, might remain insurmountable for the foreseeable future. Using data for related populations, and estimation of unknown parameters using models, it was estimated that current rates of wind turbine fatalities are sufficiently high to substantially change the probability of population stability and risk of extinction across a broad range of plausible demographic scenarios for hoary bats. The best option, to preserve these populations, until accurate measurements can be done, is to limit the growth of deployment of wind turbines [35].

Canada has now recognized the hoary, eastern red (*Lasiurus borealis*), and silver-hair (*Lasionycteris noctivagans*) bats as endangered species. They have determined that wind turbines have played a major role in their populations' declines [70]. University of Calgary professor of biological sciences Dr. Robert Barclay stated that wind turbines in Alberta kill more bats than they kill birds. It isn't necessary for bats to be struck by a turbine blade to be killed. Getting close can be deadly. According to Dr. Cori Lausen, director of bat conservation for the Wildlife Conservation Society of Canada, flying into a low pressure zone near a turbine blade literally causes the blood vessels in their lungs to explode, much as would happen to a scuba diver coming up too quickly [51].

7.6 Safety

Wind turbines are the least safe "renewable" way to generate electricity. An organization called *Caithness Windfarm Information Forum* had been collecting data for UK and some parts of Europe. They are no longer in a position to collect and publish them, so another organization, called *Scotland Against Spin* has hosted their data, and continues to collect data, which are shown in Table 7.6, with accidents in the first row and fatalities in the second [26].

Table 7.6: Total number of accidents in Caithness data: 3424

Before 2000	2000 2005	2006 2010	11	12	13	14	15	16	17	18	19	20	21	22	23
109	316	602	174	175	182	169	163	166	189	199	235	318	181	180	66
24	16	37	16	17	5	3	8	6	9	4	5	9	3	3	0

Fatal accidents: 165; Fatalities: 229

The data in Table 7.6 are indicative, but by no means comprehensive. More likely, they are just the "tip of the iceberg." *The Daily Telegraph* reported 1,500 accidents and incidents on UK wind parks during the previous five years [57]. The article from Scotland Against Spin described a 2019 report from *Energy Voice* and *Press and Journal* of 81 cases where workers had been injured in UK wind parks since 2014, but their data included only 15 of those. They described an article from *Wind Power Engineering and Development* that reported 865 UK off-shore accidents during 2019, but their data included only four of them.[k] An article from *Energy Voice* reported 500 UK onshore accidents in 2020, but Caithness data included only five of those [81]. They cited another article that reported 737 incidents, but their data included only five of those [48].

The *G+ Offshore Wind Health & Safety Organisation* has reported enormous numbers of incidents during the past decade, but fortunately no fatalities, in UK wind development, as shown in Table 7.7 [67]:

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[k] The *Scotland Against Spin* article did not provide citations for these reports.

Table 7.7: Incident Reports from G+ Global Offshore Wind Health & Safety Organisation

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
616	994	983	997	2200	854	865	743	780	868

Kim et al reported 339 wind-related accidents and 93 fatalities between 1800 and 2018. Of course, essentially all wind-related accidents occurred since about 1990. Their analysis was limited to freely available data; they did not have access to data sets that are behind paywalls. They compiled information from open sources in English, Danish, French, German, Russian, and Korean, with data in Chinese conspicuously absent. When measured in terms of the amount of energy produced, wind was by far the most dangerous, 152 fatalities per TWh, 697 times more dangerous than gas. Because of the enormous number of fatalities caused by the failures of the Banqiao and Shimantan dams in China in 1975 (26,000 fatalities), hydro was the second most dangerous, 46 fatalities per TWh, about 213 times more dangerous than gas. With the exception of 116 fatalities caused by the failure of the Belci dam in Romania in 1991, hydro in OECD countries caused only 14 fatalities between 1970 and 2018, or 0.025 fatalities per TWh [52, Table 3].

An organization called *RenewableUK* also has a database, that it has not published. The UK wind industry is apparently allowed to operate with "guarantees of confidentiality" of incidents reported; no other energy industry works with such secrecy.

The most common wind turbine operational accident is blade failure, closely followed by fire. In 2015, the industry publication *Wind Power Monthly* estimated 3,800 blade failures per year, or 0.54% of the 700,000 blades operating at that time worldwide [19].

A 2015 report by *GCube Underwriting* entitled *Towering Inferno* (which is no longer available) reported fifty turbine fires per year among 300,000 turbines operating, or a rate of one fire per 6,000 turbines per year [37]. With 72,000 turbines in service in the United States, the average is expected to be twelve fires per year, increasing as more turbines are installed. As with other accidents related to wind power, the incidence of fires is probably also under reported. Although turbine fires are greatly outnumbered by blade or gearbox failures, when they do occur they lead to high-profile losses that can have huge financial impact. Even with fire suppression devices included in turbines, a fire typically results in total or near-total loss of a multi-million dollar asset. Between asset loss and downtime, GCube estimated the loss at $4.5 million per fire, or $27 billion per year.

After a fire near Rexville, New York (shown in Figure 7.17), six local families and property owners were impacted. Several people were exposed to airborne fiberglass. Livestock were affected and croplands were contaminated. Local governments are becoming concerned, but, at least in New York, they seem to be superceded by state policy. Local zoning laws, or objections from adjacent property owners, cannot stop a landowner from making a deal with a wind energy company. Local governments are hoping they can demand more security from developers. Bonding is likely to be a central issue both for local governments and property owners.

Many multi-million dollar projects, whether they are solar, wind, pipelines, or mines, require the developer to insure against disaster or pay for deconstruction and remediation. Before the project begins construction, the bonds as required by law must be in place and remain in place during ownership. All too often, the bond issued to secure a project is not sufficient to cover the cost of a worst-case scenario. In the case of the Rexville fire, the bond is apparently only a fraction of what is needed to cover community and landowner losses [44].

Figure 7.17: Wind turbine fire near Rexville, NY.

Two engineers, aged 19 and 21 years, were killed in 2013 by a fire that started during maintenance at Deltawind's Piet de Wit wind park on the Mariadijk in Ooltgensplaat on Goeree-Overflakkee in the Netherlands. One of the victims was found on the ground under the turbine. Another was found on the turbine after the fire brigade had extinguished the fire. The turbine was 80 meters tall, so the fire brigade was not able to extinguish the fire for several hours. Two other workers escaped by jumping through flames to a staircase [84] [72].

Turbine fires have also caused bush fires in South Australia and California. As the number of installations increases in remote forested regions, the risk of consequential forest fires increases.

In 2014, the Ministry of Health in Finland mandated a minimum distance of 2 kilometers between wind turbines and housing. In 2016, Bavaria adopted a similar requirement (and required the same distance from a woodlot). Ireland is proposing a similar measure to take effect in late 2023. Buffalo County Nebraska voted to have a 3 mile (4.8 km) separation between wind turbines and churches, hospitals, and agricultural residential property, and a 5 mile (8 km) separation from villages or towns. Why are they doing that? Because if a wind turbine catches fire, and the fire brigade shows up, about all they can do is watch, and try to put out any secondary fires that result.

Solar power is about 345 times safer than wind power, but nowhere near as safe as gas or hydro in civilized countries. One estimate is that every terawatt hour of energy produced via rooftop solar PV results in 0.44 deaths, mostly from electrocution or falls [50] [23]. Data concerning industrial solar are apparently not available. California is now producing about 53 TWh per year from solar PV (see Figure 8.6). If the same death rate is assumed for rooftop and industrial solar, the yearly number of solar PV-related deaths in California alone is about 23.

7.7 Disposal

At the end of the life cycle of green energy projects, mountains of discarded solar panels and wind turbines are piling up. Many local governments have long required reclamation bonds before they will permit mines, or oil and gas wells. Some are now starting to require them for solar and wind projects.

7.7.1 Solar panel waste

Figure 7.18: Discarded solar panels.

Because of their low energy density, at the end of their useful lives, solar panels will constitute a huge amount of waste. The International Renewable Energy Agency (IRENA) estimated in 2016 that about 250,000 tonnes of solar panel waste had been accumulated worldwide. They projected this would reach 78 million tonnes by 2050 [92]. Solar panels are already a big problem, and the problem will only get bigger, expanding as rapidly as the solar PV industry expanded during the last decade, as the current generation of panels begins to wear out. Advocates insist that dumping them in landfills is safe, but antimony, lead, carcinogenic cadmium, and other toxic metals can be washed out rapidly by rainwater, so they must be dumped in expensive specially designed sealed landfills – or recycled. Unfortunately, the cost of recycling is enormously more than the value of the recovered materials. Many are simply abandoned, as shown in Figure 7.18.

The average weight of solar panels is 53.9 tonnes per megawatt of label capacity [5]. Using the 24.5% capacity factor from [24], the mass is 220 T/MW of delivered power. Jacobson et al estimated 603.7 GWe, or 37.9% of their estimate of 1,591 GWe total necessary, would be produced by solar panels (see Section 4.2). 133 million tonnes of solar panels would be in service. With a 1,700 GWe economy, the amount would be 142 million tonnes. Assuming a 25 year life, 5.7 million tonnes of solar panels would be taken out of service every year. In an all-electric 1,700 GWe American energy economy, with the proportion of solar panels advocated by Jacobson et al, during the 34 years that IRENA estimated 78 million tonnes of solar panel waste would be accumulated worldwide, 193 million tonnes would be accumulated in the United States alone.

7.7.2 Wind turbine waste

As New York State Assemblyman John Goodell (R-Jamestown) was driving down Interstate 86 year Bath, New York, he wasn't sure what he was seeing. Intrigued, he turned his car around to investigate. He saw a pile of discarded wind turbine blades more than fifty feet high, and strewn along beside the highway for more than the length of a football field. Goodell said "Although there are massive governmental incentives for the construction of green energy projects, there is virtually no consideration regarding the long-term environmental impact when these projects are no longer financially viable." He has proposed legislation, along with State Senator George Borrello (R-Sunset Bay), to create a state requirement that solar and wind companies provide the state Office of Renewable Energy Siting or Public Service Commission with reclamation bonds to decommission solar and wind projects at the end of their useful lives [94].

Figure 7.19: Blades being buried

New York is not alone. A Washington state company named Global Fiberglass Solutions, Inc., has a combined 1,300 discarded wind turbines stored at three sites in Newton, Ellsworth, and Atlantic, Iowa. Since 2017, the company has said it plans to recycle the blades. They told authorities in Sweetwater, Texas that they planned to turn old blades into plastic pellets or panels for reuse. Their website also says they plan to make railroad ties from them. So far, they have not done anything other than abandon blades at various storage sites.

Global Fiberglass Solutions faced a series of Iowa Department of Natural Resources (DNR) orders and agreements but missed deadlines to recycle the blades, bury them in certified landfills, or ship them out of state. The company also failed to provide a $2 million bond to cover the costs of disposal if the firm abandoned the sites. The owner of the Newton site considers the 868 blades to be abandoned. Global still owes the site $1 million in rent. State officials fear taxpayers could have to pay. On 7 July 2021, the Iowa Environmental Protection Commission voted to refer the DNR case against Global to the attorney general's office [10].

In Oregon, one so-called wind turbine blade "recycler" was whacked with a $57,282 fine for dumping hundreds of dilapidated blades right next to a natural spring and wetland. It made the bogus claim that the 2,741 cubic yard cocktail of fiberglass and toxic plastics amounted to "clean fill."

There is now an urgent search for alternatives in places that lack wide-open prairies. In the U.S., they go to the handful of landfills that accept them, in Lake Mills, Iowa, Sioux Falls, South Dakota, and Casper, Wyoming, where they will be interred in stacks that reach 30 feet underground.

For wind power outfits trying to play hide and seek, someone should point out that 40-60 meter long chunks of plastic, fiberglass, balsa wood, and resins – that weigh between 10 and 20 tonnes – are not that easy to miss. Especially when they're piled 50 feet high beside an interstate highway.

Tens of thousands of aging blades are coming down from steel towers around the world and most have nowhere to go but landfills. In the U.S. alone, about 8,000 will be removed in each of the next four years. Europe has been dealing with the problem longer.

They have about 3,800 coming down annually. It's going to get worse: Most were built more than a decade ago, when installations were less than a fifth of the size they are now. One study estimated that there will be 43 million tonnes of wind turbine blade waste by 2050, with 40% in China, 25% in Europe, 16% in the United States, and 19% in the rest of the world [54].

Albers et al estimated that ten tonnes of rotor blades are required for each megawatt of wind turbine label capacity [9]. With a 40% capacity factor, 25 tonnes are required per delivered megawatt. The Energy Information Agency has estimated that the ratio of solar to wind net summer capacity will be 66:34 in 2050 [83]. If an all-renewable all-electric American energy economy with an appetite for 1,700 GWe were powered exclusively by solar and wind, the contribution from wind turbines would be 580 GWe. At 25 tonnes per megawatt, the total mass of wind turbine blades would be 14.5 million tonnes. Assuming they last twenty years means it will be necessary to dispose of 723 thousand tonnes per year in the United States alone. Jacobson et al estimated wind would contribute exactly 50% of total energy, resulting in the requirement to dispose of 1.06 million tonnes of blades per year [49]. If the 1,300 discarded wind turbines in Iowa are aged one megawatt label capacity turbines, the 13,000 tonnes of blade waste accumulated there represents 1.2% of the estimated yearly total.

"The wind turbine blade will be there, ultimately, forever," said Bob Cappadona, chief operating officer for the North American unit of Paris-based Veolia Environnement SA, which is searching for better ways to deal with the massive waste. "Most landfills are considered a dry tomb. The last thing we want to do is create even more environmental challenges" [59].

What these stories tell us is "green" and "sustainable" are poisoning the Earth and destroying the lives of vulnerable populations. As Michael Shellenberger asked: "Must we destroy the environment to save the planet?" [75].

7.8 Recycling

7.8.1 Solar panel recycling

Solar panels are difficult to recycle. They are composed of about 90% glass by weight, but the glass cannot be simply recycled as float glass because it contains impurities such as plastics and toxic metals including antimony, lead, and carcinogenic cadmium. Recycling one costs $30-45, while dumping it in a landfill, where allowed, costs about $5.

The IRENA study cited in Section 7.7.1 estimated that "if fully injected back into the economy, the value of the recovered material [from solar panels] could exceed $US 5 billion by 2050" [92]. But that was the gross value, not the net after costs, and the study did not compare the value of recovered material to the cost of new material. Today, recycling costs are greater than the economic value of the materials recovered, not least because the materials in solar panels are not intrinsically valuable. About thirty years ago, a glass recycler had to dispose of several thousand tonnes of glass in a landfill because he couldn't find a buyer. That glass was relatively contaminant-free beverage bottles and food jars.

The cost of labor, even unskilled labor, to disassemble modules and separate steel and aluminum frames from panels is significant. The cost of recycling could be built into the purchase price by requiring manufacturers to accept worn out panels for recycling. But that would increase the risk of financial failures of those companies, and then the cost of recycling would be borne by the public. Most governments, even in developed countries, are not prepared to deal with an influx of toxic waste. The problem is much more severe in developing countries. Some companies that advertise themselves as solar panel recyclers simply sell them to countries that have a lot of land and just want cheap panels [74].

7.8.2 Wind turbine blade recycling

In addition to balsa wood and steel, wind turbine blades are made from polymer composites reinforced mainly with fiberglass and carbon fiber, or a hybrid combination of the two. The main resins used are high-grade epoxy and polyester. The usual manufacturing processes use pre-impregnated fabric, or vacuum-assisted resin transfer molding. The reinforcement appears to be moving toward carbon fiber, which will exacerbate the recycling and disposal problem.

The company ReFiber ApS in Roslev, Denmark, developed a process to separate resin from other components by anaerobic pyrolysis at 600°C. The evaporated resin is incinerated at 1,100°C to produce energy, either for process heat or electricity. Glass, metal, and fillers are then separated. Although the fiberglass loses 40% of its tensile strength during high-temperature pyrolysis, its ductility remains, and it can be re-used as, for example, insulation. Metals and recovered carbon or carbon fibers are sold. As of 2005, the company had plans for a 5,000 tonnes per year plant, but there is nothing newer on their web site.[1]

Before any chemical process can be applied to wind turbine blades, they must first be crushed or cut into smaller pieces. Built to withstand hurricane-force winds, the blades can't easily be crushed, recycled or repurposed. Most blades are bigger than a Boeing 747 wing. To cut them up to fit on a trailer to get to a landfill, a diamond-wire saw such as is used at a quarry is necessary. At present, there are no tools for the dimensions concerned, the abrasion of tools is tremendous, and the formation of dust and fine particles, or outgasing of residual solvents, are health and safety hazards [9].

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Chapter 8

Renewable energy storage requirements

> *Wind was extremely inconvenient for the purpose of pumping [water out of mines] because in these latitudes it is inconstant: it was costly, too, because at any time the labourers might be obliged to sit at the pit's mouth for weeks together whistling for a gale.*
> – H. G. Wells [15] (1901).

Yes, Virginia, there were wind droughts in England before 2021.

8.1 Storage situation is worse than others have calculated

Using one year of generation data for all of England and Scotland with one hour resolution, Euan Mearns calculated that to avoid outages, 390 watt hours of storage would be needed per watt of average demand [8]. Using one year of generation data from Texas with one hour resolution, Norman Rogers calculated that storage capacity of 400 watt hours are needed per average watt of wind and solar capacity [11]. Matt Shaner et al used 36 years of geophysical data for all of North America with one hour resolution to calculate that 400–800 watt hours of storage are needed, depending upon location and the mix of solar and wind [12].

The following graphs were prepared using data from the California Independent System Operator (CAISO) with one hour resolution from 1 January 2011 until 30 November 2020, and five minute resolution thereafter [10], and nationwide data from the US Energy Information Administration with one hour resolution since 1 July 2018 [13].

They show the net energy content (or deficit) that would have been in storage, assuming all supply came from renewable sources and storage charge and discharge are 100% efficient. At first, the analyses assume a system with unlimited but empty storage capacity at the beginning of the study period. Analyses are repeated with bounded storage capacity.

At first, quantities in storage are calculated by assuming average renewable capacity is equal to average demand. In later sections, the effect of average renewable supply being larger than average demand is analyzed. The method of calculation used here is explained in Section 8.7 below.

8.2 Daily average for solar and wind

The top left graph in Figure 8.1 shows that solar and wind outputs decrease at the time when demand increases – people come home from work, plug in the EV, turn on the air conditioner, turn on the television, and cook dinner.

The bottom left graph shows the average daily trend for solar and wind output, as a fraction of average total demand during the period of analysis.

The top right graph shows what fraction of total demand would be satisfied by solar and wind, if they were the only sources and their average output were magnified to equal average demand.

The bottom right graph shows the average daily variation of the amount of energy that would be in storage if solar and wind were the only sources and their average output were magnified to equal average demand. The vertical axis is watt hours in storage per watt of average solar + wind production. This rather rosy average-day picture is the basis for claims that only small amounts of storage are necessary. But look carefully and you'll notice that the average daily deficit is four watt hours per watt, while the average surplus is three watt hours per watt: Storage is being continuously depleted.

8.3 California energy in storage 2011-2023

When a time range longer than one day is considered, it is clear that the daily average is not an adequate description.

Some days are better than average, and some are worse. It is necessary to consider the cumulative effect of good and bad days, especially the cumulative effect of consecutive good and bad days.

The graph in Figure 8.2 shows the amount of energy that would have been in storage in California with an all-renewable energy system. The units of the vertical axis are watt hours in storage per watt of average demand, compared to the amount in storage on 1

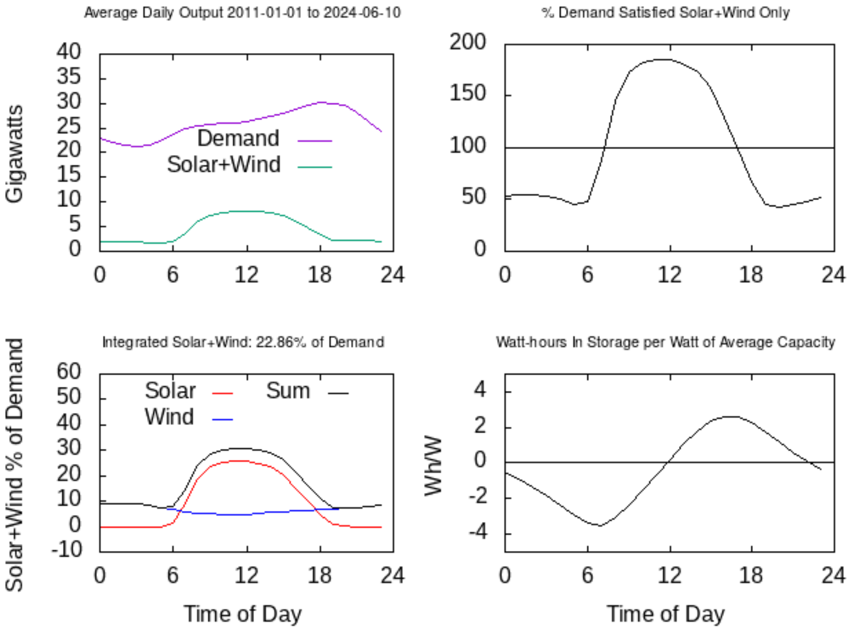

Figure 8.1: Daily Averages

January 2011.

The "Unweighted" (green) line multiplies the output of all renewable generators by the same factor so that their total average output is equal to average demand. It is unlikely that biomass, biofuel, and hydro can grow much. Environmentalists want to remove dams, and they complain that fracking for geothermal causes earthquakes.

The "Weighted Increase" (purple) line is computed by magnifying renewables in proportion to the rate of change of their capacities, with a different rate in each year.

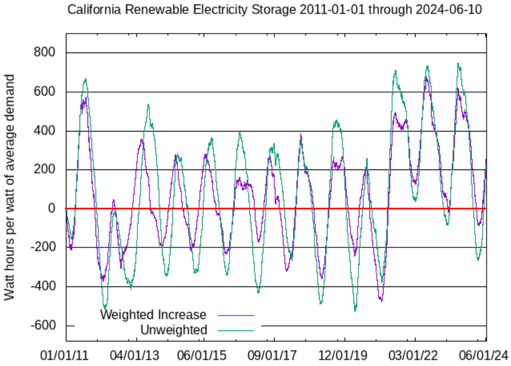

Figure 8.2: Energy in storage

The maximum surplus calculated using "Weighted Increase" was 492 watt hours per watt on 22 August 2011. The deepest deficit was 673 watt hours per watt on 23 March 2023. To avoid outages and to avoid dumping power when more is available than demand, and storage is already charged to full capacity, a storage system would need to have a capacity of 492 + 673 = 1,165 watt hours per watt of average demand (almost 50 days), and to have been precharged to 673 watt hours per watt of average demand on 1 January 2011 to avoid outages. The effect of precharging would be to shift the graphs upward by 673 watt hours, and the "Weighted Increase" (purple) line would nowhere have been negative.

The yearly average maximum and minimum were 372.6 watt-hours per watt and −198.9 watt-hours per watt, an annual swing of 571.5 watt-hours per watt. The surplus-deficit cycle has an obvious one year period. Although there would, on average, be daily charge-discharge cycles of about 7 watt hours per watt of average demand, during their ten year lifetimes, batteries would be nearly fully charged and discharged ten times. To break even on operating (not capital) costs, they would need to sell electricity at 57 times the usual rate. This assumes that batteries could hold the surplus for six months until it is needed, and wouldn't be damaged by deep discharge cycles.

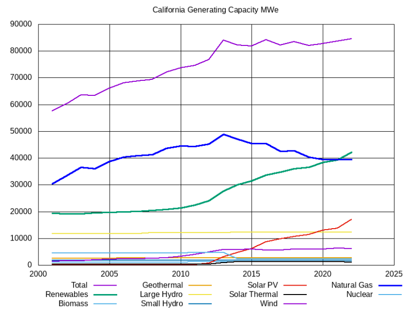

Figure 8.3: California Generating Capacity

Renewable sources provided 35.8% of electric energy. Without storage and with only renewable sources, when the trend of the amount was negative, i.e., 23.9% of the time, there would have been outages. With unlimited storage capacity, not precharged, when the amount in storage was negative and the trend of the amount was negative, i.e., 13.5% of the time, there would have been outages (see Section 8.7 below). The industry definition of *firm power* is 99.97% availability, or about two hours and forty minutes of outage per year.

Total label generating capacity amounts, shown year by year for each generation method in Figure 8.3, were obtained from the California Energy Commission [5].

The rate of change of total renewables has not changed significantly since 2012, when solar PV began increasing rapidly, and wind and solar thermal stopped increasing.

8.4 Nationwide analysis

The Energy Information Administration provides nationwide hourly generation data from 1 July 2018 onward [13]. The same analysis was conducted using these data. The growth factors used to magnify individual renewable generation methods, shown in Table 8.1, were calculated as the difference between 2021 capacity and 2027 projections (GWe) provided by the Energy Information Administration [1]. These were divided by their sum to provide relative magnifications. See Section 8.7 below.

Table 8.1: Unnormalized Weights

Geothermal	Biomass	Municipal Waste	Wind
0.4	0.0	0.7	20.3
Solar PV	Solar Thermal	Hydro	
103.7	0.0	0.2	

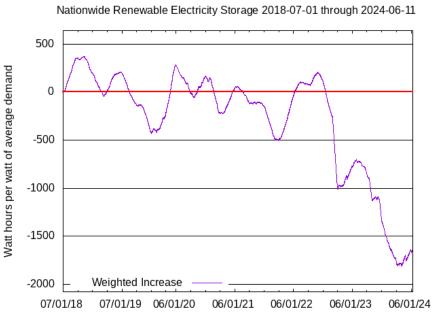

Figure 8.4: Nationwide Storage

The largest surplus shown in Figure 8.4 was 267 watt hours per watt of demand on 21 June 2022. The deepest deficit was 696 watt hours per watt of demand on 2 March 2023. The storage capacity required to avoid outages is 267 + 696 = 963 watt hours per watt of average demand, i.e., 40 days of storage capacity would have been necessary.

Jacobson et al described a nationwide system containing only wind, water, and solar generators. They estimated a requirement for 541.6 TWh storage. Providing 963 watt hours of storage per watt of average demand, for average demand of 1.7 TWe, would require 16.4 quadrillion watt hours of storage, about 30,500 times more than Jacobson et al envisioned [7, Table S11].

Renewable sources provided about 10% of nationwide electric energy, or about 3% of total energy. Without storage and with only renewable sources, when the trend of the amount was negative, i.e., 59.9% of the time, there would have been outages. With unlimited storage capacity, not precharged, when the amount in storage was negative and the trend of the amount was negative, i.e., 19.9% of the time, there would have been outages.

8.5 Cost of Storage

The May 2020 price for Tesla PowerWall 2 was $0.543 per watt hour (not kilowatt hour) of capacity, including associated electronics but not including installation. Individual installation costs range from $0.142 to $0.214 per watt hour of capacity. Industrial scale systems might get price breaks. Instead of projected decreases, the price of a 13.5 kWh Tesla PowerWall 2 is now between $.681 and $1.33 per watt hour.

Activists insist that an all-electric United States energy economy would have average demand of about 1,700 GWe. Assume that 963 watt hours of storage per watt of average demand is adequate forever (this is optimistic). The total cost for Tesla PowerWall 2 storage units, not including installation, using the 2020 price, with $963 \times 1.7 \times 10^{12} = 1.64 \times 10^{15}$ watt hours' capacity would be $1.64 \times 10^{15} \times \$0.543 = \$0.89$ quadrillion, or about 52 times total US 2018 GDP (about $20 trillion). Assuming batteries last ten years (the Tesla warranty period), the cost would be **4.4 times total US 2018 GDP per year.** The cost for each of America's 128 million households would be about $694,350 per year. Prices that include installation would be 25–40% greater. This analysis assumes 100% battery charge and discharge efficiency. They're closer to 90% (81% round-trip), so the necessary capacity increase would add about 25% more. Taking both installation and the necessary capacity increase into account results in a 75% cost increase to about **7.8 times total GDP every year**. Using current prices, the cost would be **almost 17 times total GDP every year**.

Elon Musk would have more money than God.

California average electricity demand is 26 gigawatts. The 1,700 GWe average demand that activists insist an all-electric American energy economy would have is about 3.83 times total current electricity demand of 444 GWe. Assuming the same ratio for California, total electricity demand in an all-electric California economy would be 99.6 GWe, so the total storage required would be $99.6 \times 10^9 \times 1,216 = 121$ trillion watt hours. The cost for California would be $6.57 trillion per year (using 2020 prices), or "only" about three times total California GDP every year, or about 5.25 times total California GDP when accounting for installation and 81% round-trip efficiency.

The energy density of lithium ion batteries is 230 watt hours per kilogram (see Section 6.1). A capacity of 1.64×10^{15} watt hours for the entire USA would weigh 7.1 billion tonnes, about 2.56 times more than Professor Michaux's optimistic estimate for the total amount of storage needed worldwide. Table 8.2 shows most of the ingredients of a lithium ion battery, and uses Michaux's optimistic estimate to compare requirements to reserves [9].

Table 8.2: Materials Needed for Lithium Ion Batteries

Material	Proportion in batteries (%)	Mass in 2.779 billion tonnes of batteries	Global Reserves (2018)	Required ÷ Reserves
Copper	17.0%	498	880.0	1.69
Aluminum	8.5%	236	32,000	0.022
Nickel	15.19%	422	95.0	14.1
Cobalt	2.79%	67.5	6.9	33.5
Lithium	2.17%	60.3	22	13.0
Graphite	22.0%	611	320.0	5.51

Other than aluminum, the Earth does not contain enough metals to make the first generation of necessary batteries for the United States alone! Batteries last about ten years, and are not completely recyclable. Even if the first generation could be built, where would the second generation come from?

Presented with these quantities, activists propose other methods, such as pumping water up mountains. In California, where would we get the water and where would we put it? The Oroville Dam at 771 feet or 235 meters is the highest dam in the country. The area of Yosemite Valley is 6 square miles, or about 15 square kilometers. Assuming it's flat (which it isn't), building a 235 meter dam across the entrance could impound 4.17 trillion liters, or 4.17 trillion kilograms, of water. The mouth of the valley is 1,200 meters above sea level, so the top of the full reservoir would be 1,435 meters above sea level. The potential energy, in joules (watt-seconds), of a mass m lifted to a height h in a gravitational field with acceleration g (9.8 meters per second squared at the surface of the Earth) is mgh. Assuming a power plant at sea level, not at the base of the dam, the water in such a reservoir would have potential energy of about $4.17 \times 10^{12} \times 1,200 \times 9.8/3600 = 13.6$ trillion watt hours. The Betz limit for the efficiency of a turbine is 57% [3]. California would need at least 104 trillion / (0.57×13.6 trillion) = 13.5 of these reservoirs. If the power plant were at the mouth of the valley instead of at sea level, about 94 would be required. The nation as a whole would need almost 1,300. All of this assumes optimal conditions and unrealistically large efficiency, in particular, no loss to friction or turbulence in the tunnels, so in reality much more would be required.

Corrected 2024 April 10

Opportunities for reservoirs the size of Yosemite Valley are limited. The *Snowy 2* project in Australia is planned to connect two reservoirs with capacity of 254099 million liters, separated by an elevation of 680 meters. Water is to be pumped between the reservoirs in 27 kilometers of tunnels (Yosemite Valley is 250 kilometers from San Francisco Bay). One of the three tunnel boring machines, called "Florence," was stopped by a cave-in less than a kilometer from the start, and has not been recovered or restarted. If the capacity of Snowy 2 were calculated as above, the result would be 470 GWe-hours. The advertised efficiencies are 67-76% depending on output of 1,000–2,000 MWe, or 315–357 GWe-hours [4].

The United States would need 8,200 such systems. There are currently 1,450 conventional hydroelectric power plants, and 40 pumped storage plants, in the United States. The current budget for Snowy 2 is $AU 4.8 billion = $US 3.26 billion, but many expect the project to exceed $AU 20 billion = $US 13.6 billion. The project is scheduled to be completed in 2029, but many believe it will not be completed. The total cost for 8,200 such projects in the United States would be $96 trillion – if we could find places for them and water to use them.

Total rainfall in a particular river's watershed is cyclical. In 2022, Lake Mead was almost empty. Texas has a more difficult problem than California, with water in the East but no mountains, and mountains 1,000 miles to the West but no water. A statistical analysis of data from the Shuttle Radar Topography Mission showed that Kansas is indeed as flat as a pancake.

The next proposal is towing weights up mountains or old mine shafts. How many are required? The storage requirement is 963 Wh/W × 1,700,000,000,000 W × 3600 seconds/hour = 5.9 quintillion watt seconds, or joules. Assuming 100% efficiency, a ten tonne weight, and a one kilometer lift, the result is "only" 57 million such devices. Where would these be put? How much would they cost, per year and per kWh, taking into account capital, amortization, operations, safety, maintenance, replacement, decommissioning, environmental effects, and disposal or recycling?

8.6 EU Analysis

Generation data for solar and wind, and total demand, were obtained for EU countries from 1 January 2015 until 30 September 2020 with resolution of one hour [6]. Generation data were not provided for any other renewable sources. Not having projections for capacity growth, the relative weights for the increase of solar and wind were taken from their average generation growth rates: 24.23% per year for solar and 32.48% for wind (see Section 8.7 below). Unfortunately, data for the 2022 Dunkelflaute were not available.

During the interval for which data were available, renewables provided 11.4% of electricity for EU as a whole, 46% for Denmark, and 28.3% for Germany. Figure 8.5 shows that if solar and wind had been the only generators, for EU as a whole, the largest surplus in storage of unlimited capacity would have been 355 watt hours per watt of average demand, and the deepest deficit would have been 598 watt hours per watt.

To provide firm power without dumping energy when batteries are fully charged, 355 + 598 = 953 watt hours of storage capacity per watt of average demand would have been needed. Without storage and without other generation sources, there would have been outages 55.5% of the time, i.e., whenever the slopes of the lines in this graph are negative. Although the patterns for EU as a whole, and for Denmark and Germany alone, are different, the storage situation is almost identical for Germany: 969 watt hours of storage would be required, and there would have been outages 55.2% of the time without storage if the only generators were renewable sources. Denmark fared somewhat better, requiring only 783 watt hours storage, and would have had outages 54.9% of the time without storage and if the only generators were renewable sources.

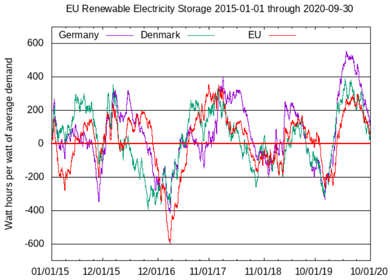

Figure 8.5: EU Storage

8.7 How the graphs were computed

To compute the amount of energy accumulated into (or discharged from) storage at any particular instant, using historical data, start by computing the difference $\delta(t)$ between what instantaneous power production would have been if renewables were the only source, and instantaneous demand, both in watts per watt of average demand.

The amount of energy in storage at time t since the beginning of the analysis, in watt hours per watt of average demand, is then obtained by accumulating the instantaneous power surplus (or deficit) $\delta(t)$ in each measurement interval, multiplied by the interval length (energy = power × time), i.e., computing the integral:

$$S(t) = \int_0^t \mathrm{d}\tau\, \delta(\tau) \approx \sum_{n=1}^{N} \delta(t_n)\, \Delta t_n$$

where $\delta(t)$ has units of watts of surplus (or deficit) per watt of average demand, N is the number of measurement instants, Δt_n (the duration of a measurement interval) has units of hours, and $S(t)$ has units of watt hours per watt of average demand. $S(t)$ is plotted in the graphs.

Rectangular quadrature is justified by the fine resolution of measurements – Δt_n was one hour for California from 1 January 2011 until 30 November 2020, and five minutes thereafter, and one hour for the other data.

To use historical data to compute what $\delta(t)$ would have been if all sources were renewable sources, it is necessary to increase measured renewables' average production to match average demand. Let $\overline{R}$ be current average renewables' production, and $M\overline{W}$ be the additional average renewables' production needed to match average total demand $\overline{T}(t)$, where $\overline{W}$ is a weighted average of renewables' production, and M is a magnification factor. Then

$$\overline{R} + M\overline{W} = \overline{T}, \text{ or } M = \frac{\overline{T}\,\overline{R}}{\overline{W}} .$$

To compute the relationship of $S(t)$ to average total demand, that is, how much storage capacity is needed per watt of average demand, we need

$$\delta(t) = \frac{R(t) + GMW(t)}{\overline{T}} - \frac{T(t)}{\overline{T}} = \frac{R(t)}{\overline{T}(t)} + G\frac{W(t)}{\overline{W}(t)}\left(1 - \frac{\overline{R}(t)}{\overline{T}(t)}\right) - \frac{T(t)}{\overline{T}} ,$$

where G is a general growth factor that allows to increase the weighted average of renewables' production above average demand,

$$R(t) = \sum_{i=1}^{N} R_i(t), W(t) = \sum_{i=1}^{N} g_i(t) R_i(t), \text{and } \sum_{i=1}^{N} g_i(t) = 1\,.$$

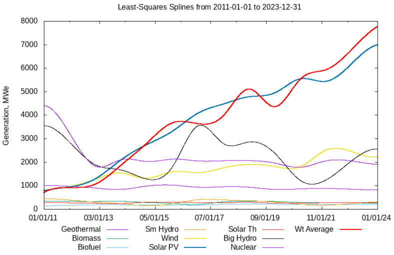

Figure 8.6: Least-Squares Splines

As remarked above, $g_i(t)$ were computed as the rate of change of each renewable's generating method, separately in each year for California, and once using a projection for nationwide generation. Therefore, for California, the proportions by which different methods are increased are different each year, and the accumulated surplus (or deficit) of energy in storage is computed as if the generation capacities had been magnified, during that year, to be sufficient to meet average demand. The relationships of rates of increase in California have not significantly changed since about 2012, when solar photovoltaic capacity began increasing rapidly, and construction of new wind capacity stopped. If all $g_i(t)$ were equal and constant, this method would assume that all renewable sources can be magnified by the same amount $(\overline{T} - \overline{R})/\overline{W}$ so as to increase their total average output to total average demand (the green line in the graphs). This is not going to happen. For example, environmentalists want to remove dams, not build more of them. In the initial analysis we assumed $G = 1$. Later, we examine the effect of larger G.

Because neither average demand nor average renewables' production are constant, the "instantaneous" average demand and production were computed using least-squares fits to cubic splines having second-order continuity,[a] with slope (m_i) constraints at the ends of the interval given by least-squares fits to straight lines, $\overline{R}_i(t) \simeq m_i t + b_i$. The slope constraints are necessary because the interval of analysis does not necessarily begin or end at the end of a year. Without it, the "instantaneous" average near the beginning or end of the interval would be anomalously small or large compared to a similar instant in the middle of the interval. The results are shown in Figure 8.6.

The "Wt Average" line in Figure 8.6 is for the weighted average $\overline{W}(t)$.

An example of this method to compute the "instantaneous" average is illustrated for total demand in Figure 8.7. The end point yearly averages are anomalously large and small compared to other years because data are available for only a fraction of the year.

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[a] A *spline* is a curve consisting of segments. Cubic splines are composed of cubic polynomials. Second-order continuity means "continuous through the second derivative," so the splines have continuous values, continuous slopes, and continuous curvatures.

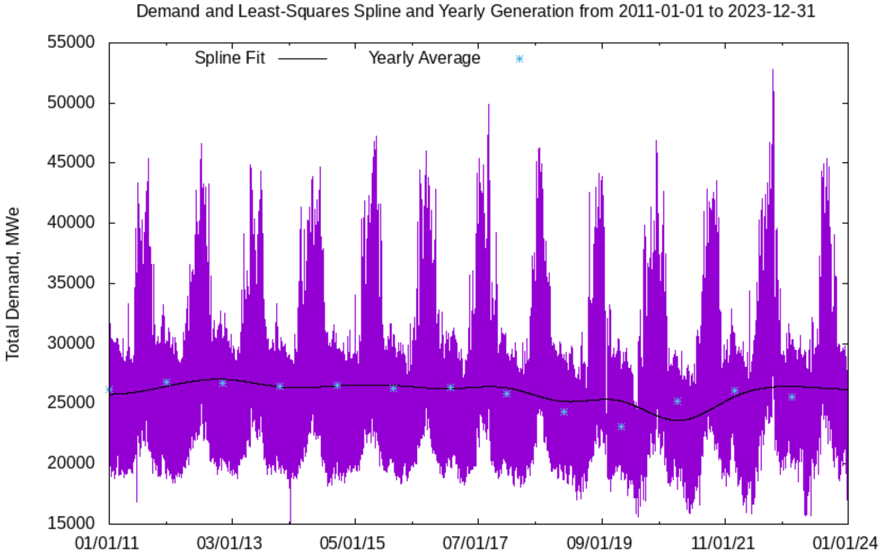

Figure 8.7: Demand and Least-Squares Spline and Yearly Generation

8.8 How to read the graphs

The quantity $\delta(t)$ in Section 8.7 is the slope of the lines in the graphs of storage content. Where $\delta(t) > 0$ and therefore $S(t)$ is increasing, more electricity was produced than demand, and energy would have been flowing into storage. Where $\delta(t) < 0$ and therefore $S(t)$ is decreasing, less electricity was produced than demand, and energy would have been withdrawn from storage. Where $S(t) > 0$, renewable sources plus stored electricity produced sufficient power to satisfy demand. Where $S(t) < 0$, renewable sources plus stored electricity did not produce sufficient power to satisfy demand, and outages would occur where $S(t)$ is decreasing ($\delta(t) < 0$), for example, between November and March. This shows the necessity for non-renewable sources – coal, gas, and nuclear – or significant storage, in renewable electricity systems.

Observe that in mid 2020, total energy that would be in storage as a result of all renewables being increased equally, and renewables having produced more than demand, was about 400 watt hours per average watt of capacity. When the amount in storage is negative, for example between November 2020 and June 2021, any time that demand exceeds supply, i.e., $\delta(t) < 0$, there would be outages.

If an all-renewable generating system had been in place in California on 1 January 2011, with a storage system having capacity less than about 1,165 watt hours per watt of average demand, and had not been precharged to 673 watt hours per watt of average demand, there would have been prolonged outages.

8.9 What causes the variation in stored energy?

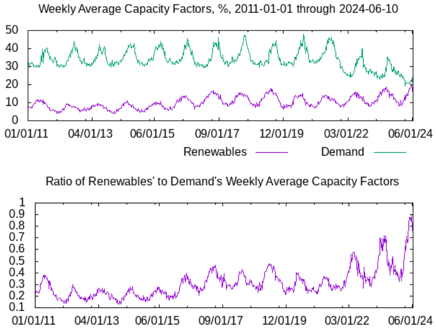

Figure 8.8: Capacity Factors

There is clearly a difference between generation during days and nights. Annual variation in stored energy is caused by renewables' generating capacity not being synchronous with demand. Demand begins to increase each year just as renewables' output is beginning to decrease. The capacity factor for demand is total demand divided by total generating capacity. This assumes that dispatchable sources, such as gas, are adjusted so their output equals their demand. Other capacity factors are computed by dividing output by label capacity. The graphs in Figure 8.8 show the capacity factors in California for demand and renewables, so as to remove the effect of inter-annual demand and generation variation, and changing capacity.

The yearly periodic asynchronous relationship of renewables' output compared to demand is evident in the second graph in Figure 8.8.

Phases were computed by fitting each phenomenon to $\beta_1 \sin(\omega t) + \beta_2 \cos(\omega t)$, where $\omega = 2\pi/8765.81$ (the number of hours per year), and t is time in hours since the beginning of the period of analysis (1 January 2011). The phase of each phenomenon with respect to the beginning of the period of analysis is then $\tan^{-1}(\beta_2/\beta_1)$, and the difference in phases is 46 days, i.e., demand begins to increase about 46 days after output from renewable sources begins to decline.

With the limited amount of data available (twelve years), by fitting to $\beta_1 \sin(\omega t) + \beta_2 \cos(\omega t) + \beta_3 \sin(\lambda t) + \beta_4 \cos(\lambda t)$, where ω is as above and λ is to be found, a longer term variation with a period of 8.24 years was found. The phase differences of this variation, $\tan^{-1}(\beta_4/\beta_3)$, compared to demand, range from -28 days (wind) to +172 days (solar) to +515 days (hydro). The average phase difference between demand and renewables is 45 days. Each time that more data are used, the solved-for period $(\lambda/2\pi)$ increases. Long-term variation frequencies are probably related to the Sun's eleven year activity cycle. There might be even longer term variations that are related to solar activity cycles of about 70 and 1,500 years, but these cannot be measured by using only twelve years of generation data.

8.10 Effect of increasing generating capacity above average demand

California data were analyzed again with average renewables' generating capacity increased to $G = 1.25$ times average demand, with the same relative output magnifications $g_i(t)$, and a 100 Wh/W storage capacity. The results are shown in Figure 8.9. The "flat line" bounding the maximum storage amount means that excess generation would be dumped. Solar thermal and wind output can be adjusted somewhat but solar PV output cannot be adjusted if the panels have fixed mountings. Articulated mountings would be very expensive. 776,000 gigawatt hours of output – 44% of total demand – would have been dumped. There would have been outages 19% of the time, i.e., when the slope of the line in this graph is negative.

If average renewables' generating capacity were to have been increased to $G = 3$ times average demand, and 12 hours' storage were provided, as is claimed to be sufficient by many activists, there would have been outages 3.4% of the time, i.e., when the slope of the line in Figure 8.10 is negative. 6,300,000 gigawatt hours of output – 355% of total demand – would have been dumped.

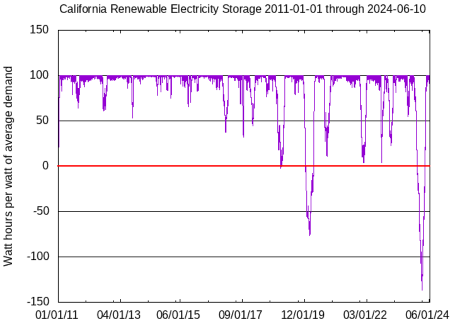

Figure 8.9: Average Capacity = 1.25 × Average Demand and Storage = 100 Wh/W

The cost for only twelve hours' storage, for an all-electric 1.7 TWe American energy economy, would be $11.1 trillion, or about $1.1 trillion per year, or 5.5% of total GDP (using 2020 prices). The cost for each of America's 128 million households would be about $8,654 per year for batteries alone.

Renewables provided 33.4% of California electricity between 1 January 2011 and 1 January 2023. Electricity satisfies about one third of total California energy demand [2]. To provide all California energy from renewable electricity sources whose average generating capacity is three times average demand would require a capacity increase of $3 \times 3/0.334 = 2,695\%$ above the capacity to satisfy all current California electricity demand. Increasing hydro at all, or increasing biogas, biomass and geothermal by 2,695%, is unlikely.

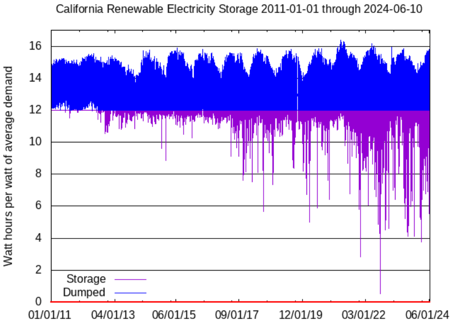

Figure 8.10: Average Capacity = 3 × Average Demand and Storage ≤ 12 Wh/W

Dumping output reduces the energy return on energy invested (EROI). EROI at least seven is required for economic viability (see Section 7.2). With storage, and even without dumping, solar PV and wind are not viable without subsidies. Subsidies do not eliminate costs – they just hide them in your tax bill – so they do not actually make solar and wind viable. California appears to have stopped building solar thermal generators, and the EIA does not predict any increase in

US solar thermal capacity [1].

If 355% of total renewables' output were dumped, the EROI from solar PV would be reduced to 0.56, i.e., less energy would be produced than invested in the devices. Where would that extra required energy come from? The EROI from wind would be reduced to 1.13. Figure 7.2 shows the EROI for several generation technologies [14].

8.11 Problem with increasing generation capacity

The problem with renewable energy in general, and increasing capacity in particular, is materials.

Professor Simon Michaux has quantified the problem (see Section 6.1) [9]. For copper alone, if production were to continue at the 2019 rate, 189 years would be required to build the "technology units" demanded by the IEA. The amount required is almost six times the total amount that humans have so far extracted from the Earth, and five times more than is known to exist in forms that can be extracted. If all known reserves were completely used, 19% of the units could be built.

8.12 The next supervolcano eruption

This analysis of storage assumes that the period analyzed includes the deepest deficit that will ever occur – which is, of course, false. When Mount Tambora on the island of Sumbawa in Indonesia erupts again and produces another "year without a summer" such as in 1816 – and either it or another like it definitely will, the only question is when – there will be no times for several years when $\delta(t) > 0$. The trend of storage content will always and everywhere be downward. The deepest deficit will be far deeper than any shown here. No physically feasible or economically viable amount of storage could suffice. Renewable generation capacity and storage capacity could not be increased sufficiently rapidly. There would be energy available for only a small fraction of demand. Politicians' homes, and (maybe) hospitals, would have first priority. Industrial economies would collapse. Civilization would collapse.

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Chapter 9

Nuclear power

Foregoing chapters have shown that the Great Green Energy Transition is not possible if everything must be electrified, or even if electricity sources to satisfy only present electrical power needs are limited to the minor players listed in Chapter 5, together with solar and wind.

Many are coming to realize that if we accept the proposition that CO_2 emissions that result from energy production must be limited, the only alternative to coal, petroleum, and natural gas, is nuclear power.

Among those who have not reached this realization, and even among some who have, there are lingering objections to nuclear power:

1. Nuclear power is not safe.
2. No one knows what to do about nuclear waste.
3. Nuclear power is too expensive.
4. Nuclear power leads inevitably to nuclear weapons.
5. Even if all the other objections can be overcome, there isn't enough uranium to power the world's economy for very long.

All of these objections are false, but have been perpetrated and perpetuated by individuals and groups who are ignorant, or have special interests to which nuclear power would be a competitor.

9.1 Nuclear power is not safe (yes it is)

Every discussion between advocates and opponents of nuclear power very soon becomes an argument about safety. Opponents insist it is not safe. Advocates too frequently do not know how to respond.

Of course, we want everything to be safe, but why is nuclear power singled out by activists as being uniquely unsafe? It is necessary to begin with a condensation of the detailed description by Conley and Maloney of a long story of scientific fraud that affects the assessment of nuclear safety [19].

9.1.1 The linear no-threshold theory and scientific misconduct

Hermann J. Muller exposed fruit flies (*Drosophila melanogaster*) to X-ray doses that were tens of millions of times greater than background radiation. In 1927, He published a linear no-threshold (LNT) model of radiation risk assessment [37]. He falsely claimed that there is no safe dose of radiation, and that all doses are cumulative. This provably false claim has created an atmosphere of irrational and hysterical fear of nuclear power. Muller's 1927 paper was never peer reviewed. His model has been refuted by modern science, and indeed was challenged at the time by his friend and colleague Edgar Altenburg, who thought that Muller had "blasted out" huge chunks of genes, rather than causing point mutations. His data indeed showed a linear relationship between X-ray dose and observed transgenerational phenotype changes in fruit flies. It's what he did next that is unforgivable: He decided to extrapolate. He went outside the observational data, and not just a little bit. He went from thirty million times the normal background level, down to and below that all the way to zero.

Muller had known James McKean Cattell at Columbia. At the time, Cattell owned the journal *Science* (he did not transfer ownership to AAAS until two decades later). Cattell was also a colleague and close friend of Thomas Hunt Morgan, who had been Muller's PhD advisor at Cornell University. Cattell might have sought to profit from the likely intense publicity. "Thus, in some ways Muller and Cattell exploited each other for personal profit at the expense of society" [15].

In 1929, Barbara McClintock developed a vastly improved method of staining the interiors of cells using a bright red pigment called *carmine* that exposed cellular structures to direct observation with existing microscopes for the first time, allowing direct assessment of the characteristics and appearance of chromosomes in corn [36].

In conclusion #10 in his 1931 dissertation, Clarence P. Oliver wrote that "it is not possible to produce gene mutations without producing gene rearrangement, or vice versa." Oliver was Muller's student at the University of Texas, and Muller approved his dissertation [42]. This undercuts Muller's assertion that he produced "point mutations" at doses far higher than Oliver or McClintock had used. Once nucleotide sequencing methods were developed, it has conclusively been shown that Muller achieved his transgenerational phenotype changes by "punching holes" in chromosomes, both modest or extraordinarily large deletions rather than point mutations, using a bazooka rather than a scalpel.

Lewis J. Stadler, a corn geneticist at the University of Missouri, had reached the same erroneous conclusion several months before Muller. Stadler's publication was delayed because it was peer reviewed. He invited McClintock to the University of Missouri during the summers of 1931 and 1932, where he introduced her to the use of X-rays as a mutagen. Using her method of direct observation of chromosomes, after Stadler allowed her to stain his slides, McClintock concluded that the so-called "gene" mutations were in fact gross chromosomal deletions. Stadler disavowed his earlier claim of point mutations, and formally rebutted Muller's work at the Sixth International Genetics Conference at Cornell in 1932. Everyone in the audience (except McClintock) was astonished when Stadler claimed that Muller had confused an observation with a mechanism, saying "to state that an induced variation is a gene mutation is not to explain it, but merely to label it." He didn't just mention this once in passing; he hammered it home in more than a dozen quite explicit ways during his presentation.

Muller, who was next to speak, was profoundly shaken because his work had just been upended in the presence of an international audience of his peers and acolytes. He stumbled through his address. A few weeks later, back at home in UT Austin, in the midst of an unpleasant divorce, his students found him dazed and wandering after sleeping off an attempted suicide using the (ironically) wrong dose or barbiturates [19]. He never recanted his views.

McClintock was elected a member of the National Academy of Sciences in 1944, and was awarded the Nobel Prize in Physiology or Medicine in 1983 for her discovery of genetic transposition. She remains the only woman who has earned an unshared Nobel Prize in that category.

Curt Stern had long been an admirer of Muller. He fled Germany in 1939 and landed a job with the Manhattan Project to conduct genetics research at the University of Rochester. He asked the project to hire Muller to serve as a paid consultant to explore the health effects of ionizing radiation. Muller's and Stern's work continued after the Manhattan Project, sponsored by the newly-formed Atomic Energy Commission (AEC). McClintock's and Stadler's 1932 criticisms of Muller's work had not gone away. In the 1930's, Muller convinced a PhD candidate at Edinburgh named Sachi Prasad Ray-Chaudhuri to conduct what turned out to be a deeply flawed experiment that purported to show a linear response to continuous low doses of radiation. Ray-Chaudhuri knew he was in over his head, not least because his only guidance was occasional correspondence with Muller, who was busy being a celebrity. Stern asked Warren Spencer, a fellow supporter of the LNT theory and PhD geneticist who specialized in *Drosophila* to run a year-long comprehensive acute-dose study at Rochester. Muller and Stern claimed that Spencer's work proved Muller's high-dose linear-response theory, but Spencer had made many serious methodological mistakes, including combining data for very different cohorts of *Drosophila*.

Knowing that Ray-Chaudhuri's work was flawed, Stern asked Ernst Caspari to re-do the Edinburgh chronic low-dose study to confirm his cumulative-dose theory. Muller hoped that together, Spencer's and Caspari's work would prove his twin theories. But Caspari wasn't a struggling grad student working in the dark with no guidance. He was a seasoned scientist with a PhD in entomology, using modern equipment with precision controls at one of the best labs in the world, all funded by the bottomless purse of the Manhattan Project.

When Caspari compiled his data in August of 1946, it became uncomfortably clear that his work had produced no evidence to support Muller's linear no-threshold theory in the low-dose range, that is, that Muller's earlier extrapolation could not be experimentally supported. In fact, Caspari's data showed clear evidence of a rather substantial threshold, below which there were no observable excess mutations in the offspring, compared to control groups that had experienced background levels of about 2.3 mSv (millisieverts), not the 50 mSv per week of his experimental cohorts. Spencer had delivered the same 500 mSv dose, but rather than delivering it slowly during ten weeks, he delivered it in fifteen minutes. Funny thing, the offspring of his cohorts had a high rate of mutation.

The cumulative-dose theory was clearly wrong. Biology clearly had some kind of self-repair mechanism at work in reproductive cells that provided a safety threshold against inherited mutations in the low dose rate range. This shouldn't have been a surprise, because the Earth has always been radioactive, and without such a mechanism, life would never have evolved and thrived. The cumulative dose theory doesn't hold, and indeed doesn't hold for most hazards, whether radiation or biological or chemical exposures. This has been known since the Renaissance, when the term hormesis was invoked to explain it. It's precisely the reason that kings intentionally took low doses of arsenic.

Caspari's 1946 study was finally published in January of 1948, without peer review, in a journal for which Stern was the editor-in-chief. They had submitted a draft to Muller as a sort of peer review from on high. Seventy years later, Edward Calabrese discovered the draft, and upon comparing it to the published article, discovered that "the results presented open up the possibility that a tolerance dose for radiation may be found" had been removed from the conclusions paragraph.

Between the time of his 1927 paper and his death in 1967, Muller never published any conclusive data, or an experiment, and others never replicated his alleged work. Nonetheless, Muller was awarded the Nobel Prize for Medicine in 1946. In his Nobel Prize lecture on 12 December 1946, he deliberately deceived the audience by arguing that there was no possibility of a threshold of dose response for radiation induced mutations. On 6 November 1946, five weeks before the lecture, Stern had sent Caspari's data refuting that conclusion. Muller recognized Caspari's work as significant, and recommended in a letter to Stern a week later that "funds would be forthcoming for a re-test of the matter." Muller didn't mention Caspari's work during his lecture. Instead, he cited Ray-Chaudhuri's work. Five weeks after the lecture, he recommended publication of Caspari's work. Having this work in hand, and clearly having not changed his mind about it, why did he proclaim, on the most important stage in the scientific world, that "there is no escape from the conclusion that there is no threshold" of dose response for radiation induced mutations [13]?

Stern eventually secured more AEC funding to test Caspari's findings. But the war was over and the wartime team at Rochester had dispersed. He selected an inexperienced first-year Master's student named Delta E. Uphoff. She conducted three major studies to test Caspari's findings, with Muller, who was by then at the University of Indiana, acting by remote control as her consultant. Nine months into her first study in 1947, Uphoff realized that her control group, which had been given to Stern by Muller, had a 40% lower mutation rate than normal *Drosophila* in the wild. She asked Muller about the discrepancy, which would have made comparison to Caspari's results impossible. Muller responded that a proper control group, similar to Caspari's should be used.

Ultimately, Stern and Uphoff submitted a report to the AEC, admitting that the results of her studies were "uninterpretable." Stern blamed it on "bias of the experimenter," when he in fact knew that the problem was the control group provided by Muller. The AEC wanted answers because they were concerned about the effects of radiation on soldiers and citizens. Uphoff and Stern eventually published a paper in *Science* magazine in which they rejected Caspari's findings because the control group had anomalously high resistance to radiation, and referred instead to Ray-Chaudhuri's flawed studies. All three of Uphoff's studies had suddenly become interpretable, and they accepted Spencer's study. They failed to mention that Caspari's study had examined chronic low dose, while Spencer's had examined large acute dose. They failed to mention that Muller had confirmed that Caspari's controls were the correct ones to use to confirm (or refute) his and Uphoff's findings [60]. The Spencer study and the Uphoff-Stern meta-study remain the single most-cited works used to support the continued use of the LNT theory for radiation risk assessment.

Even as late as early postwar years, most research was being done by private organizations. With concern about radioactive fallout from atmospheric nuclear weapons testing on the public mind, the Rockefeller Foundation, awash in petroleum funding, saw it as their civic duty to clear the air – so to speak – on the question of radiation risk. Nuclear power might be too dangerous, so the world might have to continue to burn petroleum. The question was important. The responsible thing to do was to sponsor more research. Luckily for the Rockefellers, Detlev Bronk was not only the president of the Rockefeller Institute for Medical Research (now Rockefeller University), but he was also the president of the National Academy of Sciences. Dean Rusk, a board member of the Rockefeller Foundation, wrote to President Eisenhower to offer private funds for radiation research.

> Our Trustees wish to contribute to a full exploration of the effects of radiation on living organisms, *with particular attention to the possible danger to the genetic heritage of man himself* .... Our Trustees wish to act with

> the utmost seriousness and to make substantial private resources available for the purpose [emphasis added].

With Eisenhower's approval, and generous funding from the Rockefeller Foundation, the National Academy of Sciences formed the first committee, with six expert panels to study the Biological Effects of Atomic Radiation – the BEAR-1 committee. One of the panels in the committee was a new genetics panel, which had previously been part of the pathology panel. Was it a coincidence that nearly the entire genetics panel favored the LNT model? Muller was their honored member. The chair was Muller's acolyte Spencer from Rochester, who had conducted the flawed acute-dose study with Curt Stern. The panel included William Russel, who by 1956 had been conducting a study of mice at Oak Ridge for a decade. Alfred Sturtevant, a young Caltech professor who had been arguing against the AEC position that fallout from nuclear weapons was essentially harmless was brought onto the panel.

Academy president Bronk invited Warren Weaver, the director of research at the Rockefeller Foundation, to get the ball rolling. Committee members knew of Weaver. At one time or another, he had funded most of the members of the genetics panel. He had supported radiation genetics research at the University of Indiana to the tune of $4 million ($40 million today), which covered Muller's salary. Muller's stint in Europe, and a Fullbright Scholarship, had been sponsored by Rockefeller. Altogether, Rockefeller had subsidized their superstar for more than two decades. After Weaver got things started by announcing "I am not talking about a few thousand dollars, gentlemen. I am talking about a substantial amount of flexible and free support to geneticists," one of Muller's colleagues from Indiana, named Tracy Sonnenborn said that "dose-response for radiation-induced mutations was linear down to a single ionization. Radiation genetic risk assessment was best explained based on total dose. Dose-rate, regardless of how low, would only result in cumulative damage."

No one on the genetics panel voiced support for a threshold model. No one was surprised when the committee voted for Muller's LNT model, rejecting the pathology panel's recommendation to adopt the standard dose-response model from pharmacology and toxicology. Both of those disciplines assume that just like every other substance, radiation has a safety threshold below which there is no detectable harm that cannot be repaired by a healthy organism. The pathology panel's recommendation to conduct research to determine a threshold for low-dose effects was rejected. The committee's 12 June 1956 report affirmed Muller's no-safe-dose model. Although each panel also submitted separate papers to their professional journals, the committee report was written for the layman. Arthur Sulzberger's New York Times launched a media blitz, with a copy sent to every library in the country. Like Detlev Bronk, Arthur Sulzberger had been a member of the board of the Rockefeller Foundation for many years. This report burrowed nuclear fear deep into the public psyche, a cultural bogeyman with staying lower. Popular songs are still raising the spectre of genetic damage, and equating nuclear power with nuclear weapons.

In 1956, the National Academy of Sciences published a book by James Neel and William Schull that described their work with the decade-long Life-Span Study (LSS) of survivors of the atomic bombs at Hiroshima and Nagasaki, and their children, sponsored by the Atomic Bomb Casualty Committee (ABCC). The work studied the ten-year health effects of real-world radiation on more than 100,000 Japanese survivors of the atomic bombs, as well as 25,000 unaffected Japanese, and descendants of both groups.[a]

James Neel wasn't a struggling graduate student. He was a medical doctor with a PhD. Using interviews and on-site observations, LSS staff had carefully determined the disposition of each survivor at the moment of the blast: Their age and health status, exactly where they were, what they were doing, what they were wearing, what if anything they were carrying, how far they were from a window or wall, whether there was any shielding in the path of radiation, ... The LSS staff thereby were able reliably to estimate the dose received by each survivor [40] [41].

The bomb blasts caused more than 200,000 immediate injuries and deaths, mostly from shock waves and consequent fires and falling debris. The intense radiation had consequences for more than 100,000 survivors of both sexes, spanning a wide range of ages and health conditions. The 1956 book showed, however, that a decade after the atomic blasts, contrary to the LNT theory, no offspring of the Hiroshima and Nagasaki *hibakusha* (survivors) had shown any perceptible signs of inherited mutation. Neel and Schull had written

> In summary, then, there emerge from this analysis no really clear indications that the radiation history of the parents has affected the characteristics of their children here under consideration.... In order to avoid all possible misunderstandings we hasten to state that under no circumstances can this study be interpreted as indicating that there were no genetic consequences of the atomic bombings.

They didn't find any deleterious genetic effects, but they were careful to say that that did not mean that there were none. It was a carefully diplomatic way of not refuting Muller's LNT theory, while in fact an ongoing ten-year study using real data and humans, not fruit flies, had done exactly that.

Neel and Schull sent a summary to the genetics panel of the BEAR-1 committee. Needless to say, the paper caused a great deal of consternation. The LSS work clearly contradicted the LNT theory. Warren Weaver quietly resigned. The hypothesis that the BEAR-1 committee had publicly hung their hats on, with the help of the New York Times – the absolutism of the LNT model – was almost certainly wrong. The kids

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[a] The ABCC was replaced by the Radiation Effects Research Foundation in 1975. Their work continued until 2012.

were OK. As diplomatic as Neel and Schull had tried to be, the paper was forcefully rejected by Muller and his acolytes on the genetics panel. Jim Neel was a respected NAS scientist who had spent the last decade in Japan working with the LSS. Here he was on another NAS committee whose remit was to examine the biological, especially genetic, effects of atomic radiation, and they wouldn't even read his paper!

Neel quietly sent his paper to the British Medical Research Council (BMRC), who had their own genetics committee, busy preparing their own report, to be published contemporaneously with the BEAR-1 committee report. The BMRC flatly rejected the LNT model and established a sensible threshold-based safety standard instead. That Neel had convinced them is quite clear:

> For the purposes of assessing risk and defining standards of safety, it is necessary to know the nature of the relationship between the dose of radiation and the effect induced.... All the evidence suggests that the relation between dosage and radiation effects occurring within a few weeks of exposure is of the latter [curvilinear] type, and that the curve shows a "threshold" level, implying that a certain quantity of radiation must be exceeded before these particular effects are produced.

While the U. S. NAS had concluded that there is no safe radiation dose or dose rate, the BMRC was recommending a threshold of 200 Roentgens, spread over a period of "tens of years." This works out to 140 mSv per year, while the average dose rate at sea level is 2.3 mSv per year. Caspari's study had been buried in 1949 by Uphoff and Stern's 1949 *Science* article. But here was the BMRC endorsing Caspari's threshold, based upon even larger doses of 2,500 mSv/yr (albeit in fruit flies, not humans).

Two months later, Neel gave a convincing presentation against Muller at the First International Conference on Genetics in Copenhagen. Muller had tried to prevent him from speaking, but the British delegation had threatened to walk out. Back in the USA, the BEAR-1 committee put on a stoic public face, but behind closed doors they were in disarray. The new chairman, George Beadle, head of the Caltech biology department, who had been selected when Warren Weaver quietly went back to his funding job at the Rockefeller Foundation, added a new bogeyman. He suggested that the committee should perhaps turn their attention from inter-generational hereditary effects to the issue of radiation and cancer, that is, what might people acquire directly as a consequence of radiation exposure, rather than inherit from their parents?

Early in the 1950's, Caltech had become a hotbed of environmental activism, led by Nobel Chemistry Laureate Linus Pauling. In his biology department, Beadle tried to drum up enthusiasm to refute Caspari and Neel, and reaffirm Muller and Uphoff and Stern. He got only one taker, a young professor and *Drosophila* geneticist named Ed Lewis. Lewis accepted the challenge and became especially interested in the leukemia statistics gathered by LSS. The United Nations Scientific Committee for the Effects of Atomic Radiation (UNSCEAR) was preparing a report on the first decade of this study, to be published in 1958, and Neel's work, which Muller had forcefully rejected for BEAR-1 consideration, was a big part of it. Muller's stated reasoning was that "field data" gathered on humans in real-life situations could be incomplete and misleading, and that lab testing under controlled conditions was to be preferred. Studying 100,000 fruit flies and their offspring, with their four chromosomes, in controlled conditions, could tell us more about human disease and genetics than studying 100,000 humans and their offspring in real-world conditions, with their 46 chromosomes.

Nonetheless, Beadle gave Lewis access to the same unpublished data that Muller had rejected. Beadle could do this because, not only was he the new head of the BEAR committee, but he was also a member of NAS and ABCC, so he had access to the latest unpublished LSS data. Lewis (remember he was a *Drosophila* specialist) analyzed the human data without any formal collaboration, even though he had no experience in oncology, radiology, epidemiology, or mathematical modeling. Beadle shared a draft with the BEAR committee, who offered notes. Lewis published the paper, which tried persuasively to advance the original flawed hypothesis, first advanced by Muller thirty years earlier, supposedly confirmed by Stern and Uphoff, that the same mechanism of radiation-induced mutation of reproductive cells also applies to somatic (non-reproductive) cells. He really had no competence to reach that conclusion from the data at hand; he had made a giant speculative leap that turned out to be wrong – the same leap that Muller had made thirty years earlier [34].

Conley and Maloney give a clear explanation, only two or three pages, of why reproductive cells are very different from somatic cells [19]. Apparently this distinction, which had been known since about 1870, was not known to Lewis. The unique ability of germ cells to divide into gametes, each containing half of a genome, which must then fuse with gametes of the opposite sex, also each containing half of a genome, to create a new individual, is the evolutionary bridge that opened the way to more complex life forms. Lewis mistakenly crossed that bridge with Muller's LNT model in tow, and people have been freaked out about the risk of cancer being caused by radiation ever since. It turns out that ionizing radiation is one of the *least* effective ways to cause cancer. Toxins, pollutants, and even oxygen are far more effective. Except in extremely high doses, ionizing radiation is a remarkably weak carcinogen. That this runs counter to public perception is a testament to the power of the first law of propaganda: The bigger the lie and the more frequently it is told, the more likely it is to be believed.

Even though understanding of reproductive biology was well along by the 1950's, there was one crucial detail that Lewis (and Muller) didn't know, and that was only gradually being brought into focus by the Oak Ridge Mouse Study: The female gamete, the ovum, or oöcyte, includes a full set of repair mechanisms to protect against damage from radiation, oxidation, toxins, mutagens, and other stressors. Male gametes start out with that, but when they mature from spermatogonia to spermatozoa, they lose the ability. When they fuse with an ovum, their chromosomes, and those of the ovum, unroll and fuse over a period of ninety minutes. Being all unwound and laid out, this is an incredibly vulnerable time. Like having two jewelers working on the same watch, or two cooks working on the same soup, nature has decided that both gametes doing repairs would make a mess, so the ovum's mechanisms repair both sets of half-chromosomes. Muller's mistake was to blast gametes during this exceptionally vulnerable period with exceptionally high doses of radiation, tens of millions of times more than the normal background radiation for which nature had evolved repair mechanisms. As McClintock and Stadler had shown, Muller's experiments had not induced mutations; they had blasted out huge chunks of chromosomes.

Lewis's mistake was to apply to all reproductive cells, at all stages of their development, and every cell of the body, the observation that when spermatozoa mature from spermatogonia they lose their repair mechanism. Lewis examined the available data relating leukemia to radiation in four well-defined cohorts:

- People heavily X-rayed to treat ankylosing spondylitis (spinal arthritis),
- 1,400 infants irradiated for thymus conditions,
- Radiologists administering these and other high doses, and
- The *hibakusha*, or survivors, in Japan.

The data about subsequent occurrence of leukemia in the 90,000 blast survivors, that is, Neel's data, which Muller had rejected, would likely yield the most reliable results. Lewis must have felt he was onto something big. Leukemia rates were massively elevated in survivors who were closest to the hypocenter. Lewis did correctly observe proportional effects in the high-dose range. Unfortunately, exactly as Muller had done, he extrapolated those results to the low dose and low dose rate range. Using that extrapolation, he concluded that every last bit of ionizing radiation, no matter how small, contributes to an accumulation of damages resulting in an ever-increasing risk of cancer. After Lewis's paper appeared in the 17 May 1957 issue of *Science* magazine, one of the six senior editors, Bentley Glass, a member of the BEAR genetics panel, a former grad student of Muller, and an LNT acolyte, gave a glowing review in the next issue:

> E.B. Lewis (p. 965) shows that there is a direct linear relation between the dose of radiation and the occurrence of leukemia.... The meaning of such findings is that any amount of radiation takes its toll of the population and any increase takes a greater toll.

At the same time, Pauling at Caltech was claiming that Britain's planned 5 megaton H-bomb test would cause 1,000 cases of leukemia. This got a lot of attention, especially among his fellow scientists who wanted to know where he got that number. Pauling had received a preprint of Lewis's paper and was understandably concerned. What he didn't notice, and of course Lewis also didn't, was that the analysis was deeply flawed and couldn't stand up to scrutiny. Aside from the pesky detail that the Lewis paper was bad science, the conclusions were obvious to the man in the street: All ionizing radiation, down to a single X-ray photon, would doom you to death from leukemia or some other cancer. The risk from high doses was obvious, but Lewis's paper, and Pauling's calculations based on it, actually said nothing about low dose or low dose rate.

Pauling's 1958 book *No More War!* had characterized Lewis's work as the "most significant direct information about whether or not small doses of radiation produce cancer in the irradiated human being." Lewis was a *Drosophila* geneticist, not a radiation oncologist, and was not competent to do decent mathematical analysis or modeling. He conflated somatic and reproductive cell function, combined a research cohort with a control group, and incorrectly extrapolated a high-dose response into a low-dose fog bank. George Beadle, Lewis's boss at Caltech, knew he hadn't proved his low-dose claims, and said so in writing.[b] That Pauling characterized it as "the most significant information" instead of "the most significant disinformation" was inexcusable. Was Pauling being careless, or intentionally deceitful?

Flawed as they were, Lewis's paper and Pauling's book had profound effects. AEC was being dismantled, not least in part because of those works. Despite his flat-footed moment on Capitol Hill[c] when Lewis responded to a Senator

> The point here, however, is that in the absence of any other information, it seems to me – this is my personal opinion – that the only prudent course is to assume that a straight-line relationship holds here as well as elsewhere in the higher dose region,"

Lewis had stirred up quite a ruckus. He received an appointment to the new National Council on Radiation Protection and Measurements (NCRP – why is the "M" silent?). Behind the scenes at NCRP, there was a deadlock between those insisting that Lewis prove there is harm from low doses, and those insisting that his detractors prove there is not, despite that it is scientifically impossible to prove a negative. The best that can be done is to fail to prove every contrapositive; the only ethical thing to do at that point is to admit that a future experiment might prove the contrapositive. One of Lewis's critics at NCRP was Austin Brues, who had been a member of the outvoted BEAR-1 pathology panel. Nonetheless, the first thing NCRP did was to promulgate what became known as the *precautionary principle*: If scientists can't prove that low dose and low dose rate radiation are not harmful, we have to assume they are. NCRP reached this

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[b] Edward Calabrese showed a copy of the letter in Episode 18 of an online interview with the Health Physics Society, at 7:05 `http://hps.org/hpspublications/historylnt/episodeguide.html`.

[c] Special hearing of a subcommittee of the Senate Joint Committee on Atomic Energy, 27 May – 3 June 1957.

conclusion in spite of the publication a few months earlier of one result of the decade-long "Mouse House" experiments at Oak Ridge that described a substantial self-repair threshold in female mice, concluding "the mutation rate in women exposed to chronic gamma radiation may be less than that estimated by our earlier yardstick, namely, the mutation rate obtained from acute [high dose] X-irradiation of male mice" [47].

Lewis lied to Congress again in 1959. He cited papers on leukemia that he said supported his claims of cancerous effects at low doses:

> These studies and others that have been reported since 1957 have contributed results which are in substantial agreement with the conclusions drawn in testimony presented by the present witness [i.e., by Lewis himself] at the 1957 hearing.

The problem is that these papers show the *precise opposite* of what Lewis claimed. They clearly and unambiguously state that the proportionality found at high doses *should not* be extrapolated to the low dose range. Congress took the word of the witness without checking, and we're now stuck with it [20] [61]. That Lewis had a reference in an early draft of his paper, to confounding data that showed a threshold in pigs and mice, and that reference was removed, was not discovered until 2017 [26].

William and Liane Russell began a massive long-term study of radiation effects on mammals, an outgrowth of the Manhattan Project, called the *Mouse House* study, in 1947. The study continued long after they retired in 1977, lasting 62 years, until 2009, ultimately using three million mice. Like the *Drosophila* studies, the idea was to expose them to various doses and dose rates of radiation, mate them, and compare their offspring to a non-radiated cohort of similar mice intended to represent healthy mice in the wild.

In 1956, William had served on the BEAR-1 genetics panel and supported LNT. By 1958, it was becoming clear to the Russells and their Mouse House colleagues that the ova of irradiated female mice were exhibiting a substantial self-repair threshold. Despite an enormous dose that was 27,000 times background radiation (80,000 mSv), the reproductive cells of female mice could apparently repair themselves. Spermatogonia in male mice could also apparently repair themselves:

> New data have clearly confirmed the earlier finding that specific locus mutation rates obtained with chronic gamma irradiation of spermatogonia are lower than those obtained with acute x-rays.... From a practical point of view, the results indicate that the genetic hazards, at least under some radiation conditions, may not be as great as those estimated from the mutation rates obtained with acute irradiation. [48]

Russell pushed back on Muller, but by 1963 Muller was on the board of the International Commission on Radiological Protection (ICRP), the international version of NCRP, and his word was still unchallengeable gospel truth.

In 1972 the newly-minted EPA formed a committee called the Biological Effects of Ionizing Radiation (BEIR-1). Russell was a member, who briefed the EPA on the Mouse House findings that ova and spermatogonia exhibited a robust capacity for self repair, but spermatozoa have a repair rate of only 70%. The BEIR-1 committee couldn't help but notice that these results tore a gaping hole in the LNT hypothesis. If there was self repair, the dose rate principles of pharmacology and toxicology would apply. They were concerned that spermatozoa could not apparently repair themselves nearly as well as ova. Neither they, nor anybody else, knew at the time that during conception, ova repair spermatozoa. Working with the data they had at the time, the EPA adopted the precautionary principle.

In the early 1990's, Paul Selby, a former protégé of the Russells, and William Russell's only PhD candidate, was asked to return to Oak Ridge to migrate the Mouse House data to new computers. As he was managing the data flow, he noticed some irregularities among control groups. He eventually was able to find that the control group for several of the Mouse House studies had anomalously low rates of mutation. He found that control groups with "cluster mutations," which are common in nature, were improperly not separated even though they were observed as early as 1951. Random episodes such as a group of mice spontaneously developing a mutation, such as black ears, are common among wild mice. But the trait recedes in subsequent generations. Control groups and their progeny must therefore be monitored both *before* and *after* an experiment. Failure to separate control groups had thrown the veracity of the entire six decade experiment into doubt because a falsely-low rate of mutation in a control group makes the mutation rate of an irradiated cohort seem falsely high. This makes the self-repair abilities of the cohort seem falsely low, and makes low dose radiation seem more dangerous.

Selby shared his findings with his superiors at the Department of Energy. They reviewed his data and found he had scientific standing. Selby's findings and this decision were a *very big deal*. The Russells were legends, and their work had justified stringent regulations on radiation safety in the United States and the rest of the world. But something was seriously wrong. DoE appointed a committee at Oak Ridge and invited Selby and the retired Russells to testify. The Russells eventually admitted that Selby had proven that their controls were wrong. An improper control group, used as a yardstick for all the conclusions, undermined all the statistical results. The Russells conceded that their control group was in error by 120%, even though Selby had found errors six times larger. But the debate was over, and Selby had won [46].

Because the Mouse House work had been the foundation for laboratory radiation genetics for half a century – no one else had done anything even remotely similar – the acknowledged 120% error, or more importantly Selby's observation of a 700% error, should have triggered a top-to-bottom review of radiation safety standards in academia, industry, and government, both in the United States and around the world. But *nothing happened!* It was as if the flawed Mouse House studies were as reliable as the 1972 BEIR-1 committee and the EPA assumed them to be. This unerring belief in provably bad science has been used to justify the ratcheting up of regulations and safety protocols, far above any good sense. In all fairness, the Mouse House results were good science, but there were errors in the data analysis.

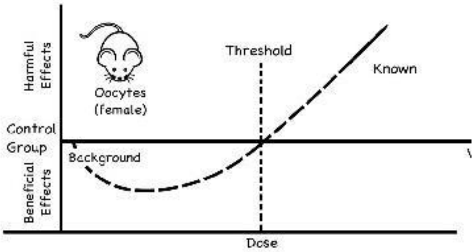

Figure 9.1: Female Mice Show Hormesis and Threshold After 120% Russell Correction [19]

In 2017, Amherst toxicology professor Edward Calabrese re-worked the analysis of the Mouse House data, using the Russells' correction of 120%. He was aware that Selby had found a 700% error, but he wanted to see first how things would change with just the Russells' correction. As shown in Figure 9.1, he found that even with only the 120% correction, mouse ova not only exhibited a high threshold to radiation damage, but in fact a strong *protective response* appeared as well: Multiple episodes of low-dose radiation damage and repair seemed to give female mice a *beneficial*, or *hormetic*, effect by stimulating and strengthening their capacity for self repair. People consume locally-sourced honey for the same reason, to build up immunity to local allergens. With the Russell correction, immature sperm in Mouse House males also showed a hormetic effect, although not as effective as in ova. Most importantly, mature spermatozoa showed a self-repair threshold at about 350 mSv. Subsequent analysis suggests the threshold is above 700 mSv.

The LNT model is wrong. There is not a straight-line relationship, from high-dose radiation down to zero, between radiation exposure and the risk of inherited mutations. The correct effect is *hormesis*, or the induction of repair mechanisms caused by repeated low dose and low dose rate exposures. This effect is well known in pharmacology and toxicology, but the mistakes made by Muller and Lewis have prevented applying this knowledge to radiation. Hormesis is not a fringe idea. This model of adaptive response has gained increasing interest in the last few decades. For example, the number of citations about it increased from fewer than 300 in 1998, to almost 7,000 by 2002, and the numbers have been increasing since then.

Applying this common-sense notion, together with its experimental support, has been hampered because it has also been embraced by a pseudo-science called *homeopathy*, which, like Muller, extrapolated the concept beyond all sensibilities to promote "remedies" with dilutions to the point where not even one molecule of the original stressor remains in the expensive potion. The supposition is that the diluent, almost always water, sometimes retains a “memory” in the form of “vibrations” or “frequencies” of the stressor. Don’t confuse hormesis with homeopathy.

Edward Lewis had access to the enormous trove of unpublished LSS data. He thought he had discovered an important proportional relationship between low-dose radiation exposure and leukemia, but because he had woefully inadequate mathematical modeling and analysis skills, he made a serious analytical mistake. Compare the extents of zones D and E from Table VII in the UNSCEAR report to the extent of zone D from Table 2 in Lewis’s paper, as shown in Table 9.1.

Table 9.1: Comparing UNSCEAR and Lewis leukemia analysis

UNSCEAR Table VII, Annex G [1, p. 165]				Lewis Table 2 [34]		
Zone	*Distance from hypocenter (metres)*	*dose (rem)*	N^b *(total cases per* 10^6*)*	Zone	Distance from hypocenter	Percentage of leukemia
A	under 1,000	1,300	12,087 ± 3,143	A	0–999	0.96
B	1,000–1,499	500	3,746 ± 647	B	1000–1499	0.30
C	1,500–1,999	50	398 ± 139	C	1500–1999	0.043
D	2,000–2,999	2	92 ± 52	D	2000 and over	0.017
E	over 3,000	0	273 ± 91			

Do you see Lewis’s mistake? His zone D combines data originally in UNSCEAR’s zones D and E, blending those importantly different zones, obscuring any distinction in the health effects on those distinctly different populations – those who received an average dose of 20 mSv, and those who received the normal background dose of 2.3 mSv. This egregious mistake covered up the significant hormetic effect clearly seen in the UNSCEAR data; it has saddled the world with unrealistic rules, regulations, and restrictions for decades.

Jerry Cuttler and James Welsh looked at the LSS data much more carefully than Lewis had done. They found that when leukemia rates in the blast survivors are properly analyzed, by dividing the population into cohorts depending upon their distance from the hypocenter, and therefore their levels of exposure, there is a threshold, the same J-shaped hormetic curve that Calabrese had observed when the Mouse House data were analyzed correctly.

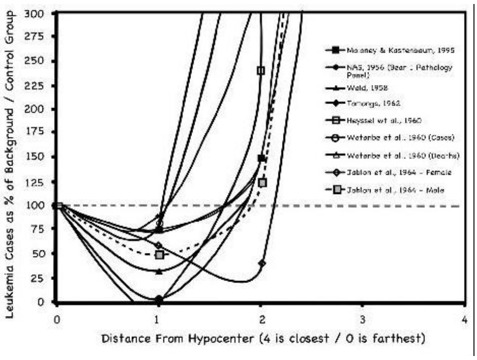

Figure 9.2: Leukemia Meta-Analysis [19]

Calabrese compiled the meta-chart shown in Figure 9.2. He had received the 2009 Marie Curie award for his body of work on hormesis, so when he saw it in Mouse House and LSS data he knew exactly what he was looking at. Interestingly, the results shown for the 1956 study are those from the 1956 BEAR-1 pathology panel report – which was out-voted by the genetics panel, and the Wald paper appears just below it [61]. Lewis's blunder is so remarkable that Cuttler and Welsh quote Lewis's reason for combining the zones:

> Since the majority of the population in Zone D (from 2000 meters on) was beyond 2,500 meters, the average dose is under 5 rem [50 mSv] and is thus so low that zone D can be treated as if it were a "control" zone.

No, the populations in the combined zones D and E in the UNSCEAR report *cannot* be considered to be a control cohort. This is where Lewis went off the rails.

When Cuttler and Welsh examined the single decade of data that Lewis had examined, they found a threshold of about 350 mSv for the hormetic effect. When they examined six decades of LSS data, they found a threshold closer to 700 mSv as the point where the curve exceeds the 273 cases per million rate of the unirradiated population [22]. When they examined the data again, even more carefully, and included Chernobyl data, they found the threshold might be as high as 1,100 mSv, nearly eight times higher than the BMRC recommendation of 140 mSv, but still only half what Ernst Caspari found in 1946 [21].

This is good news, but Jerry Cuttler explained why the news might be even better:

> Since the blood-forming stem cells in bone marrow are exceptionally radiation-sensitive, it is reasonable to expect the dose thresholds for cancer in other types of cells that are less sensitive, to be higher than 1.1 Gray [1,100 mSv], and the cancer latencies to be longer than the 3 – 12 years for leukemia. Also, the low number of cases in Zones A and B for a cancer that is commonly linked to radiation, just 48 cases in 10,051 survivors, suggests that radiation may not be a significant cause of cancer [23].

If the threshold for leukemia is 1,100 mSv delivered all at once in a whole-body blast, then the threshold for other cancers is probably higher, and little bits dribbling in slowly are probably actually protective. How else to explain that people are not dropping like flies in places like Guarapari Beach in Brazil, where the annual dose (not all at once in a full-body blast) is up to 1,148 mSv in some places, due to the sand containing large amounts of monazite, the ore from which thorium is extracted?

Since the 1950's, public fear of nuclear power has been fanned by shouting threats of Cancer! – even from the smallest dose, "down to a single ionization" as Muller stated. The data analysis by Cuttler and Welsh and Calabrese shows that the risk of cancer from doses below 1,100 mSv might not be a concern, especially for non blood-forming cells – most of the cells of the body, including reproductive cells. Cuttler and Welsh vehemently criticized the deception behind this fear:

> A world-wide radiation health scare was created in the late 1950s to stop the testing of atomic bombs and block the development of nuclear energy. In spite of the large amount of evidence that contradicts the cancer predictions, this fear continues. It impairs the use of low radiation doses in medical diagnostic imaging and radiation therapy. This brief article revisits the second of two key studies, which revolutionized radiation protection, and identifies a serious error that was missed. This error in analyzing the leukemia incidence among the 195,000 survivors, in the combined exposed populations of Hiroshima and Nagasaki, invalidates use of the LNT model for assessing the risk of cancer from ionizing radiation. The threshold acute dose for radiation-induced leukemia, based on about 96,800 humans, is identified to be about 50 rem, or 0.5 Sv. It is reasonable to expect that the thresholds for other cancer types are higher than this level. No predictions or hints of excess cancer risk (or any other health risk) should be made for an acute exposure below this value until there is scientific evidence to support the LNT hypothesis [22].

And again:

> The 1953 Atoms for Peace Speech to the United Nations proposed applying nuclear energy to essential needs, including abundant electrical energy. The widespread fear of ionizing radiation from nuclear facilities and medical procedures began after the United States National Academy of Sciences performed a study of radiation dangers to the human genome. This study, initiated and managed by an oil industry benefactor, recommended in 1956 that the risk of radiation-induced mutations be assessed using the linear no-threshold dose-response model instead of the threshold model. It was followed by a study that wrongly linked low radiation to cancer among the atomic bomb survivors. The ensuing controversy resulted in a compromise. The National Committee on Radiation Protection adopted the precautionary principle policy in 1959, justified by fear of cancer and lack of knowledge. The United States and all other countries followed this recommendation, which remains unchanged 62 years later. Its impact on nuclear energy and medicine has been profound. Many costly regulations have been enacted to prevent very unlikely human or equipment failures – failures that would lead to radiation exposures that are below the dose thresholds for lasting harmful effects. Potential low-dose radiation therapies, against inflammation, cancer, autoimmune, and neurodegenerative diseases, are shunned [21].

Since Muller's time, evidence contrary to LNT has been systematically shouted down, suppressed, and ignored.

In March 2015, Jerry Cuttler brought the Lewis affair to the attention of Dr. Marcia McNutt, the senior editor at *Science* magazine. He attached a copy of Calabrese's paper to his message. He asked that the matter be assessed, and that if Calabrese were correct the journal ought to retract the BEAR-1 genetics panel paper, first published in *Science* on 29 June 1956. McNutt rejected his request. Cuttler forwarded the exchange to Calabrese. In August 2015, Calabrese responded to several points she had made in her letter to Cuttler, and asked her to reconsider. They had a series of exchanges, ending with her writing "Please respect that the matter is closed." Calabrese continued his research into the LNT matter, and the work of Muller and Lewis, culminating in a paper published 30 October 2017, entitled *Societal Threats from Ideologically Driven Science*, which included some of his correspondence with McNutt [14]. One of the reasons that McNutt gave for refusing to retract the paper is that none of those who Calabrese accused of scientific misconduct were alive and could therefore not defend themselves. That Muller had criticized Stadler, in a *Science* magazine article, after he had died and could not defend himself, apparently made no difference to McNutt.

In 2016, Marcia McNutt was appointed president of the National Academy of Sciences (now called NASEM, or National Academies of Sciences, Engineering and Medicine). In 2022, NASEM issued a 300-page proposal for a multi-decade study, conducted by several government agencies, to explore the harmful effects of low-dose radiation, at a cost of $100 million per year. Why are these studies needed? The results are known, at least concerning the relationship between low-dose radiation and genetics and cancer. To be fair, there are troubling hints that there might be harmful non-cancerous effects, such as cardiovascular or brain issues. Further research in these areas is entirely appropriate. But for purposes of public policy, *assuming* that harm exists prior to it being *proven* is not fair, and not even a little bit appropriate.

The precautionary principle is an intentionally fear-based principle. It has nothing to do with real science. It is pure sophistry, based upon the proposition that it is possible – and necessary – to prove a negative. Once you accept that, science ends and pervasive nuclear fear begins. Because of Muller and his self-serving manipulation, with help from an enabling authority (*Science* editor Cattell), his very loyal and protective friend Altenburg,[d] a scientific community that failed to demand accountability, a Nobel Prize committee that inadequately evaluated Muller's findings, and intentionally fraudulent research funded by fossil-fuel interests, the world has believed the LNT theory for a century.

As Conley and Maloney wrote, "More than any other single factor, LNT has been the cork in the bottle that stymies advancement of nuclear power."

The truth is in the data, not in the rhetoric, so let's look at what has actually happened. In the entire civilized world, that is, in countries that have a meaningful safety culture

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[d] When Muller attempted suicide in 1932, his suicide letter was addressed to Altenburg, not to his family.

and competent nuclear power reactor licensing and regulatory authorities, no public person has been injured, made ill, or killed by nuclear power. Indeed, the incidence of cancer among nuclear power plant workers is less than in the general public – an anecdote but not definitive proof of an hormetic effect. One quip is that "nuclear power is safer than Teddy Kennedy's car."

> *I would rather have questions that can't be answered, than answers that can't be questioned.*
> – Nobel Physics Laureate Richard P. Feynman

9.1.2 Accidents

Three Mile Island

On 16 March 1979, Columbia Pictures released a film entitled *The China Syndrome*, produced by Michael Douglas, and starring Michael Douglas, Jane Fonda, and Jack Lemmon. The term *China syndrome* is a fanciful term, invented by opponents of nuclear power, to argue that if cooling mechanisms at a nuclear power plant fail, the core of nuclear fuel will melt, then will melt through the containment vessel and the floor of the building, into and through the water table, and sink "all the way to China."

Twelve days after *The China Syndrome* was released, beginning at 4:00 A.M. on 28 March 1979, a stuck-open pilot-operated relief valve (PORV) in the primary cooling system of Unit 2 of the Three Mile Island nuclear generating station in the Susquehanna River in Londonderry Township in Dauphin County Pennsylvania, near Harrisburg, allowed large amounts of cooling water to escape.

Eleven hours earlier, operators attempted to repair a blockage in one of eight devices called *condensate polishers*. These are sophisticated resin-based filters, similar to water softeners, that clean the water in the secondary cooling loop. They are designed to stop minerals and other impurities in water from accumulating in steam generators, and to decrease corrosion rates.

Blockages are common in these filters. The usual method to cleanse them is to force stuck resin out using compressed air, but in this case the method did not immediately succeed. The operators decided to blow compressed air into the water, in the hope that the force of the water would clear the resin. When resin was forced out, a small amount of water was forced past a stuck-open check valve, and found its way into an instrument air line. This eventually caused feedwater pumps, condensate booster pumps, and condensate pumps, to turn off at about 4:00 A.M. When these pumps stopped, this caused the steam turbine to "trip" – the steam feed was bypassed around the turbine.

With these pumps turned off, heat transfer from the primary reactor cooling system (RCS) was greatly reduced, resulting in significant RCS temperature increase. Rapid heating caused the coolant to expand and surge into the pressurizer, which pressurized a steam bubble above the coolant. When the pressure reached 2,255 PSI (155.5 bar, or 155.5 times atmospheric pressure), a PORV opened, which released steam to the reactor coolant drain tank. Pressure in the primary coolant system continued to rise, and when it reached 2,355 PSI (162.4 bar) eight seconds after the turbine trip, the emergency control system of the reactor initiated a "scram," that is, the control rods were released and fell into the reactor core under the force of gravity, halting the nuclear chain reaction and ending the process of heat generation by nuclear fission.

Even though fission had stopped, heat was still being generated by decay of short-lived radioactive isotopes, including fission products. This produced about 6% as much thermal power as fission had been producing. But because feedwater was not being supplied to the steam generator, heat removal was limited to boiling the small amount of water remaining in the secondary cooling loop, with steam routed directly to the condenser using turbine bypass valves.

When the primary feedwater pumps stopped, three emergency feedwater pumps started automatically. An operator noted that the pumps were running, but failed to notice that a block valve was closed in each of the two emergency feedwater lines, which blocked emergency feedwater flow to the steam generator. The valve position indicator for one valve was covered by a maintenance tag. Some speculate that the operator did not notice the other indicator because his large belly hid it from his view. The valves might have been left closed after a surveillance test two days earlier. In any case, with the block valves closed, no water was pumped to the steam generator. The closure of these valves violated a key Nuclear Regulatory Commission (NRC) rule, according to which the reactor must be shut down. NRC officials later singled out the closing of these valves, and leaving the reactor operating with them closed, as a key failure.

After the reactor scram, secondary steam valves opened to reduce steam generator temperature and pressure, which cooled the RCS, as designed. Reduced temperature caused primary coolant to contract. Because of coolant contraction, and loss of coolant through the PORV, pressure in the RCS decreased, as did the level in the pressurizer after reaching a peak fifteen seconds after the turbine tripped. At the same time, coolant pressure had reduced to 2,205 PSI (152.2 bar), the reset point for the PORV. Electric power to the PORV solenoid was cut, but the valve was stuck open, allowing coolant water to continue to be released. There was no direct indicator in the operators' control station to alert them that the valve was stuck open. A light had been installed after the PORV had stuck open during a previous test. But that light only indicated the solenoid power of the PORV, not the actual position of the valve. There was no explanation why the valve was not replaced, or at least serviced. There was a temperature indicator, for which the sensor was in the "tail pipe" between the PORV and the pressurizer relief tank, but its indicator was not part of the "safety grade" suite of indicators designed to be used after an incident, and operators had not been trained to use it. Had they noticed increased temperature in this subsystem, they would have been alerted to problems inconsistent with other indicators. But the indicator was located behind the seven-foot-high instrument panel, which meant that is was effectively not in sight anyway.

Less than a minute after this cascade of events began, the water level in the pressurizer began to rise, even though RCS pressure was falling. Because the PORV was stuck open, coolant was being lost from the RCS. This is called a *primary loss of cooling accident* or LOCA. The symptoms that operators would have expected for a LOCA were drops in both RCS pressure and pressurizer water level. The operators' training, and plant operating procedures, did not cover the case when the two parameters were changing in opposite directions.

The water level in the pressurizer was increasing because steam in the space at its top was being vented through the stuck PORV, which lowered the pressure in the RCS because of loss of inventory. Reducing pressure in the pressurizer caused water from the RCS to surge into it, which resulted in a steam bubble within the reactor pressure vessel. This was exacerbated by decay heat. The operators were not aware of this steam bubble, and they had not been trained to deal with one occurring. With the water levels rising in the pressurizer, operators were worried about the primary cooling loop "going solid," that is, no steam pocket existing in the pressurizer. Their training had instructed them never to allow this. The confusion caused by the two opposite parameter changes resulted in operators failing to realize that the real problem was a LOCA caused by a stuck PORV, exacerbated by closed valves in the emergency steam generator water supply. Those failures resulted in the operators turning *off* the emergency cooling pumps, which had automatically started after the relief valve stuck and core coolant loss began, to avoid "going solid."

With the PORV still open, the pressurizer relief tank that collected the discharge from the PORV overfilled, causing the containment building sump to fill and sound an alarm at 4:11 A.M. This alarm, along with higher than normal temperatures in the PORV discharge line and unusually high containment building temperatures and pressures, were clear indicators of an ongoing LOCA. This combination of events was initially ignored by the operators. At 4:15 A.M. the relief diaphragm of the pressurizer relief tank ruptured, and radioactive coolant began to leak into the general containment building. This coolant was pumped from the containment building sump to an auxiliary building outside the main containment, until the sump pumps were stopped at 4:39 A.M.

At about 5:20 A.M., almost eighty minutes after the steam bubble in the primary reactor vessel began growing, the primary loop's four main coolant pumps began to cavitate, that is, they were trying (unsuccessfully) to pump a mixture of water and steam bubbles. The pumps were intentionally shut down because operators believed that natural circulation would continue water movement. But steam in the system prevented flow through the core, and as water stopped circulating, more of it was converted to steam. At about 6:00 A.M., the top of the fuel core was exposed to steam instead of coolant water. The resulting intense heat caused a reaction between steam and zircalloy[e] fuel pin cladding, resulting in the formation of zirconium dioxide and hydrogen, which released additional heat. At sufficiently high temperature, zircalloy can also react with uranium dioxide, forming zirconium dioxide, metallic uranium, and yet more heat. The additional heat melted fuel pin cladding and damaged fuel pellets within the fuel pins. Radioactive materials were released into the remaining cooling water. The produced hydrogen gas is believed to have caused a small explosion within the containment building later that afternoon.

At 6:00 A.M. there was an operator shift change in the control room. A newly arrived operator noticed the elevated temperature in the PORV tail pipe and holding tanks, and used a backup to shut off the coolant venting via the stuck PORV. But by then, 32,000 U. S. gallons (about 120,000 liters) of coolant had already been lost from the primary coolant loop. At 6:45 A.M., 165 minutes after the start of the problem, radiation alarms were activated when contaminated water reached detectors. By that time, the radiation levels in the primary coolant were about 300 times higher than expected, because of the damaged fuel pins, and the containment building was seriously contaminated.

At 6:56 A.M. a plant supervisor declared a site area emergency, and less than thirty minutes later, station manager Gary Miller announced a general emergency. Metropolitan Edison (MetEd) notified the Pennsylvania Emergency Management Agency. The confusion of the operators was reflected in fragmentary and contradictory statements by MetEd and government officials. One report was that there had been "a small release of radiation" but "no increase in normal radiation levels" had been detected. Another report was that there had been no release. In reality, there had indeed been a small release of radioactive materials, but in amounts so small that they would not threaten public health, as long as releases were temporary, and that containment of the then highly contaminated containment building was maintained.

It was still not clear to control room staff that water levels within the primary coolant loop and reactor core were dangerously low. A group of workers took manual readings from thermocouples within the core, and took water samples. Seven hours into the emergency, new water was pumped into the primary cooling loop and the backup relief valve was opened to reduce pressure so that the coolant loop could be filled. Sixteen hours after the primary coolant loop pumps had been turned off, they were turned on again, and the core temperature began to fall. A large part of the core had melted and the system was dangerously radioactive, but the primary reactor pressure vessel had not been damaged. The *China syndrome* had not occurred.

Three days later, a hydrogen bubble was discovered within the pressure vessel. It was feared that a hydrogen explosion would damage the vessel, or the containment building.

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[e] Zirconium is used in fuel pin cladding because it has low neutron absorption, high hardness, ductility, and corrosion resistance. Most zirconium alloys used for this purpose, called zircalloy, contain 95% zirconium and less than 2% each of tin, niobium, iron, chromium, nickel, and other metals, which are added to improve mechanical properties and corrosion resistance.

Analysis of the gas showed that no oxygen was present, meaning no explosion could occur. The hydrogen gas was carefully and safely removed through a catalytic combiner, and the resulting nonradioactive water vapor was released directly to the open air.

The United States Environmental Protection Agency (EPA) began continuous sampling and monitoring at three stations close to the plant. By 1 April that had been expanded to eleven stations, and by 3 April expanded to 31 stations. Even though water with radioactive materials had been pumped from the containment building to an auxiliary building, an inter-agency analysis concluded that the accident had not increased radiation levels beyond normal background levels.

Researchers at nearby Dickinson College had radiation monitoring equipment sufficiently sensitive to detect Chinese atmospheric nuclear weapons testing. They collected soil samples from the area during the ensuing two weeks and detected no elevated levels of radioactivity, except after rainfalls, which they attributed to normal radon release, not the accident. Tongues harvested from white-tailed deer about 50 miles from the accident were found to have levels of caesium-137 that were greater than deer in counties surrounding the plant, but these levels were still below levels found in deer in other areas of the country during the height of atmospheric nuclear weapons testing; that caesium was almost certainly a relict of earlier atmospheric nuclear weapons testing. Had there been significant release of radioactive materials other then inert gases, increased levels of iodine-131, strontium-90, and caesium-137 would have been expected in milk samples from cattle and goats, but no such elevated levels were detected.

Essentially all of the radioactive materials that were released to the general environment were isotopes of the inert gases krypton and xenon. Because inert gases have no biological activity, this release resulted in an increase in biological hazard to the average nearby resident of 14 μSv (microsieverts) during the next year. To put this in context, the average dose from natural background sources is 2.3 mSv (millisieverts, not microsieverts) per year at sea level. The dose from one transcontinental airline flight is 35 μSv, and the dose from one abdominal and pelvic CT scan with and without contrast is about 30 mSv (not μSv). The annual dose on the Tibetan plateau is 13-20 mSv. Exposure on beaches in Guarapari, Brazil varies from 175 to 1,148 mSv/yr because the sand contains monazite, an important ore for cerium, lanthanum, and thorium. The X-ray dose to treat prostate cancer is 72 Sieverts (not mSv) delivered over a period of 56 days [45].

The conclusion is that the hypothesized *China syndrome* did not occur, no one was injured or made ill, and the in-depth redundant safety systems had in fact worked, despite significant failures of operator actions and individual components. Important lessons were learned and have been applied to NRC rules regarding operator training, and reactor instrumentation and control systems.

Chernobyl

Four reactors of the RBMK-1000 type (Reaktor Bol'shoy Moshchnosti Kanal'nyy, or High Power Channel Reactor)[f] were built at the Chernobyl Nuclear Power Station near the village of Pripyat, Ukrainian SSR, about 20 kilometers from Byelorussia (now Belarus) between 1970 and 1983, and two more were under construction. Thirteen others were put into service in various parts of the Soviet Union. None were built outside the Soviet Union and its satellites. Eight are still in service, with the last of them, Smolensk-3, to be shut down in 2034.

Each unit at Chernobyl included 5.5 megawatt diesel generators to supply power to emergency coolant pumps in the event of simultaneous rupture of a 600 mm (24 inch) coolant pipe, and station electrical blackout. About 60-75 seconds were required for each generator to reach full power.

It had been theorized that energy stored as angular momentum in the reactor's steam turbine and generator could be used to generate sufficient electricity to power the emergency core cooling system (ECCS) pumps in the event of those simultaneous failures. The turbine speed would decrease as energy was taken from it, but the theory was that this would provide sufficient power to run the pumps for about 45 seconds – not a sufficient bridge to full operation of the diesel generator, but a reduction of the problem and perhaps enough to avert catastrophe.

This needed to be confirmed experimentally. A test in 1982 using a different unit had indicated that the excitation voltage of the generator was not sufficient to maintain the necessary magnetic field (see Section 4.2.2). The supply system for the excitation voltage was modified, but a test in 1984 was unsuccessful. A test in 1985 failed due to failures of recording equipment. A test was planned for 1986 during the first planned power-down of unit 4 since it had been put into service in 1983, in preparation for scheduled maintenance.

The test was regarded as a purely electrical test of the generator. A test procedure had been written, but the authors, being electrical engineers not trained in reactor physics or operations, were not aware of the unusual characteristics of RBMK-1000 reactors during low power operations. The reactors had been designed by the Kurchatov Institute of Atomic Energy, so their details were regarded as state secrets, even kept from the operators. According to regulations in place at the time, such a test, which actually involved critical systems, did not require approval by either the chief design authority for the reactor (NIKIET) or the Soviet nuclear safety regulator. The test called for disabling the ECCS, which included a passive system that used counterweights to pump water while the diesel generator was reaching full power. This had been approved by

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[f] RBMK reactors were used both for municipal power and to produce weapons materials. They are based upon those used at Hanford during the Manhattan Project to breed plutonium. Stalin had the plans before the Hanford reactors were built.

the Chernobyl site chief engineer.

The test was to be run as follows:

1. The test was to take place during scheduled reactor shutdown.
2. The generator was to be disconnected from the regional grid.
3. The reactor thermal power was to be reduced to between 700 MW-th and 1,000 MW-th (22-30% of normal thermal power of 3,200 MW-th) to allow for adequate cooling, because the turbine would operate at normal speed when not connected to the power grid.
4. Four out of eight of the main coolant pumps were to be supplied with off-site power, while the other four were to be powered by the turbine run-down.
5. The steam supply to the turbine would be closed, and the reactor would be shut down, when the correct conditions were achieved.
6. The voltage provided by the coasting turbine would be measured, along with the voltage and speeds of the four coolant circulation pumps being powered by the turbine.
7. When the diesel generators reached full power, the turbine generator would be disconnected and allowed to free-wheel down.
8. The fission reaction in the reactor would be shut down completely, to reduce its thermal output to the level of about 6% of normal output produced by radioactive decay.

The test was to be conducted during the day shift on 25 April 1986. The shift crew had been trained in advance on the operations to be performed during the test. As planned, a gradual reduction of thermal power was begun at 01:06, and the power reached 50% of its nominal 3,200 MW thermal output before the beginning of the day shift. Several unrelated maintenance tasks were performed, and the test was scheduled to begin at 14:15. The ECCS was disabled. Another regional generator unexpectedly went offline at 14:00, and the Kiev regional grid operator requested that further reduction in Chernobyl unit 4 power be postponed.

The day shift was replaced by the evening shift, who had not been trained for the experiment. The ECCS was left disabled. Disabling the ECCS required three people to spend most of a shift turning valve wheels about the same size as the helm wheel on a sailboat. The ECCS being disabled for most of a shift had no immediate effect, but it was indicative of the general lack of a safety culture.

At 23:04, the Kiev regional grid operator allowed the reduction of power at Chernobyl unit 4 to resume. The day shift was long gone, the evening shift was preparing to leave, and the night shift would not begin duty for another hour. Because the test was to be completed by the day shift, the night shift would have been expected only to maintain decay heat cooling systems operating in an otherwise shut down plant.

The test plan called for a gradual decrease in reactor power to 700–1000 MW-th. Output of 720 MW-th was reached at 00:05 on 26 April. One of the normal fission products is iodine-135, which decays quickly to xenon-135, which is a strong neutron absorber. Although the operators had stopped control rod motion, reactor power continued to decline because of xenon poisoning. In steady-state operation, xenon poisoning does not occur because xenon-135 is rapidly transmuted to xenon-136, which is not a strong neutron absorber. Xenon poisoning is a predictable and well known effect but it made controlling the reactor at low power more difficult.

When reactor power had reduced to 500 MW-th, control was switched from the local automatic regulator to the automatic regulators (AR), to manually maintain the desired power level. AR-1 then activated, removing all four of AR-1's control rods, but AR-2 failed to activate due to an imbalance in its ionization chambers. In response, Leonid Tuponov, the Senior Reactor Control Engineer who was responsible for the reactor's operational regimen, but had been in that position for only three months, reduced power to stabilize the automatic regulators' ionization sensors by re-inserting control rods. As a result, between the effects of re-inserting control roads, and xenon poisoning, the reactor's power dropped rapidly to 30 MW-th.

With the reactor producing only 5% of the minimum power prescribed for the test, xenon-135 was not being burned off, which hindered increase in reactor power. Control room personnel removed numerous control rods from the reactor. After several minutes, the reactor was restored to 160 MW-th at 00:39, at which time the control rods were at their upper limits. Due to xenon poisoning, the reactor was within its operational reactivity margin, equivalent to having fifteen control rods inserted.

Operation of the reactor at low power and high xenon poisoning caused fluctuating core temperatures and coolant flow, and probably an unstable neutron flux. There were several emergency signals regarding low levels in one half of the steam/water separators, with accompanying low separator pressure readings. In response, operators triggered several rapid influxes of feedwater. Relief valves opened to release excess steam into a turbine condenser.

After the power level of 200 MW-th was attained, preparation for the experiment continued, even though the power level was much lower than the planned 700 WM-th level. As a planned part of the test, two additional main coolant circulation pumps were activated at 01:05. This reduced coolant temperature, which reduced steam voids within the reactor core. Because water absorbs neutrons better than steam, reactor power output decreased. Operators compensated by removing more of the manual control rods. At this time, fewer than the required fifteen control rods were within the reactor, but the operators did not know this because the reactor had no instrumentation able to count the control rod worth within the reactor.

The result of these actions was an extremely unstable reactor configuration. Unlike most light-water reactors, RBMK reactors have a *positive void coefficient*, which means that the fission reaction runs faster if steam voids form. Because nearly all 211 control rods had been extracted manually, and a very high coolant flow rate, coolant was entering the reactor at very close to its boiling point. The result was increased steam bubble formation. Unbeknownst to the operators, the void coefficient was not compensated by other reactivity effects at low power. In particular, because of the increase of power, xenon-135 was being burned off, thereby increasing reactivity. The operators did not realize that reactor unit 4 was very close to a runaway increase in core power with nothing to restrain it.

At 01:23:04, the test began. Four of the eight coolant circulating pumps were to be powered by voltage from the coasting turbine, while the remaining four received power from the grid. Steam supply to the turbines was shut off, beginning a run-down of the turbine. The diesel generators started automatically and began to pick up load. They were expected to pick up the entire main circulation pump loads by 01:23:43. As the power output from the coasting turbine decreased, coolant flow rate decreased, which increased steam voids in the reactor core.

At 01:23:40, a "scram" emergency shutdown was initiated as the experiment was completing. This was started when the AZ-5 button of the reactor emergency protection system was pushed. This engaged the drive mechanisms on all control rods to fully insert them, including the manual control rods that had been withdrawn earlier. The reactor control mechanism moved the control rods at 0.4 meters per second, so that the rods required 18 to 20 seconds to reach the full 7-meter depth of the reactor core. RBMK control rods include a 1.25 meter section of graphite. In most light-water reactors, water serves as the *moderator*, which reduces the average speed of neutrons to the range most suitable for fission. In RBMK, graphite is used for moderation, and the effect of water is to *absorb* neutrons and slow the reaction. When the control rods are fully withdrawn, there is a 1.25 meter graphite extension centered in the core, with 1.25 meters of water above and below it. Consequently, inserting a control rod initially displaces neutron absorbing water, replacing it with neutron moderating graphite. Therefore, the initial effect of inserting control rods is to *increase*, not decrease, the fission rate. This effect was already known; it had been observed in 1983 at another RBMK reactor at the Ignalina Nuclear Power Plant in Lithuania.

A few seconds into the scram, a power spike occurred, causing some of the fuel rods to fracture, and possibly blocking some of the control rod columns. As the scram continued, reactor power increased to around 30,000 MW-th, ten times normal operational output. This is the last indicated reading before the recording instrument was destroyed. The power output might have reached 300,000 MW-th. Because instruments had been destroyed, it is impossible to reconstruct precisely what happened, but mathematical simulations indicate that a steam explosion occurred, which damaged fuel elements, and allowed damaged fuel channels to escape into the reactor's exterior cooling structure, wherein another steam explosion destroyed the reactor casing, blowing the reactor cover, called the top biological shield, to which the entire reactor was fastened, through the roof of the building.

This explosion further ruptured fuel channels, and severed most of the coolant lines feeding the reaction chamber. Remaining coolant flashed to steam, and the resulting voids, combined with a large and positive void coefficient, further increased the reactor's thermal power. A third explosion, more powerful than the second, occurred about three seconds later, dispersing the core and effectively terminating the nuclear chain reaction. The ejected hot graphite, and graphite still within the demolished core, exposed to air, caught fire. Hot graphite in contact with steam created a mixture of carbon monoxide and hydrogen, both of which also burned in contact with air. These effects contributed to the spread of radioactive debris. The fire in the reactor core continued to burn until 4 May 1986.

Two of the operators died immediately from the explosion or falling debris. A third suffered a fatal heart attack. All the radiation dosimeters read "off scale" so there was no immediate indication of the severity of exposure by operators or firefighters. 237 workers were hospitalized, of whom 134 exhibited symptoms of acute radiation syndrome (ARS) – the taste of metal, and a pins-and-needles sensation, exactly as Louis Slotin, a worker at Los Alamos and the first to die from ARS, had described. Among those hospitalized, 28 died within the following three months, all of whom had symptoms of ARS. During the next ten years, 14 more workers, nine of whom had been hospitalized with ARS, died from various causes not related to radiation exposure.

Major radioactivity releases were ^{133}Xe, 6,500 PBq,[g] ^{131}I, 1,760 PBq, ^{132}Te, 1150 PBq, ^{103}Ru, 168 PBq, ^{140}Ba, 240 PBq, and ^{134}Cs and ^{137}Cs, 132 PBq combined. Being a noble gas, xenon is completely biologically nonreactive. ^{132}Te has a half life of 55 minutes; ^{103}Ru has a half life of 39 days; ^{140}Ba has a half life of 12.75 days. Tellurium, ruthenium, and barium do not have significant biological activity. Iodine-131, which has a half life of eight days, is by far the most dangerous, because the thyroid concentrates it. When there is excess iodine in the body, the thyroid does not take up any more of it. The risk of thyroid cancer due to exposure to ^{131}I is easily and significantly reduced by iodine pills, which were not distributed to the population. ^{134}Cs has a half life of two years; ^{137}Cs has a half life of 30.08 years.

The United Nations Scientific Committee for the Effects of Atomic Radiation (UNSCEAR) report noted that there is "no scientific means to determine whether a particular cancer in a particular individual was or was not caused by radiation," and "no scientific evidence of increases in overall cancer incidence or mortality rates or in rates of non-malignant disorders that could be related to radiation exposure" had been found. Nonetheless, it speculated that fifteen excess cases of fatal juvenile thyroid cancer, compared to earlier decades, out of 6,000 cases of thyroid cancer reported between 1991 and 2005, might have been caused by the accident. In the most affected countries (south-

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[g] PBq means *peta Becquerel*, or one quadrillion decays per second. Another commonly-used unit is the Curie, 37 billion Becquerels.

western Russia, Belarus, and Ukraine), the average additional radiation dose to the general public over the period 1986-2005 was about 9 mSv, or 0.9 mSv/yr (sea level average is 2.3 mSv/yr). 49% of this exposure is contributed by caesium [31]. Caesium-137 is the only long-term hazard for casual exposure. Strontium is dangerous only if ingested. Every caesium salt is soluble, so it is washed out of soils to the Black Sea, where it is diluted beyond detectability. Having biological activity similar to sodium, with a biological half life of 70 days, it is not biologically concentrated [55]. The report advised that residents "need not live in fear of serious health consequences" [39].

If those fifteen hypothetical cases of juvenile thyroid cancer occurred, that they were fatal is inexcusable. In a country with a competent health care system, thyroid cancer is easily treated. The population was also not advised to avoid locally produced foods, especially milk, during the next three months.

Altogether, the official direct death toll due to the Chernobyl accident was 46, three who were killed immediately, 28 who died from prompt radiation exposure, and fifteen speculated to have died from latent cancers.

Two RBMK reactors near Leningrad (now St. Petersburg or Sankt Petrograd) had had damages resulting in partial meltdowns that did not damage their buildings. These incidents were considered to be state secrets at the time and were not known until about twenty years ago.

Fukushima

Construction of the Fukushima Daiichi [number one] Nuclear Power Plant began in 1967. The first reactors entered service in 1971. There were six reactor units, which had a combined output of 4.7 GWe, putting the plant among the fifteen largest in the world.

At 14:46 JST on 11 March 2011, a magnitude 9.1 undersea megathrust earthquake, lasting about six minutes, occurred about 72 kilometers east of the Oshika Peninsula of the Tōhoku region. This was the most powerful earthquake recorded in or near Japan, and the fourth most powerful ever recorded since modern seismography began in 1900.

Reactors 4, 5, and 6 were not operating when the earthquake struck. All of the fuel had been removed from reactor number 4, but reactors 5 and 6 were still fueled, although shut down.

Units 2, 3, and 5 were designed to withstand seismic forces of 0.45, 0.45, and 0.46 g respectively, for continued operation. The measured forces were 0.56, 0.52, and 0.56 g. The seismic forces measured at units 1 and 4 were within design tolerances. Even though the seismic forces at units 2, 3, and 5 exceeded design limits, none of the reactors were damaged by the earthquake, which is a tribute to the conservative engineering by General Electric for these reactors. This is a continuation of the tradition described by Washington Roebling when asked how he determined the necessary strength of the Brooklyn bridge: "I calculate what I can, then make everything six times stronger."

The reactors were initially to be built on a bluff, 35 meters high, overlooking the sea. The altitude of the bluff was reduced by 25 meters, putting the reactors at ten meters above sea level, so that the reactors would be built directly on bedrock to reduce susceptibility to earthquake damage, and to reduce the energy cost to pump seawater for cooling. Emergency diesel generators were in the basements of the turbine buildings of reactors 1 through 4, and on palettes outside buildings 5 and 6.

When the earthquake occurred, automatic mechanisms shut down all three operating reactors. Shortly after the reactors shut down, power from the regional grid was lost, and emergency diesel generators started supplying electric power for pumps providing cooling water through the cores of the reactors, to remove heat caused by radioactive decay, which is initially about 6% of normal operating heat generation.

The earthquake had caused a tsunami estimated to be forty meters high. When the tsunami arrived at Fukushima, it was 13–14 meters high. The seawall, which had been constructed in anticipation of a tsunami, was only 5.7 meters high, and was instantly inundated. The auxiliary generator rooms were flooded at approximately 15:41, and generators outside the buildings were swept away by the tsunami. Fuel tanks were on stilts outside the buildings, and they were also swept away by the tsunami.

Because coolant circulation in the reactors' cores had stopped, their temperatures rapidly increased. The cores of reactors 1, 2, and 3 were damaged, with fuel pins ruptured and fuel melted. Exposures of the cores to steam resulted in a reaction with zircalloy fuel pin cladding that created zirconium dioxide and hydrogen, which also generated more heat. At high temperature, zirconium can react with uranium dioxide to form zirconium dioxide, metallic uranium, and yet more heat. Released hydrogen caused explosions in buildings 1, 2, and 3 between 12 March and 15 March.

The building for unit 4 was damaged, either by the hydrogen explosion in building 3 or by explosion of hydrogen from unit 3 that reached unit 4 through common piping, but neither the reactor, not its spent fuel storage pool, were damaged. There was initial speculation that hydrogen arose from the building 4 spent fuel storage pool by the same zircalloy reaction, but later inspection showed that had not happened.

In 1990, the US Nuclear Regulatory Commission, and the IAEA, advised the Japanese Nuclear and Industrial Safety Agency (NISA) that having the backup generators in the basements of the reactors' turbine buildings was a hazard in the event of a tsunami. The reactors and the seawall had been designed to withstand a 5.7 meter tsunami, which was thought to be the maximum possible at that location, and the generators were not moved. Three additional backup generators for units 2 and 4 were installed in buildings on higher ground. All six units were given access to these generators, but the switchgear that controlled their power to the auxiliary coolant pumps remained in the original auxiliary generator rooms in the basements of reactor buildings 1 through 5. These additional generators operated correctly after the earthquake. Had their switch gear been moved into their new building, instead of remaining in the basements of the units, they could have provided adequate power to the emergency coolant circulation pumps.

Although the reactor in unit 4 was not damaged, and units 5 and 6 had no damage, neither to the reactors nor their buildings, TEPCO has decided not to repair the unit 4 building and reactivate the reactor, nor to reactivate units 5 and 6. Two other units, 7 and 8, to be advanced boiling water reactors, were to be added, but orders for them were cancelled in 2013.

By 12 March, 50,000 people had been evacuated. By 13 March, the figure had increased to between 170,000 and 200,000. On the morning of 15 March, the zone was extended to 20 km. Some people in hospitals who were removed from life support equipment, to prevent the one-in-a-billion chance that they might be injured by radiation, died as a result. When people who were forced to leave their homes arrived at shelters in Tsukuba, in Ibaraki prefecture, about 285 km from Fukushima, they were refused entry into shelters, alleging they *might* be carrying "radioactive contamination." As of September 2011, 100,000 residents were still prevented from returning to their homes. Tens of thousands of children were kept inside of school buildings during the hot summer, and were required to wear masks, even though the windows were closed and air conditioning was turned off. This mistreatment is a direct result of the scientific misconduct described in Section 9.1.1.

The major releases of radioactivity were ^{133}Xe, 7,300 PBq, ^{131}I, 120 PBq, ^{132}Te, and ^{134}Cs and ^{137}Cs, 17.9 PBq combined. Total cumulative exposure over thirty years is estimated to be 570 mGy per initial deposition of 1000 kBq/m^2, with 98% contributed by caesium [31]. With the exception of caesium-137, which is a strong gamma emitter, the only way to suffer harmful effects from those radioactive materials is to ingest them. Excess thyroid cancers have not occurred because iodine pills were distributed. Even though all caesium salts are water soluble, and caesium is therefore washed into the sea where it is diluted beyond detection, it remains a concern. Caesium has biological activity similar to sodium, which has average residence within living tissues of about 70 days, so it is not accumulated.

On 23 June 2013, an announcement was made that most residents would be allowed to return to their homes, even though radiation levels were still between 0.32 and 0.54 μsv/hr – 2.8–4.7 mSv/yr, or 0.5–2.4 mSv/yr greater than normal sea-level exposure. Even though the dirt in most of the area near the power plant is half as radioactive as the dirt in Denver, about 15,000 Japanese are still living as refugees in their own country.

Some areas near the power plant are estimated to be contaminated with materials that would expose trespassers with up to 500 mSv per year, about half the amount that causes residents of Guarapari, Brazil exactly zero verified health problems.

The UNSCEAR reported in October 2013 that "Japanese people receive an effective dose of radiation from normally occurring sources of, on average, about 2.1 mSv annually and a total of about 170 mSv over their lifetimes.... No radiation-related deaths or acute diseases have been observed among the workers or general public exposed to radiation from the accident.... For adults in Fukushima Prefecture, the Committee estimates [the increase in] average lifetime effective dose to be of the order of 10 mSv or less... discernible increase in cancer incidence in this population that could be attributed to radiation exposure from the accident is not expected."

The nearby Fukushima Daini [number two] Nuclear Power Plant, about 13.5 kilometers from Fukushima Daiichi, was also struck by the tsunami, but design changes that improved resistance to flooding had been incorporated. In particular, the reactor buildings were watertight, and the generators and associated electrical equipment were within the watertight buildings. Seawater intakes of those reactors were damaged by the tsunami, but the reactors were shut down safely, coolant circulation was maintained, and they were ultimately not damaged.

9.2 EBR-II – a walk-away safe design

As early as the 1950's, engineers and scientists at Argonne National Laboratory had been concerned about fuel economy because the true abundance of uranium was not known. They set out to solve all the world's energy problems with one system that initially had the following objectives:

- It consumes existing nuclear waste, effectively destroying it,
- It is economical to build and operate, and
- It creates more fuel than it consumes.

Two more were eventually added:

- It is inherently safe, and
- It is extremely resistant to diversion of materials for nefarious purposes.

Their first project directed toward these goals was called Experimental Breeder Reactor I, or EBR-I. This was a tiny reactor, with a core about the size of a football [53, p. 24], for which the primary goal was to prove that fissionable plutonium-239 could be created from non-fissionable uranium-238, the most abundant uranium isotope, at a faster rate than uranium-235, the fissionable isotope of uranium, is consumed. All isotopes of plutonium, not just plutonium-239, are fuel in the right kind of reactor. Construction began in October 1949. Criticality was achieved on 24 August 1951, and full thermal thermal power of 1.4 MW-th was first produced on 19 December 1951. The project proved that more fuel was produced than consumed. After separating it from used fuel, plutonium was used to power the reactor.

A secondary goal for EBR-I was to prove that a nuclear reactor could produce meaningful amounts of electricity. It included a generator as part of its original design. At 1:50

P.M. on 20 December 1951, operators connected a string of four 200-watt light bulbs to its generator, and proved it was in fact generating electric power. The following day it produced enough power to light the entire building – about 200 kW. The reactor is no longer in service, but was not demolished. It has been designated a National Historical Landmark and converted to a public museum on U.S. Highway 26, about twenty miles east of Arco, Idaho. This was the first real demonstration of a nuclear reactor producing electricity. Some claim that the X-10 reactor at Oak Ridge National Laboratory was first. As an afterthought "experiment," operators took some fuel from it, put it into an aluminum tube, and ran some water through it. This produced some steam, which drove a toy Jensen Steam Engines #50, connected to a toy generator. It briefly produced only a tiny amount of electricity, barely enough to light a single Christmas tree light bulb. Although it demonstrated that decay heat produces steam, it didn't actually demonstrate a reactor producing electricity.

On 17 July 1955, the third reactor in the earlier Boiling Water Experimental Reactor program, BORAX III, was connected to the grid for about an hour, providing 2,000 kW to Arco, which thereby became the first city served by nuclear power in the United States. In Russia, the 5 MWe Obninsk Reactor produced the first nuclear electricity for a municipality, the town of Obninsk, starting on 26 June 1954.

EBR-I was decommissioned in 1964, and followed by *Experimental Breeder Reactor II* or EBR-II, which began operation in 1964 at Argonne National Laboratory-West, about halfway between Arco and Idaho Falls in Idaho. Argonne National Laboratory-West was merged into the Idaho National Laboratory in 2005. Rather than being a minimal-size reactor to demonstrate physical feasibility, it was of a more realistic size: 62.5 MW-th, about 20 MWe. It provided power for Argonne-West, and sold a surplus to the local utility grid.

The goals of EBR-II were to demonstrate all aspects of the ambitious plan of scientists and engineers at Argonne National Laboratory.

EBR-I and EBR-II were what is called a *liquid-metal fast breeder reactor*, or LMFBR. The liquid metal is used as a coolant, not as fuel. In EBR-I it was a low melting-point eutectic[h] alloy of sodium and potassium, called NaK. In EBR-II, it was molten sodium. Na-22%/K-78% melts at a temperature of -11°C or 12.2°F, and pure sodium melts at a temperature of 97.8°C, or 208°F.

EBR-II uses sodium as a coolant instead of water – or lead or a lead-bismuth (PbBi) eutectic alloy – for several reasons.

- The optimum average neutron speed to transmute uranium to plutonium (that is, to breed more fuel) is much greater than the speed that would result from using water for cooling – hence the term *fast reactor*. It's the neutrons that are fast, not the reactor. In a water-cooled reactor, neutrons are slowed because collisions

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[h] An *eutectic* alloy is a mixture with a minimum melting point, below that of any of the pure metals.

with hydrogen atoms transfer more of the neutrons' momentum to the hydrogen atoms than to oxygen atoms, or to sodium atoms.

- Sodium boils at 882.8°C, about 1621°F. A pressure vessel is not necessary to prevent it from boiling.
- Water, lead, and PbBi are corrosive to steels. Sodium is not.
- Sodium thermal conductivity is 230 times greater than water, 2.3 times greater than Na-22%/K-78%, and 4.6 times greater than PbBi.
- Although the heat capacity by weight of sodium is only 29% that of water and 71% that of PbBi, it is 1.3 times greater than Na-22%/K-78%.
- Liquid sodium is more viscous than water, but PbBi is 5.2 times more viscous than sodium.
- Sodium density is 82% of water density. PbBi density is twelve times greater.
- Sodium has only one stable isotope, and all radioactive isotopes that result from neutron absorption have very short half lives, the longest, sodium-24, being only fifteen hours. Polonium-210, transmuted from bismuth by neutron absorption, with a half life of 138 days, is an extreme radiotoxic hazard. Alexander Litvinenko was poisoned by about 250 milligrams of polonium-210, in green tea, on 1 November 2006, and died on 23 November 2006 [29].
- Sodium has a much lower neutron absorption cross section than PbBi, which means that sodium's innocuous activation products are created at a much lower rate than the dangerous activation products created from lead and PbBi. And it doesn't soak up the neutrons that are necessary for perpetuating the fission chain reaction.

To prevent water from boiling, a water-cooled reactor must be operated at up to 140 times atmospheric pressure, which requires a very strong vessel. In EBR-II, sodium coolant remains about 140°C below boiling under all conditions, so a simple tank is sufficient. Higher density and higher heat capacity (by weight) of PbBi result in higher volumetric heat capacity than sodium, but higher viscosity would require larger coolant channels, with more structural components to maintain spacing. Higher density and viscosity would require about ten times more pumping power than using sodium cooling, which would make the reactor economically infeasible. Worse, higher coolant volume fraction and higher density mean that PbBi coolant would weigh about fifteen times more than would sodium in the same capacity reactor, even though PbBi is only twelve times more dense than sodium [53, §14.2.2].

An important eventual (although not initial) goal of the EBR-II project was to demonstrate a "walk-away safe" reactor. Several factors must combine to achieve that. The short story is that most feedbacks must be negative, and the combination of all feedbacks must be negative.

The first negative feedback in EBR-II is that the physical layout, and the materials, of the fuel and structures in the EBR-II core are such that as temperature increases, the core expands, neutrons leak out of the core, and the fission chain reaction slows.

The propensity of a fissionable atom to absorb a neutron and thereby be induced to fission depends upon what is called the *fission cross section*, measured by a tiny area called a *barn*, 10^{-28} square meters.[i] The name comes from the old insult about somebody being such a poor marksman that “he couldn’t hit the broad side of a barn.” Who said nuclear physicists had no sense of humor? The fission cross section, not of an individual atom but the average of an ensemble of atoms, also depends upon the relationship between average neutron velocity and average fuel atom velocity. If one measures fission cross section as a function of neutron velocity, one observes peaks in the distribution. The wider a peak, the more likely a neutron with a random velocity near the optimum velocity is to be absorbed and cause fission. When an atom is hot, it jiggles a lot, meaning its average velocity, compared to an incident neutron, is greater, randomly in the same or opposite or some other direction compared to the neutron. The result is what is called *doppler broadening* of the absorption peaks: The absorption peaks’ widths increase with temperature, and therefore reactivity increases with fuel temperature.

Once you have the average neutron speed adjusted to the desired range, in order to reduce thermal feedback, you want to reduce *doppler reactivity*, that is, you want to decrease reactivity caused by doppler broadening of absorption spectral features, which requires fuel to operate at a lower temperature [53, §7.6.1]. One way to do that is to increase coolant conductivity, which as we have seen above is much greater with sodium than with other coolants.

Another way to reduce fuel temperature is by using fuel that has high thermal conductivity. The fuel in most reactors is a ceramic, usually an oxide, although sometimes a carbide or nitride. The thermal conductivity of uranium metal at a reactor’s operating temperature is about ten times greater than the thermal conductivity of uranium oxide. EBR-II used metallic fuel. The average temperature of oxide fuel in a conventional nuclear reactor is 2,000°C. As shown in Figure 9.3, the operating temperature at the surface of a fuel pin in EBR-II was about 1030°F, or 550°C, so doppler reactivity was much less than in an oxide-fueled reactor. Fuel elements in EBR-II were only 0.174 inches (4.4 mm) in diameter, so the temperature at the center was not much greater [32].

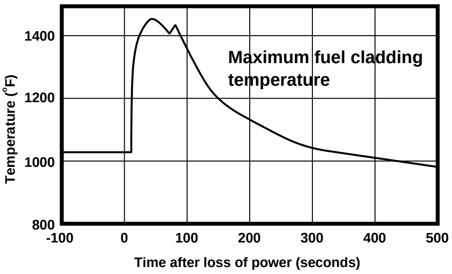

Figure 9.3: Loss of coolant flow test

The structural materials and design, together with the high thermal conductivity of sodium and metallic fuel, gave EBR-II a strongly negative relationship between temperature and reactivity, called a *negative temperature coefficient*. Engineers and scien-

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[i] Even smaller units are called an *outhouse* and a *shed*.

tists had calculated these relationships (and other factors related to reactor safety), but to convince others, and to verify their calculations, on 3 April 1986 they conducted a test for an invited international audience.

While the reactor was operating at full power, operators turned off automatic shutdown mechanisms – the kind that had initiated "scram" at Three Mile Island and Fukushima Daiichi. Of course, they kept manual shutdown mechanisms available. Then they turned off coolant circulation. Remember, this is what operators did at Three Mile Island, believing they had to do it to avoid the cooling system "going solid," as explained in Section 9.1.2. EBR-II operators *did not* "scram" the control rods into the reactor. They sat back and watched. As shown in Figure 9.3, the temperature of fuel pin cladding spiked from about 1030°F (550°C) to 1430°F (780°C) within about thirty seconds. Then, within 400 seconds (less than seven minutes), without any automatic systems or operator intervention, the cladding temperature was below normal operating temperature [9] [43].

The "loss of coolant circulation without scram" test did not damage the reactor. It did not injure the operators or observers. The Argonne engineers and scientists had also calculated what would happen in what's called a *loss of heat sink test*. This is the same sort of event that started the problems at Three Mile Island, when the PORV opened and the feed pumps for the steam generator were turned off, and the kind of event for which operators at Chernobyl were hoping to test the auxiliary response of steam-turbine run-down.

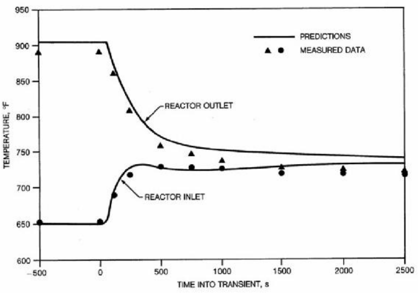

Figure 9.4: Loss of heat sink test

Operators at EBR-II restarted the reactor. Once again, they turned off automatic shutdown mechanisms. Once again, of course, they kept manual shutdown mechanisms available. Then they turned off the pumps for the intermediate sodium loop.[j] Once again, they *did not* "scram" the control rods into the reactor. Coolant kept circulating through the reactor core, but because the intermediate sodium loop was not operating, heat was not removed from the primary cooling system. As Figure 9.4 shows, the coolant temperature at the inlet to the reactor fuel core increased from 650°F (345°C) to about 730°F (about 390°C), but leveled off after about ten minutes. Because the increased temperature introduced negative overall reactivity, and therefore the rate of heat production, the reactor fuel core coolant outlet temperature decreased from 905°F (about 500°C) to about 760°F (about 400°C). The inlet and outlet temperatures were clearly within manageable ranges: They had converged to a difference of less than about 30°F (about 15°C) within about ten minutes, at a much lower temperature than the

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[j] EBR-II used an intermediate sodium loop, in addition to primary sodium coolant, to avoid having radioactive coolant in the steam generator.

boiling point of sodium, and a much lower temperature than would damage fuel, cladding, or structures [16].

The two tests demonstrated that the EBR-II design was not just calculated and modeled, but demonstrated, to be *walk away safe*.

Three weeks later, operators at Chernobyl tried to test whether the angular momentum stored in the turbine and generator could keep their emergency cooling system going during the time it took for their backup generators to start up after they turned off the steam feed to the turbine. They botched that test, and ended up causing a transient overpower event because they didn't understand xenon poisoning and *increased* reactivity during scram, leading to a steam explosion and a graphite fire, as described in Section 9.1.2.

In both the loss of primary cooling and loss of heat sink tests, coolant temperature remained stable, despite fission still proceeding, albeit much more slowly, and radioactive decay decay heat generation, for several reasons. One is that EBR-II is a *pool* reactor instead of a *loop* reactor. The reactor vessel was surrounded by a coolant vessel containing 86,000 gallons (about 325,000 liters) of liquid sodium [32]. Compared to a pressurized light-water reactor such as Three Mile Island, Chernobyl, or Fukushima Daiichi, EBR-II contained much more coolant, with much higher thermal conductivity, per watt of thermal power, and therefore the reactor as a whole had a much higher heat capacity. Even with a complete loss of coolant circulation, or heat sink, the pool had sufficient capacity to keep the reactor safe for at least a week [53, §7.6.3]. Of course, much more quickly than a week after a serious accident, operators would insert control rods and shut down fission completely. The reactor was not walk-away-and-leave-it safe, but it could, in principle, be operated safely with only one shift of staff per day.

Decay heat is normally removed from EBR-II by the usual intermediate heat exchanger to the steam generator, using a small electromagnetic pump. In addition, there is a passive device of what is called a *bayonet* type – a long tall system of concentric pipes, with the two innermost pipes having insulation between them, connected at top and bottom, and filled with NaK. When heated, normal convection would cause NaK to circulate upward within the inner pipe. Because the outer NaK pipe was cooled by natural convective air cooling between the two outermost pipes in about the top half of the device (also connected to each other at their top and bottom), NaK in the outer pipe became more dense and circulated downward. The system was prevented from wasting heat during normal operation by a damper held closed by an electromagnet, but which opened automatically when power output stopped. This device did not require electric power [32]. It did not contribute significantly to the inherent physical (not fancy engineering) self-regulating reduction of fission during the two 1986 tests.

The most important factors that resulted in inherent safety as demonstrated at EBR-II were

- Materials and configuration of structures that expand when heated, allowing neutrons to escape, reducing the fission rate,
- Sodium coolant with large margins between operating temperature – or even temperatures reached during severe accident scenarios – and boiling temperature,
- Pool configuration with large heat capacity and therefore large thermal inertia, and
- Metal fuel with low stored Doppler reactivity [53, §7.8].

9.3 No one knows what to do about nuclear waste (yes we do)

9.3.1 Spent fuel composition and processing

A simple rule of thumb is that fissioning one tonne of heavy metal (actually 989 kilograms in the average pressurized light-water reactor or LWR) produces one gigawatt-electric year (GWe-yr), or 8,765,810,000 kilowatt hours, of electricity. The usual practice is to remove and replace fuel when it is about 5% used, so producing one GWe-year of electricity produces twenty tonnes of 5% used fuel. That is, those removed twenty tonnes contain about one tonne of fission products and 19 tonnes of unused fuel. Those twenty tonnes ought more properly to be called *spent fuel* rather than *nuclear waste* because it's actually valuable – only 5% of the fuel has been used.

Would you go to a service station, buy 20 gallons of gasoline, drive your car twenty or thirty miles, then go to a $40 billion facility and pump 19 gallons into it, to be stored for 300,000 years? I don't think so.

Spent fuel that has been "cooled" for ten years would be harmful if held in your hand, but standing five or ten meters from it is not harmful. For anyone who has defective kidneys and is stupid enough to eat it within the next 300,000 years, it would be dangerously radiotoxic – an apparently intractable problem. Examining the composition of spent fuel leads to a different conclusion. A tonne of spent fuel typically consists of about 52 kilograms of fission products and 948 kilograms of uranium and transuranic actinides (uranium and metals with greater atomic number), that is, unused fuel.

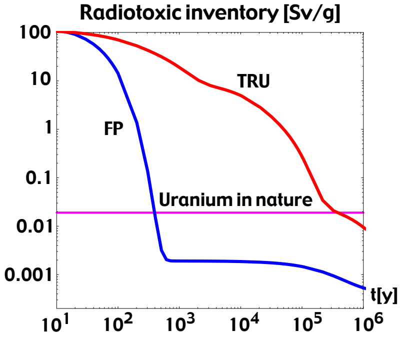

Figure 9.5: Spent fuel radiotoxicity

As shown in Figure 9.5, fission products are less radiotoxic than uranium ore in nature, with daughter products in equilibrium, after 400 years; unused fuel remains dangerously radiotoxic for 300,000 years. Custody of fission products separated from unused fuel would be much simpler than for spent fuel taken as a whole. It would make much more sense to store fission products, and consume the unused fuel to make more electricity, and more fission products.

After ten years' storage, two fission product elements in spent fuel, strontium and caesium, produce 99.4% of radiotoxicity, but constitute only 9.26% of the mass of fission products – five kilograms per tonne of spent fuel, or about 92 kilograms per GWe-year, as shown in Appendix B.

Ten year old spent fuel contains 45 kilograms per tonne, or 900 kilograms per GWe-year, of low-level waste, which is less radiotoxic than uranium ore in nature within 30 years, and much simpler custody is adequate. Details for fission products are shown in Figure 9.6, and details for transuranics are shown in Figure 9.7. The level for uranium in nature was taken from [62].

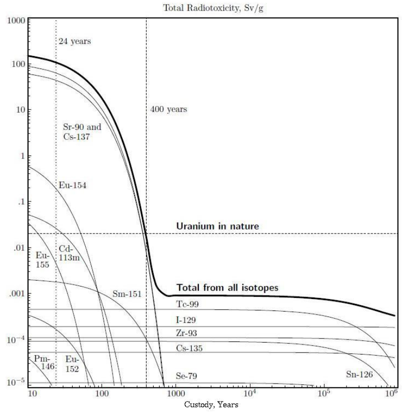

Figure 9.6: Fission product radiotoxicity

The process used to separate fission products from unused fuel in France and Russia, and in Britain before Thorp was closed, and will be used in Japan if Rokkasho ever enters service, and would have been used in the United States if the Barnwell facility had not been cancelled, is called PUREX, for Plutonium-URanium EXtraction. This process separates chemically pure but isotopically mixed plutonium and uranium from spent fuel, leaving other actinides – especially americium, curium, and neptunium – with the fission products. Because the fission-product stream contains these extremely long-lived actinides, although the process reduces the volume of material that must be stored, it does not reduce the duration of custody demanded by those who believe humans will become more stupid and ignorant, and therefore might eat it.

The PUREX process starts by dissolving fuel pins using nitric acid, resulting in an aqueous solution of nitrate salts. Water is a good moderator that brings neutrons' average speeds into the range that best results in fission. The concentration of spent fuel must therefore be kept very low to avoid criticality accidents, that is, to avoid turning the processing facility into a reactor. A facility to process hundreds of tonnes per year must necessarily be very large. It occupies several thousand hectares, has several kilometers of pipes and hundreds of pumps, valves, and mixing devices, and is very expensive to build, operate, and maintain.

Another facet of the EBR-II project was fuel processing, to recover unused fuel, and reduce the waste material to only fission products. Because EBR-II fuel was metal, not oxide, the first method that was tried to process fuel consisted simply of melting it. This process, called *pyrometallurgy*, is commonly used in many metal refining systems. It separated many fission products from unused fuel, but did not separate *noble* metals such as molybdenum and zirconium, nor did it separate higher actinides; in particular, it did not separate plutonium. There was also a loss of 6–8% unused fuel in each cycle. Fuel could be cycled only about four or five times.

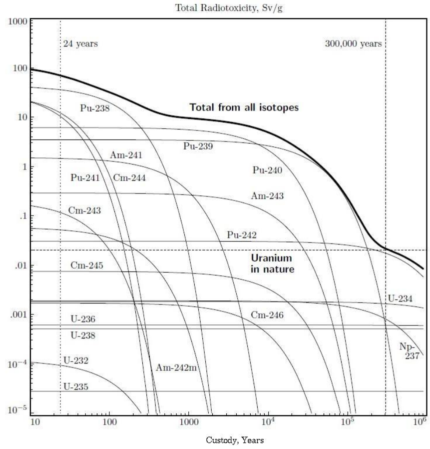

Figure 9.7: Actinide radiotoxicity

A second process was therefore developed, beginning in 1983. This is an electrical process, conducted in molten salt, in the same way that aluminum and zinc are refined, and is therefore called *pyroelectric* reprocessing.

At EBR-II, when a fuel assembly was to be taken from service, it was first removed from the reactor core to another area within the sodium pool, to a place where a fission chain reaction could not proceed. After it had cooled and the shortest-lived fission products had decayed, it was removed from the sodium pool, put into a cask called a *coffin*, and transported through a tunnel to an adjacent wash station. Throughout this transport, the fuel assembly was actively cooled by forced circulation of cooled argon. Within the wash station, sodium was removed from the fuel pins and structural elements first by a high velocity argon stream, and then by steam, which converted sodium to lye (sodium hydroxide) and hydrogen. After hydrogen and argon were vented and separated, lye was removed with water. The fuel assembly was then transferred to the inert argon atmosphere in the fuel cycle facility where it was disassembled. Individual fuel pins, laid out on racks, were adequately cooled by passive circulation [53, §8.1].

In early operations, it was found that metallic fuels swelled because of accumulation of low-density solid fission products (2 g/cm^3 compared to 19 g/cm^3 for fuel), changes in the fuel's crystal structure, and most importantly by accumulation of fission gases, eventually rupturing fuel cladding. This is the reason that in commercial reactors, ceramic fuels, which do not swell significantly, are used. Engineers and scientists at Argonne National Laboratory wanted to use metallic fuel because of its higher thermal conductivity, so they set out to examine the expansion problem. They found that by reducing fuel slugs' cross section area to 75% of the inner cross section of fuel pin cladding, fuel could be allowed to swell and voids containing fission gases – mostly xenon and krypton but also some iodine – would swell and interconnect, resulting in a condition of essentially open porosity, at about 1.6% burnup, allowing fission gases to escape to the plenum, and swelling largely stopped. Thermal conductivity also increased because sodium, which has higher thermal conductivity than uranium (and much higher thermal conductivity than fission gases), intruded into the voids [30].

Rather than fabricating metallic fuel slugs with almost exactly the same diameter as the inside diameter of the fuel pin cladding, at EBR-II they were fabricated with about 85% that diameter, resulting in a cross section area about 75% of the inside of fuel pin cladding. To provide good thermal contact between fuel and coolant, the gap between fuel pins and cladding was filled with sodium for thermal bond. A space called a *plenum* was left empty at the top of the fuel pin, for fission gases, with a size chosen so that gas pressure would not become anywhere near sufficient to rupture the fuel pin. During irradiation, fuel slugs swelled to about the same diameter as the inside diameter of fuel pin cladding. Excess thermal bond sodium was squeezed out to the plenum. Even if fuel slugs made contact, cladding was not mechanically damaged. Rather than cladding strain, the primary constraints on fuel residence were interaction of the fuel bundle with the coolant duct [53, p. 118], and fuel-cladding chemical interaction [30].[k]

Unfortunately, the EBR-II reactor was unwisely shut down in 1994 before the pyroelectric system could be used to recycle fuel. Pyroelectric processing began in 1996, and is ongoing. Spent fuel pins are processed by first chopping them into short segments. Sodium is removed from these chopped pieces, primarily to keep sodium out of the next process, which would result in pointlessly storing harmless sodium with fission products. The pieces are put into an *anode basket* and submerged within a vat, about the size of a dishwasher, containing molten electrolyte, consisting of an eutectic mixture of lithium and potassium chloride salts. A *cathode* consisting of an iron rod is inserted into the vat near the anode basket, and a voltage is applied between the anode and cathode. The applied voltage causes some of the metals in spent fuel to ionize and combine with chlorine to form chloride salts. Noble metals remain in the anode basket. The chloride activities of remaining fission products are well separated from uranium's activity. The result is that nearly pure uranium is deposited at the cathode, while fission products with high chloride activity remain in the electrolyte. At the end of this process, fission products, plutonium, neptunium, americium, curium, and small amounts of other actinides remain as chlorides in solution with the salts. Several methods were developed to separate the remaining uranium, along with plutonium and other actinides, from fission products. The process ultimately reduces the concentration of actinides in electrolyte, relative to fission products, to 100 ppm by weight. Chemically pure plutonium is not produced. It never appears as more than 60% of a product [53, §§8.2, 8.3] [64].

Fission products were initially separated from electrolyte using zeolite-A, similar to the active material in a water softener. A process based on fractional crystallization was later developed, after which fission products were combined with zerolite-A. Cleansed electrolyte was returned to the processor. Waste-laden zeolite-A was mixed with crushed waste glass frit and then melted under pressure to form an impervious insoluble ceramic called *sodalite,* ideal for long-term storage. The fission-product density in the storage material is about 4% by weight, and the actinide density is about 4 ppm by weight.

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[k] FCCI was primarily formation of an iron-plutonium eutectic alloy.

In addition to demonstrating the inherent walk-away safety of the EBR-II design, the research program also proved that fissionable fuel, mostly plutonium, could be created by neutron transmutation of the non-fissionable isotope uranium-238, which is an otherwise useless nuisance composing 99.3% of mined uranium, in a greater quantity than is consumed. This is called *breeding* and the reactor is therefore called a *breeder reactor*. Using breeder reactors, all uranium, not only 0.7% of it, becomes fuel. By building and operating the fuel cycle facility adjacent to the reactor, the project demonstrated these could be integrated in a single facility, thereby essentially eliminating transportation of spent or processed fuel. The system came to be called the *Integral Fast Reactor* or *IFR*.

The same breeding method can be used to convert non-fissionable thorium-232 to fissionable uranium-233, but the process operates only one fifth as fast as breeding plutonium from uranium-238.

The research program was unwisely terminated on 30 September 1994 after thirty years of very successful operation. The reactor, which Nobel Physics Laureate Hans Bethe had described as "the best research reactor ever built" was shut down, removed, and destroyed, and the reactor cavity in the building was filled with concrete [53]. When told that it would cost more to terminate the research program than to finish it, President Clinton's deputy science advisor, Frank von Hippel, said "I know; it's a symbol. It has to go."

The fuel cycle facility at EBR-II, clearly not an industrial-scale system, achieved a maximum throughput of about 2.9 tonnes of fuel per year [53, §8.1]. Argonne National Laboratory and Merrick & Company, sponsored by the Landmark Foundation, prepared a conceptual design of a pyroprocessing facility that would have a capacity of 100 tonnes per year and occupy about 52 acres (21 hectares). The capital cost would be about $400 million, and operating cost would be $53 million per year. Scaling up to a commercial plant with a capacity of 400 tonnes per year was expected to realize economies of scale, without requiring significantly larger buildings or more land. Rather than being the size of a dishwasher, the electrorefiner would be about $2 \times 2 \times 4$ meters – about $6 \times 6 \times 12$ feet. It was estimated to require $911 million capital investment, and $90 million per year for operations [4] [17].

If $911 million were capitalized using a 30 year loan at 5% interest, and fuel were processed after 5% burnup, total operating cost, including capital amortization, would be 0.085¢/kWh. Fuel processing cost per kWh decreases with burnup: If you leave the fuel in the reactor as long as it continues to produce energy at a sufficient rate, say twice more burnup, the amount of fuel needing processing would be less per kWh, about half as much. To put these costs into context, estimated costs for pyroprocessing 5%-burnup fuel and actual costs for PUREX reprocessing at THORP and La Hague, and estimated costs for Rokkasho and Barnwell in 2020 dollars, are shown in Table 9.2.

The Nuclear Waste Act of 1982 required nuclear power plant operators to pay 0.1¢/kWh into the Nuclear Waste Fund. In 2013, a Federal Appeals Court suspended the payments because the Department of Energy had reneged on the legal responsibility imposed upon them by the Act to take custody of spent fuel. The fund now stands at $43 billion. The Act prohibits using any of the funds to process spent fuel.

Table 9.2: Costs for reprocessing [12]

Plant	Area Hectares	Maximum Capacity T/yr	Capital Cost $US	Operating Cost ¢/kWh
Rokkasho	380	800	21 billion	0.52
THORP	285	900	6.3 billion	0.16
La Hague	300	1,700	18 billion	0.15
Barnwell	113	1,500	6.8 billion	0.46
Pyroprocessing [4] [17]	17	400	911 million	0.085

Because the Department of Energy never accepted its responsibility under the Nuclear Waste Act of 1982 to accept spent fuel, and the Yucca Mountain storage project has been cancelled, after the San Onofre Nuclear Generating Station (SONGS) was closed, 1,610 tonnes of spent fuel remain at that site. If a 400 tonne per year facility were to be built, which would fit comfortably into the 84-acre site, it could process that entire inventory in about four years, at a cost of $1.27 billion.

The 1,610 tonnes of spent fuel at SONGS contains 1,530 tonnes of unused fuel, and 84 tonnes of fission products that would be divided into three groups by pyroelectric processing:

- 22.6% of fission products, about 19 tonnes at SONGS, would remain in electrolyte after pyroelectric processing and then be separated into and sequestered at 4% concentration in an impervious insoluble ceramic consisting of sodalite and glass, having a total weight of about 475 tonnes and a volume of about 206 cubic meters, about 2.7 40-foot high-cube shipping containers – 76 cubic meters each – which would, of course, not be used for either shipping or storage, but you get the idea how big the problem would be. This product could be stored at a repository such as the Waste Isolation Pilot Plant in New Mexico.

- 16.5% of fission products, about 14 tonnes at SONGS, are inert gases – krypton and xenon. Krypton has a half life of 10.85 years. Xenon is essentially non-radioactive, with a half life about 1,000 times greater than the age of the universe. Inert gases are not biologically relevant so these can simply be released to the atmosphere.

- 60.9% of fission products, about 51 tonnes at SONGS, are noble metals that remain in the anode basket, or lanthanides (also called rare earth metals) that are collected at a third cathode. These would be combined with zircalloy from cladding. The resulting alloy has a density of about 6 kilograms per liter. There are no significantly radiotoxic isotopes in this product. It could also be stored as low-level waste at a repository such as the Waste Isolation Pilot Plant in New Mexico.

These metals include about 3.8 tonnes of palladium, having a market value of $47.72 per gram or $181 million altogether, and 984 kilograms of rhodium, having a market value of $112.57 per gram or $111 million altogether, if they could be separated economically.[1]

The 1,530 tonnes of unnused SONGS fuel would be divided into two groups:

- A product consisting of 39% uranium, 60% reactor-grad plutonium, and small amounts of higher actinides, weighing about 165 tonnes and occupying about 8.65 cubic meters, and
- 1,365 tonnes of very pure uranium, about 99.4% non-fissile but fertile uranium-238, future fuel in the right kind of reactors, occupying about 72 cubic meters.

Both of these heavy metal inventories could be sold to nuclear fuel supply companies. The 2023 price of uranium as oxide (U_3O_8) is about $25/kg, so the 1,365 tonnes of pure uranium metal would have a value of about $35 million, or almost $9 million per year, more because it would be pure metal rather than oxide, but less because of the lower concentration of the fissionable isotope, uranium-235. The current price of plutonium is about $4 million per kilogram. The 165 tonnes of mixed uranium and plutonium, containing about 106 tonnes of plutonium, would have a value of at least $400 million, about $100 million per year. The value of heavy metal would be about $109 million per year, or about 0.06¢/kWh of processed fuel.

Counting amortization, the facility would not make a profit from processing SONGS fuel, but the plant could continue to operate for many years, processing spent fuel from other reactors such as Diablo Canyon, Rancho Seco, and Palo Verde. At 5% interest on a 30 year loan, amortization plus operating expenses would be about $149 million per year, or about $43 million after selling heavy metal, so to make an unsubsidized profit, it would need to charge about 0.03¢/kWh to process spent fuel. That fee should come from the Nuclear Waste Fund, which explicitly forbids it. Rhodium and palladium among fission products have a value of about $170,000 per tonne of spent fuel, or about $67.7 million per year. If they (and perhaps some other fission products) can be recovered at sufficiently low cost, the facility might make a profit without charging a fee.

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[1] Dr. Prabhat K. Tripathy of the Idaho National Laboratory has applied for a patent, application number 17/819,239, for such a process.

SONGS was built on land that had been part of Marine Corps Base Camp Pendleton. It was leased from the Department of the Navy. When Southern California Edison Company announced plans to close SONGS, the Navy announced they would not renew the lease. The Navy wants its land back. So such a reprocessing facility will not be built there. But you get the idea how big it would be and how much it would cost.

The proposed uses of Yucca Mountain and the Waste Isolation Pilot Project are to store unprocessed spent fuel. If fission products were separated from unused fuel, and only fission products were stored in a permanent repository, the mass would be reduced by a factor of twenty. An important constraint is heat production. Fission products produce 1,375 kW-th per tonne of 5%-burnup spent fuel. 92.7% of that is produced by caesium (in particular ^{137}Cs), strontium (^{90}Sr), and their very short-lived decay products barium (^{137m}Ba) and yttrium (^{90}Y), which constitute only 9.26 wt% of fission products, or 0.47 wt% of spent fuel. Unused fuel produces 458 kW-th per tonne (see Appendix B). If fission products were separated from unused fuel, and further if caesium and strontium were separated, the repository design is not controlled by decay heat. A repository to store caesium and strontium alone, and a separate one (or ones) to store low-heat fission products and unused fuel, would together be less than 20% the size of one to store unprocessed spent fuel. One proposal to dispose of caesium and strontium is to store them in fairly pure forms in hastalloy[m] capsules called *salt divers* and put them into 6.5 km-deep salt domes in Louisiana, where they would quickly melt their way to the bottom, never to be seen again [25].

9.3.2 Cleansing electrolyte

Separating caesium from other Group Ia (alkali metal) elements, in particular lithium, potassium, and rubidium, is very difficult because of their similar chemistry. Separating rubidium from caesium isn't very important because there is only 14% as much rubidium as caesium. But electrolyte from the pyroelectric process must be cleansed when it contains only about 5% fission products. The method used at EBR-II initially consisted of passing electrolyte through a column of zeolite-A, but significant amounts of electrolyte are adhered, and caesium is not as well adsorbed as would be desirable [7]. A newer method based on fractional crystallization is now used.

Significant amounts of work have been done to develop methods to separate caesium from PUREX nitrate raffinates. Very little work has been done to separate caesium from chloride solutions. One method, proposed to cleanse brines from the Asse II salt mine in Germany, where spent nuclear fuel had been stored, is able to separate caesium from sodium chloride, but the presence of potassium strongly degrades the process, so

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[m] Hastalloy is a corrosion-resistant alloy consisting mostly of nickel, and including chromium, molybdenum, and small quantities of other metals. It has been used for decades to store caesium and strontium chlorides at Hanford without incident [25].

it might not work for cleansing pyroelectric electrolyte [51]. Some work has been done to separate strontium from PUREX nitrate raffinates, but very little has been done on separating strontium from chloride solutions.

Table 9.3: Electrolyte contaminant composition

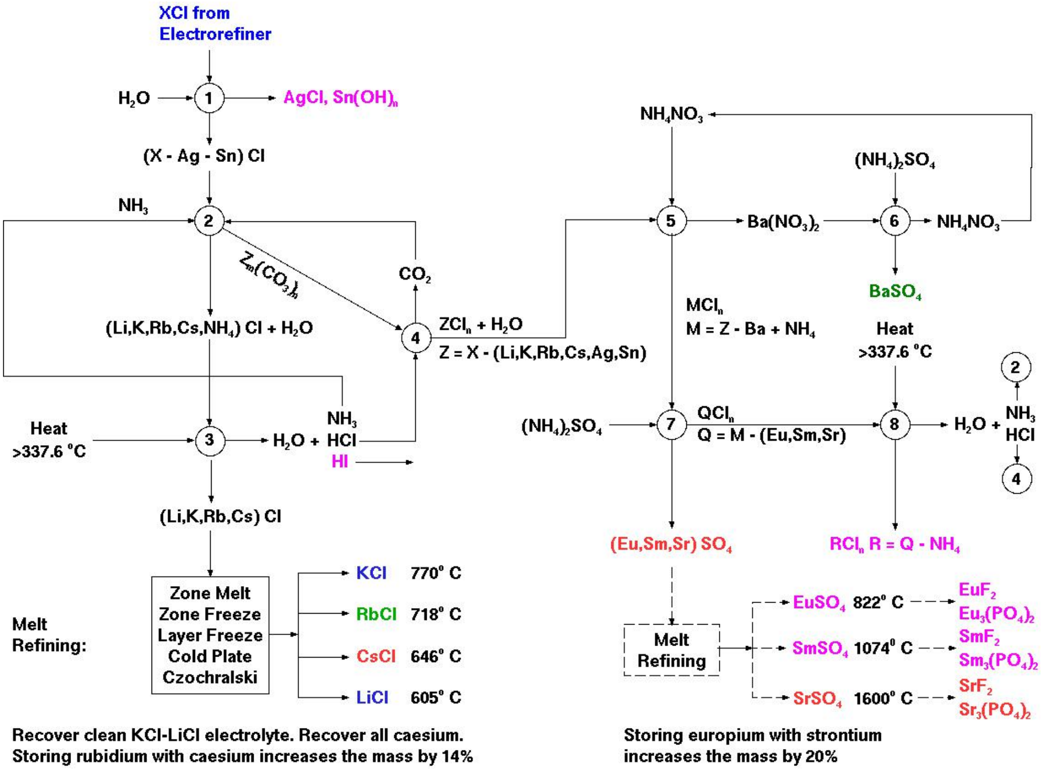
Element	Element Grams	wt. %	Chloride Grams	Power Watts (th)	Radiotoxicity Sieverts	$T_{1/2}$
Antimony (III)	29.06	0.246	54.40	5.218	6.77×10^{4}	2.759 y
Arsenic	0.2982	2.41533	0.72	0	0	∞
Barium	2776	23.5	4212.49	0	0	2.552 m
Beryllium	2.29×10^{-4}	1.90×10^{-6}	1.87×10^{-3}	5.338×10^{-9}	1.809×10^{-4}	1.6 My
Caesium	3680	31.2	4653.29	709.8	6.745×10^{7}	30.04 y
Carbon	4.02×10^{-5}	3.41×10^{-7}	4.41×10^{-4}	52.53×10^{-9}	3.844×10^{-3}	5700 y
Europium (II)	233.4	1.98	341.68	73.35	6.241×10^{5}	8.593 y
Gallium	7.93×10^{-6}	6.72×10^{-8}	2.01×10^{-5}	0	0	∞
Germanium	0.9951	8.43×10^{-3}	2.87	0	0	∞
Indium	2.892	2.45×10^{-2}	5.58	$<1\times10^{-12}$	1.998×10^{-8}	441 Ty
Iodine	357.6	3.03	357.6	22.33×10^{-6}	196.6	16.1 My
Lithium	2.57×10^{-5}	2.18×10^{-7}	1.57×10^{-4}	0	0	∞
Rubidium	524.5	4.44	735.08	26.47×10^{-9}	1.758×10^{-3}	48.1 Gy
Samarium (II)	1284	10.9	1894.60	65.21×10^{-3}	2017	90 y
Selenium	84.68	0.718	159.09	153.9×10^{-6}	66.32	377 ky
Silver	115.4	1.01	153.03	4.922×10^{-3}	30.38	249.8 d
Strontium	1135	9.78	2040.96	562.84	8.697×10^{7}	28.79
Tellurium (IV)	749.1	6.35	1572.27	0.3411	1.307×10^{4}	57.4 d
Tin	139.9	1.19	221.68	2.076×10^{-3}	213.9	230 ky
Yttrium	676.2	5.73	1486.14	0	0	2.671 d
Zinc	9.72×10^{-3}	8.24×10^{-5}	0.02	0	0	∞
Total	11810		17867	1351.5	15.51×10^{7}	
Gases	8558	Not in electrolyte				
Other FP	31812	Remain in anode or removed by third cathode				

After using the pyroelectric method developed at EBR-II to process one tonne of 5.218% burnup nuclear reactor fuel that had been stored for ten years, then drawing out trivalent lanthanides and drawing down actinides below 100 ppm [64], eutectic KCl-LiCl electrolyte would contain the amounts of fission products shown in Table 9.3, according to output from the ORIGEN-2 computer program [2]. This assumes that sodium-soluble fission products such as barium, caesium, iodine, rubidium, strontium, and tellurium have not diffused into bond sodium and then been removed by other means [52].

There are radioactive isotopes with varying half lives, and nonradioactive isotopes, for most of the elements shown in Table 9.3. Only the half life of the most radiotoxic isotope is shown.

Some of the steps of the following process might be useful on their own, or as precursors to other steps, such as proposed by Simonnet et al [51]. The overall objective of these steps is to produce high-level waste products that contain sufficiently small amounts of low-level waste that they do not increase the storage amount significantly, while producing low-level waste products that contain very little high-level waste. In detail:

Figure 9.8: Separating fission products



- Process small amounts continuously to maintain desired concentration as fuel is processed.
- Recover essentially all electrolyte in sufficient purity for re-use.
- Produce a harmless barium product with less than 100 ppm caesium, strontium or actinides.
- Produce a caesium product with only small amounts of electrolyte and other products.
- Produce an europium product with less than 100 ppm caesium, strontium or actinides.
- Produce a strontium product with only small amounts of other products.
- Produce a final form of the other fission products with less than 100 ppm caesium, strontium or actinides.
- Maximize storage density.
- Minimize consumed materials.
- No waste other than fission products.
- No hazardous or expensive materials.

The method shown in Figure 9.8 is described in succeeding paragraphs.

1. Dissolve contaminated electrolyte in water. Remove precipitates of AgCl, and precipitates of $Sn(OH)_n$ that result from hydrolysis of $SnCl_n$. Reduce water to saturate remaining solution.

2. To start the process, Add $(NH_4)_2CO_3$. After the process is running, add NH_3 from steps 3 and 8 and CO_2 from steps 3 and 4 to form $(NH_4)_2CO_3$. Metals other than those in group Ia form insoluble carbonates, but group Ia carbonates are all soluble, e.g. reactions such as,

   $$\begin{array}{ll} BaCl_2 + (NH_4)_2CO_3 \rightleftharpoons BaCO_3 \downarrow + 2\,NH_4Cl & [BaCO_3]/[BaCl_2] = 6.7 \times 10^{-5} \\ 2\,CsCl + (NH_4)_2CO_3 \rightleftharpoons Cs_2CO_3 + 2\,NH_4Cl & [Cs_2CO_3]/[CsCl] = 71.2 \end{array}$$

   remove essentially all group Ia salts. Small amounts of other fission product carbonates and chlorides in filtrate with group Ia salts are acceptable. The objective is to remove essentially all group Ia metals, not to obtain them in pure form.

3. Add HCl to filtrate from step 2 as necessary to convert any carbonates to chlorides. Save CO_2 for use in step 2. Evaporate water, then heat to decompose NH_4Cl to NH_3 and HCl (337.6°C). Save the NH_3 for use in step 2. Save HCl for use in this step and step 4. If NH_4I is decomposed to NH_3 and HI (404.7°C), and HI is used with HCl in step 4, iodine will appear in the final product in step 8. The residue consists almost entirely of group Ia chlorides, and their iodides, depending upon the extent to which iodine appears as NH_4I that is not decomposed.

4. Add HCl from steps 3 and 8 to carbonate residue from step 2. Save CO_2 for use in step 2. All carbonates are converted to soluble chlorides, except AgCl and $Sn(OH)_n$ if they are not removed in step 1. E.g.,

   $$BaCO_3 \downarrow + 2HCl \rightarrow BaCl_2 + \; CO_2 \uparrow + H_2O$$

5. Add sufficient NH_4NO_3 to solution from step 4 to cause most $Ba(NO_3)_2$ to precipitate. $Ba(NO_3)_2$ is slightly soluble (9.02 g/100 ml H_2O at 20°C). The next least soluble nitrate is $Sr(NO_3)_2$ (70.8 g/100 ml H_2O at 20°C). Reduce water and separate the $Ba(NO_3)_2$ precipitate. Wash to remove $SrCl_2$ and $Sr(NO_3)_2$, but not enough to dissolve significant amounts of $Ba(NO_3)_2$. The objective is to obtain most of the barium as $Ba(NO_3)_2$ with $[Sr(NO_3)_2]$ / $[Ba(NO_3)_2] < 10^{-4}$, not to obtain all barium.

6. Add water to dissolve the $Ba(NO_3)_2$ precipitate from step 5. Add $(NH_4)_2SO_4$. Separate the $BaSO_4$ precipitate for disposal. Use less than the stoichiometric amount of $(NH_4)_2SO_4$ so that all sulfate is removed as $BaSO_4$, and no strontium is removed as $SrSO_4$. Use the resulting NH_4NO_3 solution in step 5. If sulfate remains, step 5 will create $EuSO_4$ and $SrSO_4$ precipitates along with $Ba(NO_3)_2$. Recirculating small amounts of $Ba(NO_3)_2$ to step 5 is not harmful.

7. Add $(NH_4)_2SO_4$ to filtrate from step 5. Sulfates of barium, europium, and strontium are the least soluble. The next least soluble sulfates are $SmSO_4$ (2.7 g/100 ml at 20°C) and $In_2(SO_4)_3$ (53.92 g/100 ml). Do not precipitate excessive amounts of samarium (there is 13% more samarium than strontium, and 5.5 times more than europium). Small amounts of samarium are acceptable. The objective is to concentrate europium and strontium, and to leave very small amounts in solution, not to obtain them as pure compounds. Separate sulfate precipitates.

   $$\begin{array}{ll} BaCl_2 + (NH_4)_2SO_4 \rightleftharpoons BaSO_4 \downarrow + 2\,NH_4Cl & 0.285\,\mathrm{mg}/100\,\mathrm{ml}\,H_2O \\ EuCl_2 + (NH_4)_2SO_4 \rightleftharpoons EuSO_4 \downarrow + 2\,NH_4Cl & 0.180\,\mathrm{mg}/100\,\mathrm{ml}\,H_2O \\ SmCl_2 + (NH_4)_2SO_4 \rightleftharpoons SmSO_4 \downarrow + 2\,NH_4Cl & 2.7\,\mathrm{g}/100\,\mathrm{ml}\,H_2O\ \ [SmSO_4]/[SmCl_2] = 0.029 \\ SrCl_2 + (NH_4)_2SO_4 \rightleftharpoons SrSO_4 \downarrow + 2\,NH_4Cl & 13.2\,\mathrm{mg}/100\,\mathrm{ml}\,H_2O\ \ [SrSO_4]/[SrCl_2] = 2.5 \times 10^{-4} \end{array}$$

   It might be possible to remove europium, barium, strontium, and samarium sequentially, without using steps 5 and 6, by careful control of the rate of addition of $(NH_4)_2SO_4$. $EuSO_4$ and $SrSO_4$ can be converted to less soluble EuF_2 and SrF_2 using NH_4F, or to $Eu_3(PO_4)_2$ or $Sr_3(PO_4)_2$ using $(NH_4)_3PO_4$. Phosphates generally make good glass. Molten $EuCl_2$ and $SrCl_2$ are immiscible [44, p. 170]. Their sulfates can be converted to chlorides by way of carbonates, which might be justified if separating their chlorides is sufficiently less expensive than separating their sulfates.

8. Evaporate water from filtrate chlorides from step 7 and heat sufficiently to decompose NH_4Cl. Save NH_3 for use in step 2. Save HCl for use in step 4.

The only consumed input is $(NH_4)_2SO_4$, or NH_4F or $(NH_4)_3PO_4$ if sulfates are converted to less soluble fluorides or phosphates. There are no hazardous or expensive solvents.

Group Ia chlorides

Chlorides from step 3 are almost all in group Ia. Metals from other groups appear to the extent their carbonates are soluble.

All group Ia chlorides form binary eutectics at around 50 wt.% [44]. It is therefore not possible to perform complete separations using zone melt refining, layer freezing, or a clean cold surface. Williams et al [63] reported recovering 89% of electrolyte from a CsCl-LiCl-KCl mixture. Cho et al [18] reported recovering $>$ 90% of LiCl from a CsCl-SrCl-LiCl mixture..

Assuming optimistically that 97.5% of electrolyte is separated, in a mixture of 50 wt.% KCl-LiCl, 43.5 wt.% CsCl, and 6.5 wt.% RbCl, fission products constitute 40 wt.%. In pure CsCl, the density of fission-product caesium is 79.2 wt.%.

Borho et al proposed an alternative to vacuum distillation to separate eutectic mixtures [11]:

1. Coat a clean surface with pure crystals of the highest melting point component of the eutectic.
2. Flow or trickle molten eutectic over the surface, maintained at a temperature between the melting points of components to be separated.
3. When the surface is sufficiently laden with product, wash it to remove eutectic, but not sufficiently to remove the product.
4. Remove the product by melting or washing.

To separate an eutectic that has more than two components, either a series of devices can be used, or the same device can be used for successive separations by cleaning the surface between separations. If a surface is always used only to separate a single product, it is not necessary to clean it between successive uses.

The Borho et al process cannot be used on electrolyte without first doing steps 2 and 3 because the melting points of some chlorides are above the boiling points of others, e.g., $BaCl_2$ melts at 962°C, but $TeCl_4$ boils at 380°C, and some have nearly identical melting points, e.g., YCl_3 melts at 721°C and RbCl at 718°C.

Iodine should be recovered in step 3. Otherwise, it will appear with caesium and lithium chlorides in outputs from the Borho process. Seven surfaces instead of three would be necessary to separate it.

Melting points °C

KCl 779	RbCl 737	KI 681	CsCl 646	RbI 642	CsI 621	LiCl 614	LiI 469

Other chlorides

After actinides are drawn out of electrolyte using a third cathode process, about 100 ppm (0.01 wt.%) remain. Actinide carbonates are insoluble, so their chlorides will appear in the output from step 8. If electrolyte is cleansed when the load of fission products reaches 5 wt.%, actinide concentration is 0.2 wt.% after step 2. If samarium is removed as sulfate before step 8, the concentration of actinides among the final chlorides is about 1.1 wt.% (as chloride). These actinides should be separated, and returned to the electrorefiner to “fertilize” the next processing operation. The goal is not to recover them as useful fuel, but to allow to store the remainder as low-level waste. Storing all chlorides from step 8 with caesium as high-level waste would increase the weight by 170%. Storing all the chlorides resulting from step 3 together, instead of removing barium, europium, strontium, and maybe samarium, would increase the weight by 380% compared to storing caesium separately.

Even if an immiscible solvent process such is PUREX or TRUEX is necessary for the final actinide separation, the device would be very small because after step 8 only 3.3 kilograms of chlorides remain (assuming samarium is not removed), per tonne of 5.2%-burnup fuel processed.

Final waste form

Zeolite-A was initially used to cleanse electrolyte at Experimental Breeder Reactor II (EBR-II), and later combined with fission products separated from electrolyte by fractional crystallization. Ackerman and Johnson [7, p. 5] reported that zeolite includes “significant amounts of occluded and adhered electrolyte” but did not quantify “significant amounts.” They also remarked “it appears that Cs and I are also removed, although less strongly.” Contaminated zeolite is then mixed with glass frit and compression melted to make a final waste form consisting of glass and sodalite. The method proposed here would put less electrolyte into the final waste form, and less caesium and iodine back into the electrorefiner.

After processing one tonne of 5%-used spent fuel, caesium and strontium must be stored as high-level (154 MSv) high-heat long-duration (300 y) waste. Figure 9.9 shows that the very short-lived decay products ^{90}Y, of ^{90}Sr, and ^{137m}Ba, of ^{137}Cs, produce most of the heat after ten years (their heat production rates are almost identical). Europium is medium-level (624 kSv) medium-heat medium-duration (85 y) waste. The output from step 8 can be stored as low-level (83 kSv) low-heat (4.8 watts) waste, some of very long duration and therefore very low activity. After strontium is removed, ^{90}Y in the output from step 8 quickly decays to non-radioactive ^{90}Zr.

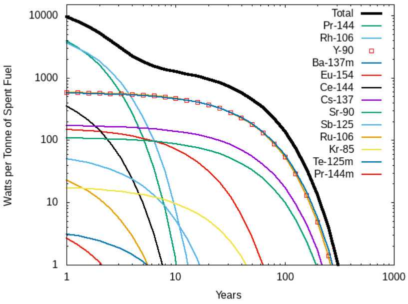


Figure 9.9: Fission products thermal power per tonne of 5%-used fuel

The final waste form produced at EBR-II contained 4 wt.% of fission products [6, p. 141]. Table 9.5 shows that storing europium and strontium as sulfates, fluorides, or phosphates increases storage density compared to storage in zeolite-A. Chlorides, including caesium, have been successfully stored in hastalloy containers at Hanford. Forsberg concluded that storing different categories of wastes separately, depending upon their heat production, reduces total storage cost to about 15% of the cost to store unprocessed spent fuel [25]. The decision whether to separate fission products depends upon whether the reduction in storage cost offsets the increase in processing cost.

Table 9.5: Fission product densities, wt.%

Element	Sulfate	Fluoride	Phosphate	Chloride
Caesium				79.2
Europium	61.3	80.0	70.6	
Strontium	47.7	69.6	55.8	

Processing rate

For burnup B, the mass of fission product metals that appear in electrolyte is $F = 11.81B/0.05218 = 226.33\,B$ kilograms per tonne of fuel.

The amount of contaminated electrolyte containing weight fraction R of fission-product metals (not chlorides) is $C = F(1 - R)/R$ kilograms per tonne of fuel.

Assuming that fissioning one tonne of heavy metal produces one tonne of fission products and one GWe-year of electricity, with power output P in gigawatts, the rate of fission product production is $D = 0.6197\,P$ kilograms per day. The amount of electrolyte that must be processed per day is $A = D\,(1 - R)/R$ kilograms per day.

A 300 MWe plant produces $D = 186$ grams per day of fission product metals that must be removed from electrolyte after the actinide and lanthanide drawdown steps.

Maintaining a weight fraction $R = 0.05$ of fission-product metals (not chlorides) in electrolyte requires processing $A = 3.532$ kilograms of contaminated electrolyte per day, and maintaining $R = 0.1$ requires processing $A = 1.673$ kilograms per day.

9.3.3 Alternative to solid metal fuel

In 10% burnup fuel irradiated at EBR-II, it was found that 70% of alkali metal fission products (caesium and strontium), and 20% of alkaline earth fission products (strontium and barium) had migrated from fuel into bond sodium [30, P. 98]. All of the metals listed in Table 9.3, except europium and samarium, are soluble in sodium, to varying degrees [24] [49]. One would expect them to migrate into sodium.

Diffusion into sodium is a process that necessarily takes place at the surface of the fuel, either at the original surface of a fuel slug, or at the surface of a pore or microcrack that has opened to the surface and into which sodium has intruded.

The relationship between volume and surface area can be increased by decreasing the size of an object. For example, the ratio of the surface of a sphere to its volume is $\frac{3}{r}$. If instead of solid fuel slugs, metallic fuel were to be fabricated as a fine powder and mixed with sodium, one would expect this fission-product migration process to increase.

An additional effect of particulate metal fuel mixed with sodium is an overall increase in thermal conductivity, because sodium has higher thermal conductivity than metallic fuel.

Motile fuel would reduce or eliminate fuel cladding mechanical interaction.

After the fuel is sufficiently used, sodium can be separated from fuel first by high-velocity argon, as used at EBR-II. Then fuel can be washed using additional clean sodium, to remove as much fission-product residue as possible and separated again, and finally cleansed of sodium using steam. Fission products that have diffused into sodium can be separated from sodium and from each other by distillation.

With more fission products removed by diffusion into sodium, the amount that must be removed by pyroelectric processing is reduced. The anode process in pyroelectric processing necessarily takes place at the surface of fuel. If the surface area per volume is increased by using small particles, the pyroelectric process can operate faster [52].

9.4 Nuclear power is too expensive (no it's not)

Nuclear power was on its way to becoming the least expensive way to make electricity. As we saw in Chapter 7, AEC Commissioner Lewis Strauss thought it might be "too cheap to meter," that is, it ought to be delivered at a flat rate, at least to homes, because he thought the cost to produce it would consist almost entirely of capital amortization and operations.

What happened?

On 26 September 1945, immediately after the bombings of Hiroshima and Nagasaki, Albert Einstein and Manhattan Project scientists formed a group called the *Atomic Scientists of Chicago*. On 10 December 1945, the first issue of the *Bulletin of the Atomic Scientists of Chicago* was published as an informal newsletter because physicist Hyman Goldsmith and the first editor, Eugene Rabinowitz, a professor of botany and biophysics at the University of Illinois, believed that Manhattan Project scientists, who were being dispersed, ought to continue to have a way to communicate with each other, and with the public. In June 1947 it published its first issue as a nontechnical academic journal under the name *Bulletin of the Atomic Scientists*. It is now published by Taylor & Francis. Although it began as a vehicle to oppose further use of nuclear weapons, it eventually became devoted to opposing nearly all things nuclear – except a few techniques of nuclear medicine, some of which, such as nuclear magnetic resonance imaging (now known as MRI), carefully omit the word "nuclear" from their names.

The Atomic Energy Commission (AEC) was created by the McMahon/Atomic Energy Act on 1 August 1946, to foster and control the peacetime development of atomic science and technology. AEC remained in control of weapons development as well. After President Dwight Eisenhower's *Atoms for Peace* speech before the United Nations General Assembly on 8 December 1953, AEC began promoting development of civilian nuclear applications, especially nuclear power.

Anti-war activists, many of whom were (and still are) influenced by foreign operators, began to conflate nuclear weapons with nuclear power, not only because they were ignorant, but because it assisted their agenda. They and others argued that there was an inherent conflict of interest caused by the AEC being chartered both to promote nuclear power and to regulate it.

At least in part because of the activities of anti-nuclear activists, the Energy Reorganization Act of 1974 created the Energy Research and Development Administration

(ERDA), which became the Department of Energy in 1977, and more importantly divided oversight of engineering, scientific, and technical matters relating to nuclear power between ERDA and the newly-created Nuclear Regulatory Commission, which began operation on 19 January 1975.

Placing energy research and weapons development in the Department of Energy, and nuclear power regulation in the now-independent Nuclear Regulatory Commission, on its face, looks like a good idea. The problem is that anti-nuclear activists, both those opposed to nuclear weapons and those opposed to nuclear power, were able to dictate the structure of the NRC, and too often insist that it be led, not by scientists and engineers, but by politicians and attorneys.

The AEC had built a competent staff of regulators, and the structure of that staff, and its legacy of competence remains in the NRC. The problem, as with the IPCC, is that the final products are dictated by politics, not engineering, science, or technology. The NRC has taken on duties both of creating safety standards, and of regulating all aspects of nuclear power development and operation. Putting oversight of development in NRC has largely hamstrung deployment of new engineering and scientific results developed by the Department of Energy.

The first nuclear power plant regulations published by the AEC were fifty pages. By the time of Eisenhower's speech, they had grown substantially, and incorporated a lot of red tape. When he asked AEC to streamline regulations, the Rockefeller foundation, and other fossil fuel interests, who were apparently afraid that nuclear power would compete with them, leapt into action and sponsored and promoted the linear no-threshold (LNT) model of the relationship between radiation exposure and the risk of cancer and heritable mutations (Section 9.1.1).

The Environmental Protection Agency (EPA) was founded on 2 December 1970. Its role in nuclear power generation is to set public health and environmental radiation protection standards. These standards are all based on the LNT model, and impose the *as low as reasonably achievable* (ALARA) standard. The LNT model and ALARA standard, and their related *precautionary principle* continue to inhibit deployment of nuclear power by artificially increasing both capital and operating expenses – as explicitly admitted by opponents. Not least because of EPA influence, the governing document for nuclear power plant operations, 10 CFR 1 part 50, is about 600 pages.

That NRC prepares and publishes safety standards, and also regulates them, remains a conflict of interest. The result has been to increase the cost of nuclear power plant construction and operation. Most other countries have separate agencies that develop safety standards, and regulate construction and operation of nuclear power plants. For example, in Japan the Nuclear and Industry Safety Administration develops safety standards, while the Nuclear Regulation Authority enforces adherence to standards of construction and operation.

Collecting both authorities in one agency has led to increased expenses.

After Mitsubishi Heavy Industries sold a defective replacement steam generator for one of the reactors in Southern California Edison Company's San Onofre Nuclear Generating Station, the Edison company was told that in order to replace it, they would need to complete a new license application. Between that requirement, and intense pressure from California Senator Barbara Boxer, they decided to close all reactors at the 2.3 GWe power plant.

While unit 4 of the Alvin W. Vogtle Electric Generating Plant, also known as Plant Vogtle, was being put into service, excessive vibration was found in a pipe. In an ordinary industrial operation of similar scale, that would have been corrected by a $30,000 pipe brace. At Vogtle, it resulted in a $3 million license revision.

The average coal-fired power plant has 50 employees. The average nuclear power plant has nearly 1,000, mostly preparing reports for NRC – which reports are almost certainly never read.

Even after a license has been approved, both by the NRC and local zoning authorities, construction can be stopped or delayed by litigation. Most of those suits have no merit, but many result in projects being abandoned. Delays resulting from those suits increase costs. Owners have obtained capital, and are making mortgage payments, but are receiving no income. The Shippingport reactor in New York was prevented from being put into operation after construction was completed. That it was not in operation played a big part in the 1977 blackout, and subsequent riots and looting.

Figure 9.10 shows overnight construction costs, in year 2010 $US/kWe, plotted in relation to cumulative global capacity, based upon construction start dates, of nuclear power reactors in seven countries. The regression lines show costs for building reactors in the United States before and after cumulative global capacity reached 32 GWe [33].

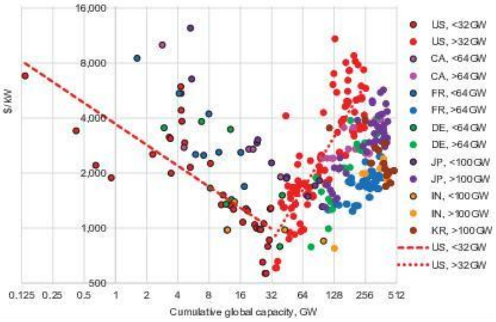


Figure 9.10: Overnight construction cost

Two Westinghouse AP1000 reactors, each with net capacity of 1,117 MWe, began construction at units 3 and 4 at Plant Vogtle on 12 March 2013 and 19 November 2013, respectively. Unit 3 entered service on 1 April 2023. Unit 4 completed hot functional testing on 1 May 2023. All inspections have been completed, and fuel has been delivered, as of 21 July 2023. It is expected to enter service in late 2023 or early 2024. Vogtle unit 3 is the first new reactor put into service in the United States in four decades.

There are now four Westinghouse AP1000 reactors in service in China. Sanmen-1 and Sanmen-2 reactors in Zhejiang province, each with capacity of 1,250 MWe, began construction on 19 April 2009 and 15 December 2009, respectively. Unit 1 entered service on 21 September 2018 and unit 2 entered service on 5 November 2018. Their combined cost was $US 7.3 billion, or about $2,920/kWe. Haiyang-1 and Haiyang-2 reactors in Shandong province, also each with capacity of 1,250 MWe, commenced construction in 2009 and entered service in 2018. Their combined cost was also near $7.3 billion. China expects construction times and costs to be reduced as they gain experience in building them. Six more reactors have been approved with a total cost of $17 billion, about $2,666/kWe, for Shandong, Jujian, and Liaoning. China accounts for 23 of 55 nuclear power reactors under construction worldwide during 2023 [38].

In December 2022, the price of electricity in Finland was €245.98 per MWh. When the 1,600 MWe reactor Olkiluoto 3 was put into service in April 2023, the price dropped to €60.55. At 1,600 MWe, Olkiluoto 3 is the largest reactor in Europe. It provides 15% of Finland's electric power. The three reactors at Olkiluoto combined provide about 30% of Finland's electric power [10]. The final cost for Olkiluoto 3 was $12 billion, about $7,500/kWe.

The two Vogtle units together cost $31 billion, or $13,876/kWe [8]. It's clear that government policy and activists' lawfare have at least as large an effect on construction cost as actual physical challenges.

Compared to what?

When anyone argues "it's too expensive," the necessary next question is "compared to what?"

Advocates for solar and wind claim that the generation cost is about 3.5¢/kWh. Then they stop speaking. The usual source for the assertion is Lazard's *Levelized Cost of Energy*. But Lazard's report explicitly admits "This analysis does not take into account potential social and environmental externalities or reliability-related considerations" [59, p. 16].

There is no system engineering. They never answer these questions:

- What is the cost of land, including the cost of other lost opportunities?
- What is the cost in lost reliability, and what would be the cost to provide the industry definition of "firm power" – 99.97% available? This question was addressed for the United States in Chapter 8: About ten times total 2018 USA GDP every year.
- What is the cost of transmission? This question was addressed in Chapter 4.
- What is the benefit of having a transmission infrastructure if there is no generation at either end of it, for example when the sun isn't shining and the wind isn't blowing, at either place?
- What is the cost of distribution if all energy consumers are converted to electricity?

They never admit these observations:

- Diablo Canyon nuclear generating station near San Luis Obispo, California produces electricity for 5¢/kWh.
- Palo Verde nuclear generating station near Phoenix, Arizona – which is cooled entirely by waste water – produces electricity for 4.3¢/kWh.
- Washington Nuclear Generating Station near Richland, Washington produces electricity for 3¢/kWh.
- Fully amortized nuclear power stations – mostly in the upper midwest and northeast United States – produce electricity for 2¢/kWh – 1.5¢/kWh for operations and 0.5¢/kWh for fuel. Most of the twelve reactors shut down in the United States in the last two decades are these reactors.

The arguments for renewable energy sources are based upon false generalizations in time and space. It doesn't much matter for a solar pool heater that clouds appear or sunset happens, but reliable electricity is important to a dialysis treatment center. Solar power works well for afternoon air conditioning in Dubai, but isn't much use for heating during a Michigan winter.

If solar and wind can generate electricity for 3.5¢/kWh in California, where 38% of electric energy is produced by renewable sources, why is the "tier one" rate 15¢/kWh, the "tier two" rate 26¢/kWh, and the "tier three" rate 74¢/kWh?

Activists began insisting that all electricity had to be produced by renewable sources, and that eventually all energy had to be consumed as electricity. They demanded and got subsidies for solar and wind generators. In 1983, the wind "industry" insisted that only seven years of subsidies were necessary to get things "off the ground." Since then, subsidies have been renewed thirteen times, without a lapse of even a millisecond. Refer again to Table 7.5.

9.5 Nuclear power leads inevitably to nuclear weapons (it doesn't)

The argument that nuclear power, and especially spent fuel processing, leads inevitably to nuclear weapons proliferation is the largest and stinkiest of all the stinking red herrings promoted about nuclear power.

No one has ever deployed operational nuclear weapons made from plutonium that was extracted from spent commercial nuclear power reactor fuel, because every other way to make them is easier and less expensive.

The primary reason is that the isotope mixture of plutonium is not suitable for weapons – but in the right kind of a reactor it is entirely suitable as fuel.

Yes, plutonium for weapons is produced in nuclear reactors. But they are very different from commercial nuclear power reactors, and are operated very differently. One significant difference is much shorter fuel residence time.

"Weapons grade" plutonium contains 94% plutonium-239 and less than 6% plutonium-240. "Reactor grade" plutonium contains 65% plutonium-239. The United States conducted one test in the 1960's using reactor grade plutonium. The result of that test was not disclosed. There were two British trials in the 1950's. In 1994, at a London conference concerning plutonium disposition, a former director of the U. K. Atomic Weapons Research Establishment flatly stated "we tried reactor grade plutonium a couple of times. We never will again."[n] Every nation that has successfully developed and deployed plutonium weapons used plutonium in which the concentration of plutonium-239 was at least 93%, which suggests there is probably a very good reason for doing so.

Chapter 12 of **Plentiful Energy** [53] has an extensive discussion of the question. Important considerations include the heat, neutrons, and gamma rays emitted by different grades of plutonium. Too much heat might distort fine tolerances and cause the weapon to fail to work. Too much neutron production might cause predetonation – not exactly what you want in your aircraft carrier or weapons bunker. Too much gamma emission requires remote fabrication, separated from workers by several feet of concrete and lead-impregnated glass. Weapons made from weapons-grade plutonium can be fabricated in glove boxes.

Table 9.6: Important Weapons Usability Characteristics

	Weapons-Grade Pu	Reactor-Grade Pu	IFR Actinide Product
Production	Low burnup PUREX	High burnup PUREX	Fast reactor Electrorefining
Composition	Pure Pu 94% Pu-239	Pure Pu 65% Pu-fissile	Pu + MA† + U 50% Pu-fissile
Thermal Power watts/kg	2–3	5–10	80-100
Spontaneous neutrons n/s/g	60	200	300,000
Gamma radiation r/hr at 1/2 m	0.2	0.2	200

† MA means "mixed actinides" – see Appendix B.

Table 9.6, a reproduction of Table 12-1 from [53], shows the differences for these grades and sources of plutonium. An important aspect of the pyroelectric reprocessing method developed by Argonne National Laboratory is that, unlike the PUREX process,

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[n] Charles Till, one of the authors of [53], was present and witnessed the remark.

it never produces chemically or isotopically pure plutonium, so additional processing would be necessary. A Lawrence Livermore National Laboratory study concluded that spent IFR fuel cannot be used to make a nuclear weapon without significant further processing [28]. That processing would include separating plutonium from uranium and higher actinides such as neptunium, americium, and curium, and plutonium isotope separation. Plutonium isotope separation is more difficult and more expensive than uranium isotope separation.

The possibility to "proliferate" nuclear weapons using plutonium from spent fuel depends upon getting the plutonium from the reactor or fuel processing plant to the would-be weaponeer. It is very unlikely that an OECD country would permit export to any country other than another OECD country, and even that export might be difficult. In order to circumvent export restrictions, one would need to steal spent fuel, or the mixture of uranium, plutonium, and mixed actinides produced by a pyroelectric processor. As can be seen in Table 9.6, a person attempting to do so would likely not survive long enough to get to the gate of the facility, and the theft would be immediately detected by simple, inexpensive, sensitive, and reliable instruments before the material could even be taken outside the building. The only realistic opportunity would be to steal the mixture of uranium, plutonium, and actinides, as packaged for shipment to another reactor for fuel fabrication. If ready-to-use fuel, that is, containing only 5% fissionables, is fabricated at the reprocessing plant, the thief and would-be weaponeer would be faced with the same problem of reprocessing as for spent fuel.

9.6 There isn't enough uranium (yes there is)

Fissioning one tonne (actually about 989 kilograms) of heavy metal in a contemporary reactor produces one GWe-year of electricity.

The United States has 86,000 tonnes of spent nuclear fuel [58]. Most of that fuel is 5% used, so the United States has about 81,700 tonnes of heavy metal amongst spent fuel. Estimates of depleted uranium vary from 700,000 to 900,000 tonnes.

The ash produced by a coal-fired power plant contains 16.3 times more energy than was released by burning it, in the form of 4.7 tonnes of uranium and 11.6 tonnes of thorium per GWe-year, or about 0.036% of a coal-fired power plant's waste [27]. About 74% of coal consumption in the United States is for electricity production. Since 1850, the United States has consumed about 1,500 quadrillion BTU (quads) from coal [3]. One tonne of coal contains about 24 million BTU's of energy, so the United States has consumed about 62.5 billion tonnes of coal. Burning one tonne of coal produces about 0.89 MWh of electricity in modern power plants, so producing one GWe-yr requires burning about 9.8 million tonnes of coal. Burning 62.5 billion tonnes of coal in modern power plants would have produced more than 6,000 GWe-years of electricity. A lower bound on the amount of uranium and thorium in the heaps of eternally toxic coal ash in the United States is therefore about 100,000 tonnes.

Using 800,000 tonnes of heavy metal as a conservative approximation to the amount of uranium in spent fuel and depleted uranium above ground in the United States, plus 100,000 tonnes from coal ash, and activists' claims that an all-electric American energy economy would have an average appetite for 1,700 GWe shows that the United States has enough heavy metal, above ground, mined, milled, and refined, to power an all-electric all-nuclear American energy economy using the right kind of nuclear power plant, in particular the Integral Fast Reactor, or IFR, for about 530 years, without mining, milling, refining, enriching, or importing one new gram of uranium.

Other nations have stocks of spent nuclear fuel, and piles of coal ash.

The Nuclear Energy Agency of the Organisation for Economic Co-operation and Development estimates that total uranium resources that can be recovered from land-based sources at $US 260/kg of uranium metal is 7.918 million tonnes. Seawater contains about one million times more uranium than can be recovered from land-based sources, but the concentration is very low, about 0.003 ppm. Uranium can be extracted from seawater using the *amidoxime process* at an estimated cost of $US 300/kg of uranium [5].

Contemporary reactors extract about 0.6% of the energy immanent in mined uranium before the fuel is removed because it is considered to be "spent." An IFR-type reactor can extract more than 99% of the energy. Activists estimate that an all-electric world economy would have an appetite of about 19 TWe. Using only known land-based uranium reserves, and the 900,000 tonnes of above-ground uranium in the United States, a total of about 8.8 million tonnes, the world economy could be powered by IFR-type nuclear reactors for more than 460 years.

At a market price of $260/kg for uranium metal, the contribution of the cost of raw uranium, as it comes out of the ground, to the cost of electricity produced by contemporary nuclear reactors, is $260,000 per tonne / 8,765,810,000 kWh per GWe-yr ≈ 0.003¢/kWh. Using 0.6% of the energy increases the cost to about 0.5¢/kWh. If it were used 165 times more efficiently, as in IFR-type reactors, the end-user price of electricity would be unchanged. This would make it economical to extract uranium from lower-concentration ores, or from seawater. There is four times more thorium than uranium. Like uranium-238, thorium is not fuel, but it can be converted to fuel in the right kind of reactor. Combine these amounts and the only possible conclusion is that heavy-metal fission is an inexhaustible energy source.

9.7 What ought to be built?

The Westinghouse AP1000 reactor type is one of the most popular types being built now. It is a Gen III+ reactor with many passive safety features incorporated. An important part of the passive safety system is a large tank of water built above the reactor, containing sufficient water to cool the core's decay heat after fission is shut down for 72 hours without electric power, before the tank would need to be refilled. The system uses multiple explosively-operated and DC-operated valves, which must operate within the first 30 minutes. This is designed to happen even if the reactor operators take no action [57]. The electrical system required for initiating the passive systems doesn't rely on external or diesel power and the valves don't rely on hydraulic or compressed air systems [35][50].

Four of the AP1000 type are in service in China at Senmen in Zhejiang province and Haiyang in Shandong province. One is in service and another has completed hot testing at the Vogtle Plant in Georgia. China added modifications and owns patents relating to a revised design, called CAP1000, with a net capacity of 1,250 MWe instead of Westinghouse's original 1,117 MWe. China has developed plans for larger units, based on CAP1000, called CAP1400 and CAP1700. The pressure vessel has been completed for a CAP1400 at Shidao Bay, also in Shandong province, equipment is being built, and construction is underway. In February 2019, the Shanghai Nuclear Engineering Research & Design Institute announced that it had begun the conceptual design process for the CAP1700.

These large units are preferred in many locations because the capital cost per megawatt of capacity is less than for smaller reactors. But they are too large for some locations, so smaller reactors are also of interest.

Several companies, including NuScale and Rolls-Royce, are offering *small modular reactors* in the 50 MWe range. It is proposed that one or a few would be installed at a location, and if demand increases more units could be added. The attraction of small modular reactors is that they can largely be constructed in factories or shipyards, rather than on site, thereby reducing capital cost.

The Westinghouse AP1000 type, similar types from other companies, and the small modular reactors from NuScale and Rolls-Royce, are all pressurized water reactors that use oxide fuel.

The GE Hitachi Nuclear Energy consortium has designed a spectrum of reactors based upon the EBR-II design, offering them initially in 150 MWe, 300 MWe, and 360 MWe sizes. These reactors are called PRISM, for *Power Reactor Innovative Small Modular*.[o] A detailed description of a 311 MWe unit has been published by Triplett at al [54]. A preapplication safety review concluded that "On the basis of the review performed, the staff, with the ACRS [Advisory Committee on Reactor Safeguards] in agreement, concludes that no obvious impediments to licensing the PRISM design have been identified" [56]. The only reason that one has not been licensed is that, so far, none have been ordered.

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[o] I prefer *Power Reactor Inherently Safe Modular*, but the GE Chief Engineer told me they're unlikely to change the designation.

As was the case for EBR-II, a PRISM reactor would operate at atmospheric pressure and would not need an expensive high-pressure vessel. It would therefore be significantly smaller than a pressurized light-water reactor of similar capacity: The vessel for the 311 MWe design described by Triplett et al [54] would be 30 feet (9 meters) in diameter and 60 feet (18 meters) high.[p] Being smaller, it would be economical to emplace it below grade. These two factors combine to require 80% less reactor-grade concrete per MWe.

Terrapower and Natrium and GE Hitachi Nuclear Energy have proposed a system consisting of a 345 MWe PRISM reactor integrated with molten-salt thermal storage to replace a coal-fired power plant in Kemmerer, Wyoming in 2030. The molten-salt thermal storage can change output very rapidly, to cope with varying output from renewable sources and varying demand, and will be able to increase plant output to 500 MWe for up to five hours. It will not need a fast-acting OCGT for "topping." The entire site will occupy 44 acres (18 ha), with the nuclear island occupying 16 acres (6.5 ha). Although PRISM is based upon EBR-II, the Natrium proposal is not an Integral Fast Reactor – it does not include a fuel cycle facility; it's planned to be a once-through system. Once-through systems will remain the rule until the Nuclear Waste Act of 1982 is revised to return the funds to power plant builders to include spent fuel processing.

Taken together, the different aspects of nuclear power conspire to recommend the Integral Fast Reactor, pioneered by EBR-II and its fuel cycle facility, writ large, probably in the form of Natrium systems or systems similar to them. Dr. Chang said it best in his acceptance speech on the occasion of receiving the the Lawrence Award[q] in 1993:

> *When you do not have natural resources, then the recycling of nuclear fuel becomes a security issue. When you are faced with the high cost of reprocessing, the IFR pyroprocessing becomes your dream solution. When you are criticized from all directions about plutonium recycling, then the IFR's inherently proliferation-resistant fuel cycle, which never separates out plutonium, becomes your dream solution. When you are faced with the hundreds of thousands of years of containment requirement for the waste, then the IFR's ability to recycle the long-lived actinides and burn them in the reactor becomes your solution. When you are faced with public concern for safety, then the IFR's demon-*

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[p] Private communication from Eric Loewen 12 August 2023.

[q] Ernest Orlando Lawrence invented the cyclotron. He was instrumental in elevating American physics to world leadership. The Lawrence Award honors U.S. scientists and engineers, at mid-career, for exceptional contributions in research and development supporting the Department of Energy and its mission to advance the national, economic and energy security of the United States. Dr. Chang's citation read "Nuclear Technology: For technical analyses, decisions, and leadership of all aspects of the Integral Fast Reactor Program, an advanced nuclear energy concept with improved safety, more efficient use of fuel, and less radioactive waste." The Clinton administration terminated the IFR research program on 30 September 1994, destroyed the EBR-II reactor, and filled the reactor cavity with concrete.

> *strated walk-away safety becomes your solution. The technology ought to speak for itself* [53, p. 75].

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Chapter 10

The entire energy economy

No one has secret blueprints in his back pocket for realistic and usable electric airplanes and ocean-going cargo ships. Yes, there are toys, but none carry 800 passengers from Los Angeles to London in eight hours, or 400,000 tonnes of cargo from Korea to Brazil at 25 miles per hour.

The *Wind, Water, Sunlight* system proposed by Jacobson et al and described in Section 4.2 envisioned powering ships and airplanes with cryogenic hydrogen, and heavy land transport using compressed hydrogen [3]. This is almost certainly neither physically feasible nor economically viable. The public might not accept aircraft powered by hydrogen (see Figure 10.1).

We will need liquid hydrocarbons indefinitely. As fossil fuels, they will eventually be depleted. Fortunately, we know how to make hydrocarbons from CO_2 and hydrogen by using the *Fischer-Tropsch* process. The process was first developed by Franz Fischer and Hans Tropsch at the Kaiser Wilhelm Institute for Coal Research in Mülheim an der Ruhr, Germany, in 1925 [1].

The Fischer-Tropsch process was originally developed in 1925 to synthesize liquid hydrocarbons from carbon monoxide and hydrogen by passing the gases over a catalyst at high pressure. It can also convert CO_2 and hydrogen to liquid hydrocarbons. The U. S. Navy is studying the process to determine the feasibility to use it to produce jet fuel at sea. Their estimated price, using electricity generated at sea by ocean thermal electric generators at 7¢/kWh was $5.78 per gallon of jet fuel [4]. They didn't provide an estimate for other fuels' prices.

CO_2 can be extracted from the atmosphere, but its concentration in seawater is 140 times larger. Eisaman et al developed an energy efficient process at PARC that uses bipolar membrane electrodialysis (BPMED) to extract 59% of the total dissolved inorganic carbon from seawater with an electrochemical energy consumption of 242 kJ (67 watt hours, not kWh) per mol of CO_2. They wrote that "cost estimates suggest that

Figure 10.1: When the Hindenburg Exploded, May 6, 1937

fuel produced in this way could be cost-competitive in the commercial market in the near future" [2].

Beyond using CO_2 extracted from seawater by the BPMED process to synthesize liquid hydrocarbon fuels, it could be used either to enhance food production, or to enhance production of fuels derived from algae.

There are many methods to extract hydrogen from water. *Green hydrogen* proposals usually advocate to use electrolysis, with electricity provided by solar panels and wind turbines. The most energy-efficient way to extract it from water is the copper-chlorine process, in which one step requires heat at almost exactly the core coolant temperature of a nuclear power reactor. No step in the copper-chlorine process uses electricity.

Extracting CO_2 and hydrogen from seawater would be reasonable applications of electricity provided by solar panels and wind turbines because the product is itself a storage medium. The processes and devices to produce and store the product would not be degraded by the unpredictably erratic nature of electricity produced by those sources. A strike against that system is that both solar panels and wind turbines required excessive amounts of materials and land, and are eventually both intractable waste (see Chapter 6). Far less land and materials would be required for a combined energy center such as shown in Figure 10.2.

Burning hydrocarbon fuels made from seawater would be a net negative CO_2 transfer to the atmosphere and oceans. CO_2 that results from burning the fuels would go into

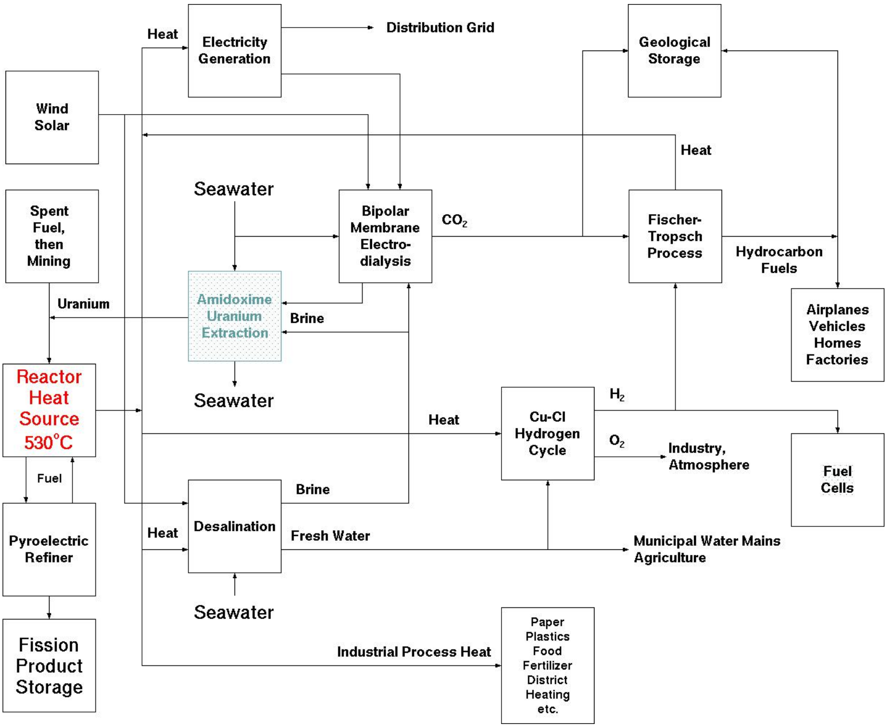

Figure 10.2: Combined energy center

the atmosphere, and eventually back into the oceans, but surely some would be trapped in plants and soils. CO_2 extracted from seawater could also be sequestered in geologic storage.

Taken altogether, using nuclear power instead of unreliable intermittent sources that require enormous amounts of land and materials, might result in what Gottfried Wilhelm Leibniz wrote in 1709 in his *Essais de Théodicée sur la bonté de Dieu, la liberté de l'homme et l'origine du mal* (Essays of Theodicy on the Goodness of God, the Freedom of Man and the Origin of Evil):

> *The best of all possible worlds.*

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Index

Appendix A

Atmospheric radiative transfer

The calculation to produce Figure 3.17 requires to solve the radiative transfer equation. In a clear atmosphere, at each frequency ν (or wavelength λ)[a] of radiation, it's a simple equation, known as the Schwarzschild equation [7]:

$$\frac{\mathrm{d}I}{\mathrm{d}s} = \alpha(B_\nu - I)\,, \tag{A.1}$$

wherein I is irradiance in watts or degrees Kelvin, B_ν is the Planck radiation function – how much irradiance is generated simply because the atmosphere is not at absolute zero temperature – see Equation 3.1 – and α is absorption. All quantities depend upon frequency ν, the position s along the line of transfer, and temperature $T(s)$ at each point.[b] The Planck radiation function is

$$B_\nu(s) = \frac{2h\nu^3}{c^2k}\,\frac{1}{\exp\left(\frac{h\nu}{kT(s)}\right) - 1}\,, \tag{A.2}$$

wherein h is Planck's constant, c is the speed of light, and k is Boltzmann's constant. Equation (A.2) clearly depends only upon temperature and frequency.

The left-hand side of Equation (A.1), $\frac{\mathrm{d}I}{\mathrm{d}s}$, is "how much does irradiance change at each point along the path of radiative transfer?" The right hand side says "irradiance that is produced at s, and irradiance that arrives at s, are both absorbed in the proportion α" (the units of α are "per kilometer").

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[a] Frequency ν and wavelength λ are related by $c = \nu\lambda$, where c is the speed of light.

[b] Several quantities also depend upon pressure, but if hydrostatic equilibrium is assumed, pressure can be calculated from altitude and the temperature profile.

The absorption α is a bit more complicated than in Equation A.1:

$$\alpha = \sum_{i=1}^{n} f_i \beta_i \,, \tag{A.3}$$

wherein n is the number of different gases at point s, f_i is the volume mixing ratio of the i^{th} gas, and β_i is the *absorption cross section* of the i^{th} gas. β_i depends upon temperature and pressure at s, wavelength or frequency, and the absorption spectrum of the i^{th} gas. It is sufficiently accurately modeled by the Faddeeva function, which is itself expensive to calculate. We needn't go into those weeds here [8].

The solution of Equation (A.1) for each frequency can be looked up in any second-year calculus textbook:

$$I(s) = I(s_0)\,\mathcal{T}(s) + \int_{s_0}^{s} B_\nu(\sigma)\,\alpha(\sigma)\,\mathcal{T}(\sigma)\,\mathrm{d}\sigma \,, \tag{A.4}$$

where $\mathcal{T}(\sigma)$ is *transmittance*:

$$\mathcal{T}(\sigma) = \exp\left(-\int_{s_0}^{\sigma} \alpha(\sigma')\,\mathrm{d}\sigma'\right) \,. \tag{A.5}$$

With good measurements of the average volume mixing ratios f_i of atmospheric gases as a function of altitude, which we have from decades of satellite and balloon observations, and temperature profiles, which we have from more than a century of observations, and spectroscopy catalogues for the relevant chemical species, which we have from decades of laboratory studies, evaluating Equation (A.4) on paths from outer space to the surface and back to outer space at many different latitudes and incidence angles is tedious but not terribly difficult. That's what was done to produce Figure 3.17.

Relationship to Stefan-Boltzmann law

Integrate the Planck radiation function in Equation (A.2) over a hemisphere, and all frequencies, *viz.*

$$\int_0^\infty \mathrm{d}\nu \int_h \mathrm{d}\Omega B_\nu \cos(\theta) \,, \tag{A.6}$$

where $\mathrm{d}\Omega = \sin(\theta)\,\mathrm{d}\theta\,\mathrm{d}\phi$, θ is colatitude taken over a hemisphere, and ϕ is longitude taken over the entire equator.

After integrating over the hemisphere and substituting Equation (A.2), Equation (A.6) becomes

$$\frac{2\pi h}{c^2}\int_0^\infty \mathrm{d}\nu \frac{\nu^3}{\exp(\frac{h\nu}{kT})-1}\,. \tag{A.7}$$

By substituting $x = \frac{h\nu}{kT}$, Equation (A.7) becomes

$$\frac{2\pi k^4 T^4}{c^2 h^3}\int_0^\infty \mathrm{d}x \frac{x^3}{e^x-1}\,. \tag{A.8}$$

Multiply the numerator and denominator in Equation (A.8) by e^{-x}, giving

$$\frac{2\pi k^4 T^4}{c^2 h^3}\int_0^\infty \mathrm{d}x \frac{x^3\,e^{-x}}{1-e^{-x}}\,, \tag{A.9}$$

which allows to use the identity

$$\frac{1}{1-a} = \sum_{n=0}^{\infty} a^n \;\; (a<1)\,. \tag{A.10}$$

Thereby, Equation (A.9) becomes

$$\frac{2\pi k^4 T^4}{c^2 h^3}\sum_{n=0}^{\infty}\int_0^\infty \mathrm{d}x\,x^3\,e^{-(n+1)x}\,. \tag{A.11}$$

With the change of variable $y = (n+1)x$, Equation (A.11) becomes

$$\frac{2\pi k^4 T^4}{c^2 h^3}\sum_{n=0}^{\infty}\frac{1}{(n+1)^4}\int_0^\infty \mathrm{d}y\,y^3\,e^{-y}\,, \tag{A.12}$$

wherein the integral can be recognized as $\Gamma(4) = 3! = 6$ [1, Eq. 6.1.1], and Equation A.12 becomes

$$\frac{12\,\pi k^4 T^4}{c^2 h^3}\sum_{n=0}^{\infty}\frac{1}{(n+1)^4}\,. \tag{A.13}$$

Riemann's ζ function, the infinite sum of the inverses of the integers, raised to the power s, is defined in [6] (reprinted and translated in [2]) as

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}\,, \text{ or in this case, } \zeta(4) = \sum_{n=1}^{\infty} \frac{1}{n^4} = \sum_{n=0}^{\infty} \frac{1}{(n+1)^4}\,. \tag{A.14}$$

The integral in Equation (A.8) is also shown in tables of integrals, e.g., [3, Eq. 3.411.1] as $3!\,\zeta(4)$.

Using Equations (A.13) and (A.14), Equation A.8 becomes

$$\frac{12\,\pi k^4 T^4}{c^2 h^3}\zeta(4)\,. \tag{A.15}$$

Riemann's $\zeta(s)$ function is listed for several even integer values of s in several places, but Kevin Krisciunas[c] gives an interesting (and clear) derivation of the result:

$$\zeta(4) = \frac{\pi^4}{90}\,. \tag{A.16}$$

Substituting Equation (A.16) into Equation (A.15) gives the Stefan-Boltzmann constant:

$$\sigma = \frac{2\,\pi^5 k^4 T^4}{15\,c^2 h^3}\,. \tag{A.17}$$

Adding clouds

> *Clouds are the Earth's sunshade, and if cloud cover changes for any reason, you have global warming – or global cooling.*
> – Roy Spencer, PhD.

When clouds or aerosols are added, Equation (A.1) becomes a true monster:

$$\frac{\mathrm{d}I}{\mathrm{d}s} + (1-\omega_0)\alpha I + \omega_0\,\alpha \oiint P(\theta,\phi)\,I(\theta,\phi)\,\mathrm{d}\theta\,\mathrm{d}\phi = \alpha\,B_\nu\,, \tag{A.18}$$

---

[c] *How to Integrate Planck's Function* https://people.tamu.edu/~kevinkrisciunas/planck.pdf

wherein ω_0 is the *single-scattering albedo* at point s due to the presence of aerosol or a particle of ice, and $P(\theta, \phi)$ is the *scattering phase function*, the probability that a photon arriving at s from direction (θ, ϕ) will be scattered onto the path being analyzed. Both ω_0 and $P(\theta, \phi)$ depend upon frequency and temperature. ω_0 depends upon the structure of the scattering particle. A theory of scattering from spheres, based upon first principles and derived from Maxwell's equations, was developed by Gustav Mie in 1908 [4] [5]. For ice, a sphere or collection of spheres is usually used because the infinite variety of snowflakes and ice particle shapes is impossible to incorporate into any model. $P(\theta, \phi)$ is itself a monster, defined by an infinite series of Hankel functions of the second kind, but it is a slowly-varying function that can be calculated in advance for many angles and temperatures. A value interpolated from that tabulation would usually be sufficiently accurate for use in Equation (A.18).

When there is no aerosol or ice, $\omega_0 = 0$ and Equation (A.18) reduces to Equation (A.1).

Notice that the radiative intensity inside the integrals in Equation (A.18) is arriving from all directions, at every point s on the path of the radiative transfer being analyzed. On all of the infinite number of paths arriving at every point s on the path, *the same equation applies*. Equation (A.18) is infinitely more difficult than Equation (A.1). The best that can be done to analyze the effect of aerosols and clouds on radiative transfer, and therefore on the Earth's radiation budget, and therefore on climate, is crude approximations such as single scattering or Monte Carlo methods, and vague handwaving. For example, we know that clouds make days cooler and nights warmer. The totality of the effects of aerosols and clouds on climate is impossible to quantify with any meaningful degree of accuracy. That's why Figure 3.16 shows that most climate models utterly fail.

Any one who claims to understand radiative transfer in detail, and to be able to make accurate computations, when aerosols or clouds are present, is either ignorant, exaggerating, or lying.

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Appendix B

Spent nuclear fuel composition

The following tables show fission products, activation products, and actinides per 1000 kg of fuel from a light-water reactor used for 50.68 GWth-day at power of 36.54 MWth and $3.14 \times 10^{14} N/\mathrm{cm}^2/s$ neutron flux, after ten years' storage, as calculated by ORIGEN-2 version 2.1 on 9 October 2013. Data are sorted into decreasing order according to total radiotoxicity per element.

ORIGEN-2 is a well-validated simulation of nuclear reactors [1]. Decay chain charts are also shown.

Each table shows

- The amount of each isotope and element, both by weight and moles,
- The parent isotope if the isotope is a decay product,
- Radiotoxicity in Sieverts, calculated from radioactivity in Becquerels using dose factors for ingestion from ICRP Publication 119 [2],
- Radioactivity in Becquerels (decays per second) for the stated amount, and per gram,
- The daughter product if the isotope is radioactive,
- The half life if the isotope is radioactive,
- The energy per Becquerel-second if the isotope is radioactive,
- The thermal power for the stated amount, and per gram, and
- The radiotoxicity for the stated amount, and per gram.

Fission Products Per Tonne of Fuel

used for 50.68 GWth-day LWR burnup at power of 36.54 MWth and $3.14 \times 10^{14} N/\text{cm}^2/s$ neutron flux,
after ten years' storage, as calculated by ORIGEN2 version 2.1 on 9 October 2013.
Radiotoxicity in Sieverts computed for adult ingestion using dose factors from ICRP publication 119

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
^{86}Sr		923.6 mg	10.75 mM									
^{87}Sr	$^{87}_{37}$Rb	7.616 mg	87.63 μM									
^{88}Sr		519.2 gm	5.906 M									
^{89}Sr		$\leq$ 1 pg	$\leq$ 1 pM	4.804 μBq	1.076 PBq	β $^{89}_{39}$Y	50.57 d	582.9 keV	$\leq$ 1 pW	100.5 W	$\leq$ 1 pSv	2.798 MSv
^{90}Sr		615.2 gm	6.843 M	3.107 PBq	5.050 TBq	β $^{90}_{39}$Y	28.79 y	195.8 keV	97.44 W	158.4 mW	87.00 MSv	141.4 kSv
E $_{38}$Sr		1.135 kg	12.76 M	3.107 PBq	2.737 TBq				97.44 W	85.83 mW	87.00 MSv	76.63 kSv
^{133}Cs		1.616 kg	12.16 M									
^{134}Cs		8.139 gm	60.78 mM	390.1 TBq	47.93 TBq	β $^{134}_{56}$Ba	2.065 y	1.715 MeV	107.2 W	13.17 W	7.412 MSv	910.7 kSv
					0.0003% →	ϵ $^{134}_{54}$Xe						
^{135}Cs		619.6 gm	4.593 M	26.41 GBq	42.62 MBq	β $^{135}_{56}$Ba	2.300 My	56.30 keV	238.2 μW	384.4 nW	52.82 Sv	85.25 mSv
^{137}Cs		1.436 kg	10.49 M	4.626 PBq	3.221 TBq	β $^{137m}_{56}$Ba	30.04 y	186.6 keV	138.3 W	96.31 mW	60.14 MSv	41.88 kSv
					5.601% →	β $^{137}_{56}$Ba						
E $_{55}$Cs		3.680 kg	27.30 M	5.016 PBq	1.363 TBq				245.5 W	66.72 mW	67.55 MSv	18.36 kSv
^{89}Y	$^{89}_{38}$Sr	676.0 gm	7.604 M									
^{90}Y	$^{90}_{38}$Sr	154.3 mg	1.716 mM	3.108 PBq	20.14 PBq	β $^{90}_{40}$Zr	2.671 d	934.7 keV	465.4 W	3.016 kW	8.392 MSv	54.38 MSv
^{91}Y		$\leq$ 1 pg	$\leq$ 1 pM	6.162 mBq	907.8 TBq	β $^{91}_{40}$Zr	58.51 d	606.0 keV	$\leq$ 1 pW	88.13 W	14.79 pSv	2.179 MSv
E $_{39}$Y		676.2 gm	7.605 M	3.108 PBq	4.597 TBq				465.4 W	688.3 mW	8.392 MSv	12.41 kSv
^{150}Eu		375.0 ng	2.501 nM	919.3 kBq	2.451 TBq	ϵ $^{150}_{62}$Sm	36.36 y	1.539 MeV	226.7 nW	604.5 mW	1.195 mSv	3.187 kSv
^{151}Eu	$^{151}_{62}$Sm	1.710 gm	11.43 mM	88.93 μBq	52.00 μBq	α $^{147}_{61}$Pm	1.700 Ey	1.905 MeV	$\leq$ 1 pW	$\leq$ 1 pW		
^{152}Eu		37.85 mg	249.1 μM	242.3 GBq	6.402 TBq	ϵ $^{152}_{62}$Sm	13.52 y	1.276 MeV	49.53 mW	1.309 W	339.2 Sv	8.962 kSv
					27.9% →	β $^{152}_{64}$Gd						
^{153}Eu	$^{153}_{64}$Gd	195.8 gm	1.280 M									
^{154}Eu		29.45 gm	191.3 mM	294.3 TBq	9.993 TBq	β $^{154}_{64}$Gd	8.593 y	1.509 MeV	71.14 W	2.416 W	588.6 kSv	19.99 kSv
					0.02% →	ϵ $^{154}_{62}$Sm						
^{155}Eu		6.383 gm	41.20 mM	109.9 TBq	17.22 TBq	β $^{155}_{64}$Gd	4.753 y	122.7 keV	2.160 W	338.4 mW	35.17 kSv	5.510 kSv
E $_{63}$Eu		233.4 gm	1.525 M	404.4 TBq	1.733 TBq				73.35 W	314.3 mW	624.1 kSv	2.674 kSv
^{99}Ru	$^{99}_{43}$Tc	43.95 mg	444.4 μM									
^{100}Ru	$^{100}_{42}$Mo	218.3 gm	2.185 M									
^{101}Ru		1.166 kg	11.56 M									
^{102}Ru	$^{102}_{45}$Rh	1.217 kg	11.94 M									
^{103}Ru		$\leq$ 1 pg	$\leq$ 1 pM	6.355 pBq	1.195 PBq	β $^{103m}_{45}$Rh	39.26 d	564.3 keV	$\leq$ 1 pW	108.0 W	$\leq$ 1 pSv	872.2 kSv
					1.198% →	β $^{103}_{45}$Rh						

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
^{104}Ru		863.0 gm	8.306 M									
^{106}Ru		231.6 mg	2.187 mM	28.70 TBq	123.9 TBq	β $^{106}_{45}$Rh	1.020 y	10.03 keV	46.10 mW	199.1 mW	200.9 kSv	867.4 kSv
A $_{44}$Ru		3.465 kg	33.99 M	28.70 TBq	8.284 GBq				46.10 mW	13.31 μW	200.9 kSv	57.99 Sv
^{146}Pm		2.661 mg	18.24 μM	43.86 GBq	16.48 TBq	ϵ $^{146}_{60}$Nd	5.531 y	850.6 keV	5.977 mW	2.246 W	39.47 Sv	14.83 kSv
					34% →	β $^{146}_{62}$Sm						
^{147}Pm	$^{151}_{63}$Eu	11.02 gm	75.01 mM	378.2 TBq	34.32 TBq	β $^{147}_{62}$Sm	2.623 y	60.52 keV	3.667 W	332.8 mW	98.33 kSv	8.923 kSv
^{148}Pm	$^{148m}_{61}$Pm	≤ 1 pg	≤ 1 pM	≤ 1 pBq	6.083 PBq	β $^{148}_{62}$Sm	5.368 d	1.299 MeV	≤ 1 pW	1.266 kW	≤ 1 pSv	16.42 MSv
^{148m}Pm		≤ 1 pg	≤ 1 pM	2.956 pBq	791.0 TBq	β $^{148}_{62}$Sm	41.05 d	2.139 MeV	≤ 1 pW	271.1 W	≤ 1 pSv	1.345 MSv
					5% →	γ $^{148}_{61}$Pm						
E $_{61}$Pm		11.02 gm	75.03 mM	378.2 TBq	34.32 TBq				3.673 W	333.2 mW	98.37 kSv	8.924 kSv
^{121}Sb	$^{121m}_{50}$Sn	12.20 gm	100.9 mM									
^{123}Sb	$^{123}_{50}$Sn	15.25 gm	124.1 mM									
^{124}Sb		≤ 1 pg	≤ 1 pM	45.23 μBq	648.0 TBq	β $^{124}_{52}$Te	60.20 d	2.238 MeV	≤ 1 pW	232.4 W	≤ 1 pSv	1.620 MSv
^{125}Sb		1.610 gm	12.89 mM	61.55 TBq	38.23 TBq	β $^{125}_{52}$Te	2.759 y	527.4 keV	5.200 W	3.230 W	67.71 kSv	42.05 kSv
					22.377% →	β $^{125m}_{52}$Te						
^{126}Sb	$^{126m}_{51}$Sb	2.019 μg	16.04 nM	6.251 GBq	3.096 PBq	β $^{126}_{52}$Te	12.40 d	3.116 MeV	3.120 mW	1.545 kW	15.00 Sv	7.431 MSv
^{126m}Sb	$^{126}_{50}$Sn	15.35 ng	121.9 pM	44.63 GBq	2.907 EBq	β $^{126}_{52}$Te	19.10 m	2.148 MeV	15.36 mW	1.001 MW	1.607 Sv	104.7 MSv
					14% →	γ $^{126}_{51}$Sb						
E $_{51}$Sb		29.06 gm	237.9 mM	61.60 TBq	2.120 TBq				5.218 W	179.6 mW	67.72 kSv	2.330 kSv
^{108}Cd	$^{108}_{47}$Ag	694.2 μg	6.434 μM	207.6 nBq	299.0 μBq	2ϵ $^{108}_{46}$Pd	410.0 Py	272.0 keV	≤ 1 pW	≤ 1 pW		
^{109}Cd		4.558 ng	41.85 pM	435.6 kBq	95.57 TBq	ϵ $^{109m}_{47}$Ag	1.267 y	19.60 keV	1.368 nW	300.1 mW	871.2 μSv	191.1 kSv
^{110}Cd	$^{110}_{46}$Pd	77.24 gm	702.8 mM									
^{111}Cd		45.72 gm	412.3 mM									
^{112}Cd		26.97 gm	241.0 mM									
^{113}Cd	$^{113m}_{48}$Cd	212.2 mg	1.879 mM	3.229 mBq	15.22 mBq	β $^{113}_{49}$In	7.700 Py	93.30 keV	≤ 1 pW	≤ 1 pW	80.72 pSv	380.4 pSv
^{113m}Cd		276.1 mg	2.445 mM	2.217 TBq	8.030 TBq	β $^{113}_{49}$In	14.10 y	283.8 keV	100.8 mW	365.1 mW	50.99 kSv	184.7 kSv
					0.14% →	γ $^{113}_{48}$Cd						
^{114}Cd	$^{114}_{49}$In	34.99 gm	307.2 mM	6.772 mBq	193.5 μBq	2β $^{114}_{50}$Sn	600.0 Py	536.0 keV	≤ 1 pW	≤ 1 pW		
^{115m}Cd		≤ 1 pg	≤ 1 pM	16.49 pBq	942.8 TBq	β $^{115}_{49}$In	44.60 d	629.1 keV	≤ 1 pW	95.03 W	≤ 1 pSv	3.111 MSv
^{116}Cd		12.55 gm	108.3 mM	42.12 μBq	3.357 μBq	2β $^{116}_{50}$Sn	34.00 Ey	2.804 MeV	≤ 1 pW	≤ 1 pW		
A $_{48}$Cd		198.0 gm	1.776 M	2.217 TBq	11.20 GBq				100.8 mW	509.2 μW	50.99 kSv	257.6 Sv
^{140}Ce	$^{144}_{60}$Nd	1.896 kg	13.55 M									
^{141}Ce		≤ 1 pg	≤ 1 pM	≤ 1 pBq	1.055 PBq	β $^{141}_{59}$Pr	32.50 d	246.9 keV	≤ 1 pW	41.72 W	≤ 1 pSv	748.9 kSv
^{142}Ce		1.711 kg	12.06 M	3.190 Bq	1.864 mBq	2β $^{142}_{60}$Nd	50.00 Py	1.417 MeV	≤ 1 pW	≤ 1 pW		
^{144}Ce		55.20 mg	383.6 μM	6.521 TBq	118.1 TBq	β $^{144}_{59}$Pr	285.0 d	111.9 keV	116.9 mW	2.118 W	33.91 kSv	614.3 kSv
					1.38% →	β $^{144m}_{59}$Pr						
E $_{58}$Ce		3.607 kg	25.61 M	6.521 TBq	1.808 GBq				116.9 mW	32.41 μW	33.91 kSv	9.401 Sv

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
^{122}Te		1.243 gm	10.20 mM									
^{123}Te	${}^{123m}_{52}$Te	21.28 mg	173.1 μM	229.1 mBq	10.77 Bq	ϵ ${}^{123}_{51}$Sb	92.00 Py	17.09 keV	$\leq$ 1 pW	$\leq$ 1 pW	1.008 nSv	47.37 nSv
^{123m}Te		2.644 pg	$\leq$ 1 pM	868.3 Bq	328.4 TBq	γ ${}^{123}_{52}$Te	119.5 d	245.6 keV	34.17 pW	12.92 W	1.216 μSv	459.8 kSv
^{124}Te	${}^{124}_{50}$Sn	963.7 mg	7.778 mM									
^{125}Te	${}^{125}_{51}$Sb	27.45 gm	219.8 mM									
^{125m}Te	${}^{125}_{51}$Sb	22.52 mg	180.3 μM	15.02 TBq	667.0 TBq	γ ${}^{125}_{52}$Te	57.40 d	141.8 keV	341.1 mW	15.15 W	13.07 kSv	580.3 kSv
^{126}Te	${}^{126}_{51}$Sb	1.322 gm	10.50 mM									
^{127}Te	${}^{127m}_{52}$Te	$\leq$ 1 pg	$\leq$ 1 pM	48.93 kBq	97.70 PBq	β ${}^{127}_{53}$I	9.350 h	227.7 keV	1.785 nW	3.564 kW	8.318 μSv	16.61 MSv
^{127m}Te		143.0 pg	1.127 pM	49.96 kBq	349.4 TBq	γ ${}^{127}_{52}$Te	109.0 d	90.71 keV	726.0 pW	5.077 W	114.9 μSv	803.6 kSv
					2.4% →	β ${}^{127}_{53}$I						
^{128}Te		170.8 gm	1.335 M	8.029 nBq	47.01 pBq	2β ${}^{128}_{54}$Xe	$\geq 10^{21}$ y	867.2 keV	$\leq$ 1 pW	$\leq$ 1 pW		
^{129m}Te		$\leq$ 1 pg	$\leq$ 1 pM	$\leq$ 1 pBq	1.115 PBq	γ ${}^{129}_{52}$Te	33.60 d	295.7 keV	$\leq$ 1 pW	52.85 W	$\leq$ 1 pSv	3.346 MSv
					37% →	β ${}^{129}_{53}$I						
^{130}Te		547.3 gm	4.213 M	70.54 nBq	128.9 pBq	2β ${}^{130}_{54}$Xe	$\geq 10^{21}$ y	2.528 MeV	$\leq$ 1 pW	$\leq$ 1 pW		
E $_{52}$Te		749.1 gm	5.797 M	15.02 TBq	20.05 GBq				341.1 mW	455.3 μW	13.07 kSv	17.44 Sv
^{146}Sm	${}^{146}_{61}$Pm	12.68 mg	86.90 μM	16.43 kBq	1.296 MBq	α ${}^{142}_{60}$Nd	100.0 My	2.538 MeV	6.681 nW	526.9 nW	887.2 μSv	69.97 mSv
^{147}Sm	${}^{147}_{61}$Pm	232.8 gm	1.585 M	195.9 kBq	841.5 Bq	α ${}^{143}_{60}$Nd	106.0 Gy	2.309 MeV	72.47 nW	311.3 pW	9.599 mSv	41.23 μSv
^{148}Sm	${}^{148}_{60}$Nd	309.5 gm	2.092 M	3.459 Bq	11.18 mBq	α ${}^{144}_{60}$Nd	7.000 Py	2.014 MeV	1.116 pW	$\leq$ 1 pW		
^{149}Sm		4.616 gm	31.00 mM	205.0 mBq	44.41 mBq	α ${}^{145}_{60}$Nd	2.000 Py	1.870 MeV	$\leq$ 1 pW	$\leq$ 1 pW		
^{150}Sm	${}^{150}_{60}$Nd	478.3 gm	3.190 M									
^{151}Sm		21.13 gm	140.0 mM	20.58 TBq	974.0 GBq	β ${}^{151}_{63}$Eu	90.00 y	19.78 keV	65.21 mW	3.086 mW	2.017 kSv	95.45 Sv
^{152}Sm	${}^{152}_{63}$Eu	178.3 gm	1.174 M									
^{154}Sm	${}^{154}_{63}$Eu	59.76 gm	388.2 mM									
E $_{62}$Sm		1.284 kg	8.600 M	20.58 TBq	16.02 GBq				65.21 mW	50.77 μW	2.017 kSv	1.570 Sv
G ${}^{3}_{1}$H		49.11 mg	16.28 mM	17.55 TBq	357.4 TBq	β ${}^{3}_{2}$He	12.33 y	5.676 keV	15.96 mW	325.0 mW	737.1 Sv	15.01 kSv
^{98}Tc		10.77 mg	110.0 μM	346.5 kBq	32.17 MBq	β ${}^{98}_{44}$Ru	4.200 My	1.532 MeV	85.02 nW	7.894 μW	693.0 μSv	64.35 mSv
^{99}Tc		1.136 kg	11.49 M	712.8 GBq	627.5 MBq	β ${}^{99}_{44}$Ru	214.0 ky	84.59 keV	9.660 mW	8.504 μW	456.2 Sv	401.6 mSv
A $_{43}$Tc		1.136 kg	11.49 M	712.8 GBq	627.5 MBq				9.660 mW	8.504 μW	456.2 Sv	401.6 mSv
^{141}Pr	${}^{141}_{58}$Ce	1.689 kg	11.99 M									
^{144}Pr	${}^{144}_{58}$Ce	2.331 μg	16.20 nM	6.521 TBq	2.798 EBq	β ${}^{144}_{60}$Nd	17.28 m	1.240 MeV	1.295 W	555.6 kW	326.0 Sv	139.9 MSv
^{144m}Pr	${}^{144}_{58}$Ce	11.65 ng	80.95 pM	78.24 GBq	6.716 EBq	γ ${}^{144}_{59}$Pr	6.900 m	57.70 keV	723.3 μW	62.09 kW		
					0.07% →	β ${}^{144}_{60}$Nd						
E $_{59}$Pr		1.689 kg	11.99 M	6.599 TBq	3.907 GBq				1.296 W	767.2 μW	326.0 Sv	193.0 mSv
^{114}Sn	${}^{114}_{48}$Cd	3.852 mg	33.82 μM									
^{115}Sn	${}^{115}_{49}$In	490.4 mg	4.268 mM									
^{116}Sn	${}^{116}_{48}$Cd	12.26 gm	105.8 mM									
^{117}Sn		12.64 gm	108.1 mM									

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
^{118}Sn		12.81 gm	108.7 mM									
^{119}Sn	$^{119m}_{50}$Sn	12.76 gm	107.3 mM									
^{119m}Sn		2.193 μg	18.44 nM	363.7 MBq	165.8 TBq	γ $^{119}_{50}$Sn	293.0 d	87.17 keV	5.079 μW	2.316 W	123.7 mSv	56.39 kSv
^{120}Sn		12.99 gm	108.3 mM									
^{121m}Sn		4.782 mg	39.55 μM	10.47 GBq	2.189 TBq	γ $^{121}_{50}$Sn	55.00 y	337.9 keV	566.7 μW	118.5 mW	3.979 Sv	832.0 Sv
					22.4% →	β $^{121}_{51}$Sb						
^{122}Sn		14.26 gm	117.0 mM									
^{123}Sn		1.506 ng	12.25 pM	458.2 kBq	304.2 TBq	β $^{123}_{51}$Sb	129.2 d	526.8 keV	38.67 nW	25.68 W	962.2 μSv	638.9 kSv
^{124}Sn		19.24 gm	155.3 mM	20.54 mBq	1.068 mBq	2β $^{124}_{52}$Te	100.0 Py	2.287 MeV	$\leq$ 1 pW	$\leq$ 1 pW		
^{126}Sn		42.49 gm	337.5 mM	44.63 GBq	1.050 GBq	β $^{126n}_{51}$Sb	230.0 ky	210.4 keV	1.504 mW	35.40 μW	209.8 Sv	4.937 Sv
					33.068% →	β $^{126m}_{51}$Sb						
E $_{50}$Sn		139.9 gm	1.152 M	55.46 GBq	396.3 MBq				2.076 mW	14.83 μW	213.9 Sv	1.528 Sv
^{127}I	$^{127}_{52}$Te	84.19 gm	663.4 mM									
^{129}I	$^{129m}_{52}$Te	273.4 gm	2.121 M	1.787 GBq	6.536 MBq	β $^{129}_{54}$Xe	16.10 My	78.00 keV	22.33 μW	81.68 nW	196.6 Sv	719.0 mSv
E $_{53}$I		357.6 gm	2.784 M	1.787 GBq	4.997 MBq				22.33 μW	62.45 nW	196.6 Sv	549.7 mSv
^{90}Zr	$^{90}_{39}$Y	207.2 gm	2.305 M									
^{91}Zr	$^{91}_{39}$Y	876.9 gm	9.646 M									
^{92}Zr		956.3 gm	10.41 M									
^{93}Zr		1.073 kg	11.55 M	99.82 GBq	93.03 MBq	β $^{93m}_{41}$Nb	1.530 My	19.59 keV	313.3 μW	292.0 nW	109.8 Sv	102.3 mSv
					2.5% →	β $^{93}_{41}$Nb						
^{94}Zr		1.125 kg	11.98 M	26.41 Bq	23.48 mBq	2β $^{94}_{42}$Mo	6.000 Py	1.144 MeV	4.839 pW	$\leq$ 1 pW		
^{95}Zr		$\leq$ 1 pg	$\leq$ 1 pM	374.5 mBq	794.9 TBq	β $^{95}_{41}$Nb	64.03 d	854.7 keV	$\leq$ 1 pW	108.9 W	355.8 pSv	755.2 kSv
					1.08% →	β $^{95m}_{41}$Nb						
^{96}Zr		1.211 kg	12.63 M	4.282 mBq	3.536 μBq	2β $^{96}_{42}$Mo	39.00 Ey	3.350 MeV	$\leq$ 1 pW	$\leq$ 1 pW		
A $_{40}$Zr		5.449 kg	58.51 M	99.82 GBq	18.32 MBq				313.3 μW	57.49 nW	109.8 Sv	20.15 mSv
^{76}Se	$^{76}_{32}$Ge	12.23 mg	161.1 μM									
^{77}Se		1.515 gm	19.70 mM									
^{78}Se		3.687 gm	47.32 mM									
^{79}Se		8.869 gm	112.4 mM	22.88 GBq	2.580 GBq	β $^{79}_{35}$Br	377.0 ky	41.99 keV	153.9 μW	17.35 μW	66.35 Sv	7.481 Sv
^{80}Se		20.17 gm	252.4 mM									
^{82}Se		50.43 gm	615.6 mM	67.30 μBq	1.334 μBq	2β $^{82}_{36}$Kr	121.0 Ey	2.995 MeV	$\leq$ 1 pW	$\leq$ 1 pW		
E $_{34}$Se		84.68 gm	1.048 M	22.88 GBq	270.2 MBq				153.9 μW	1.817 μW	66.35 Sv	783.5 mSv
^{107}Ag	$^{107}_{46}$Pd	438.3 μg	4.100 μM									
^{108}Ag	$^{108m}_{47}$Ag	$\leq$ 1 pg	$\leq$ 1 pM	156.0 kBq	27.19 EBq	β $^{108}_{48}$Cd	2.400 m	628.2 keV	15.70 nW	2.737 MW		
					2.9% →	ϵ $^{108}_{46}$Pd						
^{108m}Ag		1.817 μg	16.84 nM	1.753 MBq	964.8 GBq	ϵ $^{108}_{46}$Pd	418.0 y	1.634 MeV	458.8 nW	252.5 mW	4.032 mSv	2.219 kSv
					8.7% →	γ $^{108}_{47}$Ag						

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
^{109}Ag	$^{109m}_{47}$Ag	115.4 gm	1.060 M									
^{109m}Ag	$^{109}_{48}$Cd	≤ 1 pg	≤ 1 pM	435.6 kBq	96.76 EBq	γ $^{109}_{47}$Ag	39.70 s	86.97 keV	6.069 nW	1.348 MW		
^{110}Ag	$^{110m}_{47}$Ag	≤ 1 pg	≤ 1 pM	144.3 MBq	154.4 EBq	β $^{110}_{48}$Cd	24.56 s	1.212 MeV	28.01 μW	29.97 MW		
					0.3% →	ε $^{110}_{46}$Pd						
^{110m}Ag		61.68 μg	561.2 nM	10.85 GBq	175.9 TBq	β $^{110}_{48}$Cd	249.8 d	2.816 MeV	4.894 mW	79.35 W	30.38 Sv	492.5 kSv
					1.36% →	γ $^{110}_{47}$Ag						
E $_{47}$Ag		115.4 gm	1.060 M	11.00 GBq	95.29 MBq				4.922 mW	42.66 μW	30.38 Sv	263.3 mSv
^{102}Rh		141.1 μg	1.385 μM	6.314 GBq	44.75 TBq	ε $^{102}_{44}$Ru	2.902 y	2.151 MeV	2.176 mW	15.42 W	7.577 Sv	53.70 kSv
^{103}Rh	$^{103}_{44}$Ru	611.3 gm	5.940 M									
^{103m}Rh	$^{103}_{44}$Ru	≤ 1 pg	≤ 1 pM	5.729 pBq	1.204 EBq	γ $^{103}_{45}$Rh	56.11 m	38.82 keV	≤ 1 pW	7.490 kW	≤ 1 pSv	4.576 MSv
^{106}Rh	$^{106}_{44}$Ru	217.7 ng	2.056 nM	28.70 TBq	131.8 EBq	β $^{106}_{46}$Pd	30.00 s	1.617 MeV	7.437 W	34.16 MW		
A $_{45}$Rh		611.3 gm	5.940 M	28.71 TBq	46.96 GBq				7.439 W	12.17 mW	7.577 Sv	12.39 mSv
^{93}Nb	$^{93}_{40}$Zr	1.725 mg	18.57 μM									
^{93m}Nb	$^{93}_{40}$Zr	4.153 mg	44.70 μM	43.45 GBq	10.46 TBq	γ $^{93}_{41}$Nb	16.13 y	29.90 keV	208.1 μW	50.11 mW	5.214 Sv	1.255 kSv
^{94}Nb		1.182 mg	12.59 μM	8.198 MBq	6.936 GBq	β $^{94}_{42}$Mo	19.99 ky	1.718 MeV	2.257 μW	1.909 mW	13.94 mSv	11.79 Sv
^{95}Nb	$^{95}_{40}$Zr	≤ 1 pg	≤ 1 pM	832.0 mBq	1.448 PBq	β $^{95}_{42}$Mo	34.99 d	808.8 keV	≤ 1 pW	187.6 W	482.6 pSv	839.8 kSv
^{95m}Nb	$^{95}_{40}$Zr	≤ 1 pg	≤ 1 pM	2.780 mBq	14.10 PBq	γ $^{95}_{41}$Nb	3.608 d	234.4 keV	≤ 1 pW	529.7 W	1.557 pSv	7.899 MSv
					5.6% →	β $^{95}_{42}$Mo						
A $_{41}$Nb		7.060 mg	75.85 μM	43.46 GBq	6.156 TBq				210.4 μW	29.80 mW	5.228 Sv	740.5 Sv
^{165}Ho		285.7 mg	1.732 mM									
^{166m}Ho		3.505 mg	21.12 μM	232.9 MBq	66.45 GBq	β $^{166}_{68}$Er	1.200 ky	1.868 MeV	69.71 μW	19.89 mW	465.8 mSv	132.9 Sv
E $_{67}$Ho		289.2 mg	1.753 mM	232.9 MBq	805.3 MBq				69.71 μW	241.0 μW	465.8 mSv	1.611 Sv
^{104}Pd		463.0 gm	4.456 M									
^{105}Pd		609.7 gm	5.812 M									
^{106}Pd	$^{106}_{45}$Rh	593.8 gm	5.607 M									
^{107}Pd		361.2 gm	3.379 M	6.876 GBq	19.04 MBq	β $^{107}_{47}$Ag	6.500 My	10.00 keV	11.02 μW	30.51 nW	254.4 mSv	704.4 μSv
^{108}Pd	$^{108}_{47}$Ag	248.7 gm	2.305 M									
^{110}Pd	$^{110}_{47}$Ag	82.30 gm	748.8 mM	16.51 mBq	200.6 μBq	2β $^{110}_{48}$Cd	600.0 Py	2.000 MeV	≤ 1 pW	≤ 1 pW		
A $_{46}$Pd		2.359 kg	22.31 M	6.876 GBq	2.915 MBq				11.02 μW	4.672 nW	254.4 mSv	107.9 μSv
^{152}Gd	$^{152}_{63}$Eu	80.72 mg	531.3 μM	65.10 mBq	806.5 mBq	α $^{148}_{62}$Sm	108.0 Ty	2.197 MeV	≤ 1 pW	≤ 1 pW	2.669 nSv	33.07 nSv
^{153}Gd		193.4 ng	1.265 nM	25.25 MBq	130.6 TBq	ε $^{153}_{63}$Eu	240.4 d	152.4 keV	616.4 nW	3.187 W	6.817 mSv	35.25 kSv
^{154}Gd	$^{154}_{63}$Eu	42.53 gm	276.3 mM									
^{155}Gd	$^{155}_{63}$Eu	19.66 gm	126.9 mM									
^{156}Gd		125.8 gm	806.8 mM									
^{157}Gd		196.7 mg	1.253 mM									
^{158}Gd		33.19 gm	210.2 mM									
^{160}Gd		2.102 gm	13.14 mM	1.337 mBq	636.2 μBq	2β $^{160}_{66}$Dy	130.0 Py	1.729 MeV	≤ 1 pW	≤ 1 pW		

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
E ${}_{64}$Gd		223.6 gm	1.435 M	25.25 MBq	112.9 kBq				616.4 nW	2.757 nW	6.818 mSv	30.50 μSv
E ${}^{14}_{6}$C		40.17 μg	2.869 μM	6.628 MBq	165.0 GBq	β ${}^{14}_{7}$N	5.700 ky	49.47 keV	52.53 nW	1.308 mW	3.844 mSv	95.70 Sv
^{85}Rb	${}^{85}_{36}$Kr	162.7 gm	1.916 M									
^{87}Rb		361.8 gm	4.163 M	1.172 MBq	3.239 kBq	β ${}^{87}_{38}$Sr	48.10 Gy	141.0 keV	26.47 nW	73.16 pW	1.758 mSv	4.859 μSv
E ${}_{37}$Rb		524.5 gm	6.079 M	1.172 MBq	2.235 kBq				26.47 nW	50.47 pW	1.758 mSv	3.352 μSv
^{169}Tm		95.30 μg	564.1 nM									
^{170}Tm		$\leq$ 1 pg	$\leq$ 1 pM	9.926 Bq	221.2 TBq	β ${}^{170}_{70}$Yb	128.6 d	334.6 keV	$\leq$ 1 pW	11.86 W	12.90 nSv	287.5 kSv
					0.131% →	ϵ ${}^{170}_{68}$Er						
^{171}Tm		49.01 ng	286.7 pM	1.976 MBq	40.32 TBq	β ${}^{171}_{70}$Yb	1.917 y	26.15 keV	8.278 nW	168.9 mW	217.4 μSv	4.435 kSv
E ${}_{69}$Tm		95.35 μg	564.4 nM	1.976 MBq	20.72 GBq				8.279 nW	86.82 μW	217.4 μSv	2.280 Sv
^{9}Be		29.79 μg	3.306 μM									
^{10}Be		198.9 μg	19.86 μM	164.6 kBq	827.6 MBq	β ${}^{10}_{5}$B	1.600 My	202.4 keV	5.338 nW	26.84 μW	181.1 μSv	910.3 mSv
E ${}_{4}$Be		228.7 μg	23.17 μM	164.6 kBq	719.8 MBq				5.338 nW	23.34 μW	181.1 μSv	791.7 mSv
^{113}In	${}^{113}_{48}$Cd	195.4 mg	1.731 mM									
^{114}In	${}^{114m}_{49}$In	$\leq$ 1 pg	$\leq$ 1 pM	13.55 pBq	50.96 EBq	β ${}^{114}_{50}$Sn	1.198 m	803.4 keV	$\leq$ 1 pW	6.559 MW		
					0.5% →	ϵ ${}^{114}_{48}$Cd						
^{114m}In		$\leq$ 1 pg	$\leq$ 1 pM	14.16 pBq	856.6 TBq	γ ${}^{114}_{49}$In	50.00 d	239.3 keV	$\leq$ 1 pW	32.84 W	$\leq$ 1 pSv	3.512 MSv
					3.5% →	ϵ ${}^{114}_{48}$Cd						
^{115}In	${}^{115m}_{48}$Cd	2.697 gm	23.47 mM	621.4 mBq	230.4 mBq	β ${}^{115}_{50}$Sn	441.0 Ty	241.9 keV	$\leq$ 1 pW	$\leq$ 1 pW	19.88 nSv	7.373 nSv
E ${}_{49}$In		2.892 gm	25.20 mM	621.4 mBq	214.8 mBq				$\leq$ 1 pW	$\leq$ 1 pW	19.88 nSv	6.875 nSv
^{138}La		7.637 mg	55.38 μM	5.426 Bq	710.5 Bq	ϵ ${}^{138}_{56}$Ba	102.0 Gy	1.237 MeV	1.075 pW	140.8 pW	5.969 nSv	781.5 nSv
^{139}La		1.849 kg	13.31 M									
E ${}_{57}$La		1.849 kg	13.31 M	5.426 Bq	2.935 mBq				1.075 pW	$\leq$ 1 pW	5.969 nSv	3.228 pSv
^{159}Tb		4.337 gm	27.29 mM									
^{160}Tb		$\leq$ 1 pg	$\leq$ 1 pM	41.75 mBq	418.1 TBq	β ${}^{160}_{66}$Dy	72.30 d	1.373 MeV	$\leq$ 1 pW	91.97 W	66.80 pSv	668.9 kSv
E ${}_{65}$Tb		4.337 gm	27.29 mM	41.75 mBq	9.626 mBq				$\leq$ 1 pW	$\leq$ 1 pW	66.80 pSv	15.40 pSv
^{6}Li		241.9 μg	40.22 μM									
^{7}Li		15.49 μg	2.208 μM									
E ${}_{3}$Li		257.4 μg	42.42 μM									
^{66}Zn		53.48 ng	811.2 pM									
^{67}Zn		2.226 ng	33.26 pM									
^{68}Zn		2.128 mg	31.33 μM									
^{70}Zn		7.588 mg	108.5 μM									
E ${}_{30}$Zn		9.716 mg	139.8 μM									
^{69}Ga		5.671 μg	82.28 nM									
^{71}Ga		2.257 μg	31.82 nM									

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
E $_{31}$Ga		7.928 μg	114.1 nM									
^{70}Ge		33.14 ng	473.9 pM									
^{72}Ge		33.04 mg	459.4 μM									
^{73}Ge		66.60 mg	913.3 μM									
^{74}Ge		147.3 mg	1.993 mM									
^{76}Ge		748.2 mg	9.855 mM	82.50 nBq	110.3 nBq	2β $^{76}_{34}$Se	$\geq 10^{21}$ y	2.039 MeV	≤ 1 pW	≤ 1 pW		
E $_{32}$Ge		995.1 mg	13.22 mM	82.50 nBq	82.91 nBq				≤ 1 pW	≤ 1 pW		
E $^{75}_{33}$As		298.2 mg	3.980 mM									
^{79}Br	$^{79}_{34}$Se	1.133 mg	14.36 μM									
^{81}Br	$^{81}_{36}$Kr	31.96 gm	395.0 mM									
E $_{35}$Br		31.96 gm	395.0 mM									
^{80}Kr		358.8 μg	4.490 μM									
^{81}Kr		42.36 μg	523.5 nM	32.98 kBq	778.6 MBq	ϵ $^{81}_{35}$Br	210.0 ky	20.80 keV	109.9 pW	2.594 μW		
^{82}Kr	$^{82}_{34}$Se	2.022 gm	24.68 mM									
^{83}Kr		57.85 gm	697.7 mM									
^{84}Kr		172.8 gm	2.059 M									
^{85}Kr		18.02 gm	212.2 mM	261.8 TBq	14.53 TBq	β $^{85}_{37}$Rb	10.75 y	252.7 keV	10.60 W	588.2 mW		
^{86}Kr		282.3 gm	3.286 M									
G $_{36}$Kr		533.0 gm	6.280 M	261.8 TBq	491.2 GBq				10.60 W	19.89 mW		
^{95}Mo	$^{95}_{41}$Nb	1.116 kg	11.76 M									
^{96}Mo	$^{96}_{40}$Zr	80.49 gm	839.3 mM									
^{97}Mo		1.202 kg	12.40 M									
^{98}Mo		1.238 kg	12.64 M	1.673 kBq	1.351 Bq	2β $^{98}_{44}$Ru	100.0 Ty	112.0 keV	30.01 pW	≤ 1 pW		
^{100}Mo		1.423 kg	14.24 M	19.03 mBq	13.37 μBq	2β $^{100}_{44}$Ru	9.900 Ey	3.034 MeV	≤ 1 pW	≤ 1 pW		
A $_{42}$Mo		5.059 kg	51.89 M	1.673 kBq	330.6 mBq				30.02 pW	≤ 1 pW		
^{127}Xe		≤ 1 pg	≤ 1 pM	≤ 1 pBq	1.045 PBq	ϵ $^{127}_{53}$I	36.40 d	309.1 keV	≤ 1 pW	51.75 W		
^{128}Xe	$^{128}_{52}$Te	7.057 gm	55.17 mM									
^{129}Xe	$^{129}_{53}$I	52.40 mg	406.5 μM									
^{130}Xe	$^{130}_{52}$Te	23.11 gm	177.9 mM									
^{131}Xe		566.1 gm	4.325 M									
^{132}Xe		1.753 kg	13.29 M									
^{134}Xe	$^{134}_{55}$Cs	2.246 kg	16.77 M	20.17 Bq	8.980 mBq	2β $^{134}_{56}$Ba	11.00 Py	830.0 keV	2.682 pW	≤ 1 pW		
^{136}Xe		3.429 kg	25.23 M	1.589 mBq	463.5 nBq	2β $^{136}_{56}$Ba	210.0 Ey	2.467 MeV	≤ 1 pW	≤ 1 pW		
G $_{54}$Xe		8.024 kg	59.85 M	20.17 Bq	2.514 mBq				2.683 pW	≤ 1 pW		
^{132}Ba		3.142 mg	23.82 μM									
^{134}Ba	$^{134}_{54}$Xe	334.3 gm	2.497 M									

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Isotope ‡	Decay From	Mass grams	Moles	Radioactivity GBq	Radioactivity GBq/gm	Decay To	Half Life	Energy per Bq-s	Thermal Power Watts	Thermal Power Watts/gm	Radiotoxicity † Sv	Radiotoxicity † Sv/gm
^{135}Ba	$^{135}_{55}$Cs	1.050 gm	7.783 mM									
^{136}Ba	$^{136}_{54}$Xe	42.80 gm	314.9 mM									
^{137}Ba	$^{137}_{55}$Cs	453.5 gm	3.312 M									
^{137m}Ba	$^{137}_{55}$Cs	219.7 μg	1.605 μM	4.375 PBq	19.91 EBq	γ $^{137}_{56}$Ba	2.552 m	662.4 keV	464.3 W	2.113 MW		
^{138}Ba	$^{138}_{57}$La	1.944 kg	14.10 M									
E $_{56}$Ba		2.776 kg	20.23 M	4.375 PBq	1.576 TBq				464.3 W	167.3 mW		
^{142}Nd	$^{142}_{58}$Ce	51.65 gm	364.0 mM									
^{143}Nd	$^{147}_{62}$Sm	1.116 kg	7.809 M									
^{144}Nd	$^{144}_{59}$Pr	2.072 kg	14.40 M	83.17 Bq	40.14 mBq	α $^{140}_{58}$Ce	2.290 Py	1.905 MeV	25.38 pW	$\leq$ 1 pW		
^{145}Nd	$^{149}_{62}$Sm	975.8 gm	6.734 M									
^{146}Nd	$^{146}_{61}$Pm	1.091 kg	7.477 M									
^{148}Nd		563.2 gm	3.808 M	18.65 mBq	33.12 μBq	2β $^{148}_{62}$Sm	2.700 Ey	1.929 MeV	$\leq$ 1 pW	$\leq$ 1 pW		
^{150}Nd		273.6 gm	1.825 M	1.150 mBq	4.201 μBq	2β $^{150}_{62}$Sm	21.00 Ey	3.368 MeV	$\leq$ 1 pW	$\leq$ 1 pW		
E $_{60}$Nd		6.143 kg	42.41 M	83.19 Bq	13.54 mBq				25.39 pW	$\leq$ 1 pW		
^{160}Dy	$^{160}_{64}$Gd	612.8 mg	3.832 mM									
^{161}Dy		712.4 mg	4.427 mM									
^{162}Dy		572.7 mg	3.537 mM									
^{163}Dy		537.5 mg	3.299 mM									
^{164}Dy		133.0 mg	811.3 μM									
E $_{66}$Dy		2.568 gm	15.91 mM									
^{166}Er	$^{166m}_{67}$Ho	88.56 mg	533.7 μM									
^{167}Er		5.663 mg	33.92 μM									
^{168}Er		11.31 mg	67.35 μM									
^{170}Er	$^{170}_{69}$Tm	59.35 ng	349.3 pM									
E $_{68}$Er		105.5 mg	635.0 μM									
^{170}Yb	$^{170}_{69}$Tm	39.44 μg	232.1 nM									
^{171}Yb	$^{171}_{69}$Tm	3.377 μg	19.76 nM									
^{172}Yb		143.9 ng	836.9 pM									
E $_{70}$Yb		42.96 μg	252.7 nM									
Total		52.18 kg	443.5 M	16.84 PBq	322.7 GBq				1.375 kW	26.35 mW	155.5 MSv	2.981 kSv

ICRP Publication 119 does not report dose factors for isotopes with half lives less than ten minutes or greater than 10^9 years.
Total radiotoxicity is not the sum of the “Sv” column because ICRP Publication 119 includes radiotoxicity of daughter in radiotoxicity of parent.
Dose factors for gases are given as Sv/day per Bq/m^3. Radiotoxicity is not computed for gases.

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Decay Chains

${}^{3}_{1}\mathrm{H} \to {}^{3}_{2}\mathrm{He}$

${}^{10}_{4}\mathrm{Be} \to {}^{10}_{5}\mathrm{B}$

${}^{14}_{6}\mathrm{C} \to {}^{14}_{7}\mathrm{N}$

${}^{76}_{32}\mathrm{Ge} \to {}^{76}_{34}\mathrm{Se}$

${}^{79}_{34}\mathrm{Se} \to {}^{79}_{35}\mathrm{Br}$

${}^{82}_{34}\mathrm{Se} \to {}^{82}_{36}\mathrm{Kr}$

${}^{81}_{36}\mathrm{Kr} \to {}^{81}_{35}\mathrm{Br}$

${}^{85}_{36}\mathrm{Kr} \to {}^{85}_{37}\mathrm{Rb}$

${}^{87}_{37}\mathrm{Rb} \to {}^{87}_{38}\mathrm{Sr}$

${}^{89}_{38}\mathrm{Sr} \to {}^{89}_{39}\mathrm{Y}$
$\searrow {}^{89m}_{39}\mathrm{Y} \to {}^{89}_{39}\mathrm{Y}$

${}^{90}_{38}\mathrm{Sr} \to {}^{90}_{39}\mathrm{Y} \to {}^{90}_{40}\mathrm{Zr}$

${}^{91}_{39}\mathrm{Y} \to {}^{91}_{40}\mathrm{Zr}$

${}^{93}_{40}\mathrm{Zr} \to {}^{93}_{41}\mathrm{Nb}$
$\searrow {}^{93m}_{41}\mathrm{Nb} \to {}^{93}_{41}\mathrm{Nb}$

${}^{94}_{40}\mathrm{Zr} \to {}^{94}_{42}\mathrm{Mo}$

${}^{95}_{40}\mathrm{Zr} \to {}^{95}_{41}\mathrm{Nb} \to {}^{95}_{42}\mathrm{Mo}$
$\searrow {}^{95m}_{41}\mathrm{Nb} \to {}^{95}_{42}\mathrm{Mo}$
$\searrow {}^{95}_{41}\mathrm{Nb} \ldots$

${}^{96}_{40}\mathrm{Zr} \to {}^{96}_{42}\mathrm{Mo}$

${}^{94}_{41}\mathrm{Nb} \to {}^{94}_{42}\mathrm{Mo}$

${}^{98}_{42}\mathrm{Mo} \to {}^{98}_{44}\mathrm{Ru}$

${}^{100}_{42}\mathrm{Mo} \to {}^{100}_{44}\mathrm{Ru}$

${}^{98}_{43}\mathrm{Tc} \to {}^{98}_{44}\mathrm{Ru}$

${}^{99}_{43}\mathrm{Tc} \to {}^{99}_{44}\mathrm{Ru}$

${}^{103}_{44}\mathrm{Ru} \to {}^{103}_{45}\mathrm{Rh}$
$\searrow {}^{103m}_{45}\mathrm{Rh} \to {}^{103}_{45}\mathrm{Rh}$

${}^{106}_{44}\mathrm{Ru} \to {}^{106}_{45}\mathrm{Rh} \to {}^{106}_{46}\mathrm{Pd}$

${}^{102}_{45}\mathrm{Rh} \to {}^{102}_{44}\mathrm{Ru}$

${}^{107}_{46}\mathrm{Pd} \to {}^{107}_{47}\mathrm{Ag}$

${}^{108m}_{47}\mathrm{Ag} \to {}^{108}_{46}\mathrm{Pd}$
$\searrow {}^{108}_{47}\mathrm{Ag} \to {}^{108}_{48}\mathrm{Cd} \to {}^{108}_{46}\mathrm{Pd}$
$\searrow {}^{108}_{46}\mathrm{Pd}$

${}^{110m}_{47}\mathrm{Ag} \to {}^{110}_{47}\mathrm{Ag} \to {}^{110}_{46}\mathrm{Pd} \to {}^{110}_{48}\mathrm{Cd}$
$\searrow {}^{110}_{48}\mathrm{Cd}$
$\searrow {}^{110}_{48}\mathrm{Cd}$

${}^{109}_{48}\mathrm{Cd} \to {}^{109m}_{47}\mathrm{Ag} \to {}^{109}_{47}\mathrm{Ag}$

${}^{113m}_{48}\mathrm{Cd} \to {}^{113}_{48}\mathrm{Cd} \to {}^{113}_{49}\mathrm{In}$
$\searrow {}^{113}_{49}\mathrm{In}$

${}^{115m}_{48}\mathrm{Cd} \to {}^{115}_{49}\mathrm{In} \to {}^{115}_{50}\mathrm{Sn}$
$\searrow {}^{115m}_{49}\mathrm{In} \to {}^{115}_{49}\mathrm{In} \ldots$
$\searrow {}^{115}_{50}\mathrm{Sn}$

${}^{116}_{48}\mathrm{Cd} \to {}^{116}_{50}\mathrm{Sn}$

${}^{114m}_{49}\mathrm{In} \to {}^{114}_{48}\mathrm{Cd} \to {}^{114}_{50}\mathrm{Sn}$
$\searrow {}^{114}_{49}\mathrm{In} \to {}^{114}_{50}\mathrm{Sn}$
$\searrow {}^{114}_{48}\mathrm{Cd} \ldots$

${}^{119m}_{50}\mathrm{Sn} \to {}^{119}_{50}\mathrm{Sn}$

${}^{121m}_{50}\mathrm{Sn} \to {}^{121}_{51}\mathrm{Sb}$
$\searrow {}^{121}_{50}\mathrm{Sn} \to {}^{121}_{51}\mathrm{Sb}$

${}^{123}_{50}\mathrm{Sn} \to {}^{123}_{51}\mathrm{Sb}$

${}^{124}_{50}\mathrm{Sn} \to {}^{124}_{52}\mathrm{Te}$

${}^{126}_{50}\mathrm{Sn} \to {}^{126m}_{51}\mathrm{Sb} \to {}^{126}_{51}\mathrm{Sb} \to {}^{126}_{52}\mathrm{Te}$
$\searrow {}^{126}_{52}\mathrm{Te}$
$\searrow {}^{126n}_{51}\mathrm{Sb} \to {}^{126m}_{51}\mathrm{Sb} \ldots$

${}^{124}_{51}\mathrm{Sb} \to {}^{124}_{52}\mathrm{Te}$

${}^{125}_{51}\mathrm{Sb} \to {}^{125}_{52}\mathrm{Te}$
$\searrow {}^{125m}_{52}\mathrm{Te} \to {}^{125}_{52}\mathrm{Te}$

${}^{123m}_{52}\mathrm{Te} \to {}^{123}_{52}\mathrm{Te} \to {}^{123}_{51}\mathrm{Sb}$

${}^{127m}_{52}\mathrm{Te} \to {}^{127}_{52}\mathrm{Te} \to {}^{127}_{53}\mathrm{I}$
$\searrow {}^{127}_{53}\mathrm{I}$

${}^{128}_{52}\mathrm{Te} \to {}^{128}_{54}\mathrm{Xe}$

${}^{129m}_{52}\mathrm{Te} \to {}^{129}_{53}\mathrm{I} \to {}^{129}_{54}\mathrm{Xe}$
$\searrow {}^{129}_{52}\mathrm{Te} \to {}^{129}_{53}\mathrm{I} \ldots$

${}^{130}_{52}\mathrm{Te} \to {}^{130}_{54}\mathrm{Xe}$

${}^{127}_{54}\mathrm{Xe} \to {}^{127}_{53}\mathrm{I}$

${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{56}\mathrm{Ba}$

${}^{134}_{55}\mathrm{Cs} \to {}^{134}_{54}\mathrm{Xe} \to {}^{134}_{56}\mathrm{Ba}$
$\searrow {}^{134}_{56}\mathrm{Ba}$

${}^{135}_{55}\mathrm{Cs} \to {}^{135}_{56}\mathrm{Ba}$

${}^{137}_{55}\mathrm{Cs} \to {}^{137}_{56}\mathrm{Ba}$
$\searrow {}^{137m}_{56}\mathrm{Ba} \to {}^{137}_{56}\mathrm{Ba}$

${}^{138}_{57}\mathrm{La} \to {}^{138}_{56}\mathrm{Ba}$
$\searrow {}^{138}_{58}\mathrm{Ce}$

${}^{141}_{58}\mathrm{Ce} \to {}^{141}_{59}\mathrm{Pr}$

${}^{142}_{58}\mathrm{Ce} \to {}^{142}_{60}\mathrm{Nd}$

${}^{144}_{58}\mathrm{Ce} \to {}^{144}_{59}\mathrm{Pr} \to {}^{144}_{60}\mathrm{Nd} \to {}^{140}_{58}\mathrm{Ce}$
$\searrow {}^{144m}_{59}\mathrm{Pr} \to {}^{144}_{59}\mathrm{Pr} \ldots$
$\searrow {}^{144}_{60}\mathrm{Nd} \ldots$

${}^{148}_{60}\mathrm{Nd} \to {}^{148}_{62}\mathrm{Sm} \to {}^{144}_{60}\mathrm{Nd} \ldots$

${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{62}\mathrm{Sm}$

${}^{146}_{61}\mathrm{Pm} \to {}^{146}_{62}\mathrm{Sm} \to {}^{142}_{60}\mathrm{Nd}$
$\searrow {}^{146}_{60}\mathrm{Nd}$

${}^{148m}_{61}\mathrm{Pm} \to {}^{148}_{62}\mathrm{Sm} \ldots$
$\searrow {}^{148}_{61}\mathrm{Pm} \to {}^{148}_{62}\mathrm{Sm} \ldots$

${}^{149}_{62}\mathrm{Sm} \to {}^{145}_{60}\mathrm{Nd}$

${}^{151}_{62}\mathrm{Sm} \to {}^{151}_{63}\mathrm{Eu} \to {}^{147}_{61}\mathrm{Pm} \to {}^{147}_{62}\mathrm{Sm} \to {}^{143}_{60}\mathrm{Nd}$

${}^{150}_{63}\mathrm{Eu} \to {}^{150}_{62}\mathrm{Sm}$

${}^{152}_{63}\mathrm{Eu} \to {}^{152}_{62}\mathrm{Sm}$
$\searrow {}^{152}_{64}\mathrm{Gd} \to {}^{148}_{62}\mathrm{Sm} \ldots$

${}^{154}_{63}\mathrm{Eu} \to {}^{154}_{64}\mathrm{Gd}$
$\searrow {}^{154}_{62}\mathrm{Sm}$

${}^{155}_{63}\mathrm{Eu} \to {}^{155}_{64}\mathrm{Gd}$

${}^{153}_{64}\mathrm{Gd} \to {}^{153}_{63}\mathrm{Eu}$

${}^{160}_{64}\mathrm{Gd} \to {}^{160}_{66}\mathrm{Dy}$

${}^{160}_{65}\mathrm{Tb} \to {}^{160}_{66}\mathrm{Dy}$

${}^{166m}_{67}\mathrm{Ho} \to {}^{166}_{68}\mathrm{Er}$

${}^{170}_{69}\mathrm{Tm} \to {}^{170}_{68}\mathrm{Er}$
$\searrow {}^{170}_{70}\mathrm{Yb}$

${}^{171}_{69}\mathrm{Tm} \to {}^{171}_{70}\mathrm{Yb}$

Actinides and Daughters Per Tonne of Fuel

used for 50.68 GWth-day LWR burnup at power of 36.54 MWth and $3.14 \times 10^{14} N/\mathrm{cm}^2/s$ neutron flux,
after ten years' storage, as calculated by ORIGEN2 version 2.1 on 9 October 2013.
Radiotoxicity in Sieverts computed for adult ingestion using dose factors from ICRP publication 119

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
^{236}Pu	$^{236}_{93}$Np	5.150 ng	21.82 pM	101.3 kBq	19.67 TBq	α $^{232}_{92}$U	2.858 y	5.870 MeV	95.27 nW	18.50 W	8.813 mSv	1.711 MSv
^{237}Pu	$^{241}_{96}$Cm	$\leq$ 1 pg	$\leq$ 1 pM	$\leq$ 1 pBq	447.4 TBq	ϵ $^{237}_{93}$Np	45.30 d	62.18 keV	$\leq$ 1 pW	4.457 W	$\leq$ 1 pSv	44.74 kSv
					0.004% →	α $^{233}_{92}$U						
^{238}Pu	$^{238}_{93}$Np	300.4 gm	1.262 M	190.4 TBq	633.8 GBq	α $^{234}_{92}$U	87.70 y	5.590 MeV	170.5 W	567.6 mW	43.79 MSv	145.8 kSv
^{239}Pu	$^{239}_{93}$Np	6.183 kg	25.86 M	14.23 TBq	2.301 GBq	α $^{235m}_{92}$U	24.11 ky	5.198 MeV	11.85 W	1.917 mW	3.557 MSv	575.4 Sv
					0.06% →	α $^{235}_{92}$U						
^{240}Pu	$^{240m}_{93}$Np	2.957 kg	12.32 M	24.94 TBq	8.434 GBq	α $^{236}_{92}$U	6.563 ky	5.253 MeV	20.99 W	7.098 mW	6.235 MSv	2.109 kSv
^{241}Pu	$^{245}_{96}$Cm	1.109 kg	4.601 M	4.230 PBq	3.814 TBq	β $^{241}_{95}$Am	14.33 y	5.227 keV	3.542 W	3.194 mW	20.30 MSv	18.31 kSv
					0.002% →	α $^{237}_{92}$U						
^{242}Pu	$^{242}_{95}$Am	873.8 gm	3.610 M	123.5 GBq	141.3 MBq	α $^{238}_{92}$U	373.5 ky	4.982 MeV	98.57 mW	112.8 μW	29.64 kSv	33.92 Sv
^{243}Pu	$^{247}_{96}$Cm	$\leq$ 1 pg	$\leq$ 1 pM	33.76 kBq	96.35 PBq	β $^{243}_{95}$Am	4.956 h	194.7 keV	1.053 nW	3.005 kW	2.870 μSv	8.189 MSv
^{244}Pu	$^{248}_{96}$Cm	31.02 mg	127.1 μM	20.37 kBq	656.7 kBq	α $^{240}_{92}$U	80.00 My	4.891 MeV	15.96 nW	514.5 nW	4.889 mSv	157.6 mSv
^{246}Pu	$^{250}_{96}$Cm	$\leq$ 1 pg	$\leq$ 1 pM	3.610 mBq	1.811 PBq	β $^{246m}_{95}$Am	10.85 d	142.0 keV	$\leq$ 1 pW	41.19 W	11.91 pSv	5.977 MSv
C ${}_{94}$Pu		11.42 kg	47.66 M	4.460 PBq	390.4 GBq				207.0 W	18.12 mW	73.92 MSv	6.471 kSv
^{241}Cm		$\leq$ 1 pg	$\leq$ 1 pM	$\leq$ 1 pBq	557.3 TBq	ϵ $^{241}_{95}$Am	32.80 d	693.0 keV	$\leq$ 1 pW	61.88 W	$\leq$ 1 pSv	507.2 kSv
					1% →	α $^{237}_{94}$Pu						
^{242}Cm	$^{242}_{95}$Am	1.843 mg	7.614 μM	225.6 GBq	122.4 TBq	α $^{238}_{94}$Pu	162.9 d	6.214 MeV	224.6 mW	121.9 W	2.707 kSv	1.469 MSv
^{243}Cm		585.7 mg	2.410 mM	1.120 TBq	1.912 TBq	α $^{239}_{94}$Pu	30.00 y	6.186 MeV	1.110 W	1.895 W	168.0 kSv	286.8 kSv
					0.24% →	ϵ $^{243}_{95}$Am						
^{244}Cm		57.94 gm	237.4 mM	173.6 TBq	2.996 TBq	α $^{240}_{94}$Pu	18.00 y	5.897 MeV	164.0 W	2.831 W	20.83 MSv	359.5 kSv
^{245}Cm	$^{245}_{95}$Am	5.615 gm	22.91 mM	35.70 GBq	6.358 GBq	α $^{241}_{94}$Pu	8.500 ky	5.597 MeV	32.01 mW	5.701 mW	7.497 kSv	1.335 kSv
^{246}Cm	$^{246}_{95}$Am	716.6 mg	2.912 mM	8.150 GBq	11.37 GBq	α $^{242}_{94}$Pu	4.730 ky	5.521 MeV	7.209 mW	10.06 mW	1.711 kSv	2.388 kSv
^{247}Cm	$^{251}_{98}$Cf	9.829 mg	39.78 μM	33.76 kBq	3.435 MBq	α $^{243}_{94}$Pu	16.00 My	5.390 MeV	29.15 nW	2.966 μW	6.414 mSv	652.6 mSv
^{248}Cm	$^{252}_{98}$Cf	760.1 μg	3.064 μM	119.7 kBq	157.5 MBq	α $^{244}_{94}$Pu	340.0 ky	20.98 MeV	402.4 nW	529.4 μW	92.17 mSv	121.3 Sv
^{250}Cm	$^{254}_{98}$Cf	4.745 pg	$\leq$ 1 pM	14.44 mBq	3.043 GBq	SF	8.000 ky	123.2 MeV	$\leq$ 1 pW	60.08 mW	63.54 nSv	13.39 kSv
					3% →	α $^{246}_{94}$Pu						
C ${}_{96}$Cm		64.87 gm	265.7 mM	175.0 TBq	2.698 TBq				165.4 W	2.549 W	21.01 MSv	323.9 kSv
^{241}Am	$^{241}_{94}$Pu	738.5 gm	3.064 M	93.86 TBq	127.1 GBq	α $^{237}_{93}$Np	432.8 y	5.602 MeV	84.23 W	114.1 mW	18.77 MSv	25.42 kSv
^{242}Am	$^{242m}_{95}$Am	9.073 μg	37.48 nM	271.6 GBq	29.93 PBq	β $^{242}_{96}$Cm	16.04 h	191.4 keV	8.329 mW	918.0 W	81.48 Sv	8.980 MSv
					16.8% →	ϵ $^{242}_{94}$Pu						
^{242m}Am		758.5 mg	3.134 mM	272.9 GBq	359.8 GBq	γ $^{242}_{95}$Am	141.0 y	66.63 keV	2.913 mW	3.840 mW	51.85 kSv	68.36 kSv
					0.463% →	α $^{238}_{93}$Np						
^{243}Am	$^{243}_{94}$Pu	196.9 gm	810.1 mM	1.453 TBq	7.379 GBq	α $^{239}_{93}$Np	7.365 ky	5.421 MeV	1.262 W	6.409 mW	290.6 kSv	1.476 kSv

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
^{245}Am	$^{249}_{97}$Bk	≤ 1 pg	≤ 1 pM	2.953 Bq	228.7 PBq	β $^{245}_{96}$Cm	2.050 h	313.1 keV	≤ 1 pW	11.47 kW	183.1 pSv	14.18 MSv
^{246}Am		≤ 1 pg	≤ 1 pM	3.610 mBq	1.132 EBq	β $^{246}_{96}$Cm	39.00 m	1.361 MeV	≤ 1 pW	246.9 kW	≤ 1 pSv	65.66 MSv
C $_{95}$Am		936.2 gm	3.877 M	95.86 TBq	102.4 GBq				85.50 W	91.33 mW	19.11 MSv	20.42 kSv
^{232}U	$^{236}_{94}$Pu	402.3 μg	1.734 μM	318.8 MBq	792.4 GBq	α $^{228}_{90}$Th	69.80 y	5.414 MeV	276.5 μW	687.3 mW	105.2 Sv	261.5 kSv
^{233}U	$^{233}_{91}$Pa	4.079 mg	17.50 μM	1.462 MBq	358.4 MBq	α $^{229}_{90}$Th	159.3 ky	4.901 MeV	1.148 μW	281.4 μW	74.56 mSv	18.28 Sv
^{234}U	$^{234}_{91}$Pa	193.1 gm	825.1 mM	44.67 GBq	231.3 MBq	α $^{230}_{90}$Th	245.7 ky	4.859 MeV	34.77 mW	180.1 μW	2.189 kSv	11.34 Sv
^{235}U	$^{239}_{94}$Pu	7.418 kg	31.56 M	593.6 MBq	80.02 kBq	α $^{231}_{90}$Th	703.8 My	4.418 MeV	420.1 μW	56.63 nW	27.90 Sv	3.761 mSv
^{236}U	$^{236}_{93}$Np	5.526 kg	23.41 M	13.23 GBq	2.394 MBq	α $^{232}_{90}$Th	23.70 My	4.571 MeV	9.688 mW	1.753 μW	621.8 Sv	112.5 mSv
^{237}U	$^{241}_{94}$Pu	34.33 μg	144.8 nM	103.7 GBq	3.021 PBq	β $^{237}_{93}$Np	6.750 d	319.3 keV	5.304 mW	154.5 W	78.81 Sv	2.296 MSv
^{238}U	$^{242}_{94}$Pu	921.7 kg	3.872 kM	11.47 GBq	12.44 kBq	α $^{234}_{90}$Th	4.468 Gy	4.279 MeV	7.863 mW	8.531 nW	516.2 Sv	560.0 μSv
^{240}U	$^{244}_{94}$Pu	≤ 1 pg	≤ 1 pM	20.34 kBq	34.28 PBq	β $^{240}_{93}$Np	14.10 h	138.4 keV	450.9 pW	760.0 W	22.37 μSv	37.71 MSv
C $_{92}$U		934.8 kg	3.928 kM	174.0 GBq	186.1 kBq				58.32 mW	62.39 nW	3.539 kSv	3.785 mSv
^{236}Np		2.483 mg	10.52 μM	1.211 MBq	487.7 MBq	ϵ $^{236}_{92}$U	152.0 ky	340.2 keV	66.00 nW	26.58 μW	20.59 mSv	8.291 Sv
					11.8% →	β $^{236}_{94}$Pu						
^{237}Np	$^{237}_{92}$U	654.6 gm	2.761 M	17.08 GBq	26.09 MBq	α $^{233}_{91}$Pa	2.140 My	5.157 MeV	14.11 mW	21.56 μW	1.879 kSv	2.870 Sv
^{238}Np	$^{242m}_{95}$Am	142.2 ng	597.4 pM	1.365 GBq	9.599 PBq	β $^{238}_{94}$Pu	2.117 d	807.6 keV	176.6 μW	1.242 kW	1.242 Sv	8.735 MSv
^{239}Np	$^{243}_{95}$Am	169.2 μg	707.8 nM	1.453 TBq	8.587 PBq	β $^{239}_{94}$Pu	2.355 d	407.7 keV	94.91 mW	560.9 W	1.162 kSv	6.870 MSv
^{240m}Np		≤ 1 pg	≤ 1 pM	20.34 kBq	3.919 EBq	β $^{240}_{94}$Pu	7.400 m	977.4 keV	3.185 nW	613.7 kW		
C $_{93}$Np		654.6 gm	2.761 M	1.471 TBq	2.248 GBq				109.2 mW	166.8 μW	3.042 kSv	4.648 Sv
^{227}Th	$^{227}_{89}$Ac	239.9 pg	1.057 pM	273.1 kBq	1.138 PBq	α $^{223}_{88}$Ra	18.72 d	6.155 MeV	269.3 nW	1.123 kW	2.403 mSv	10.02 MSv
^{228}Th	$^{228}_{89}$Ac	10.55 μg	46.27 nM	320.2 MBq	30.35 TBq	α $^{224}_{88}$Ra	1.913 y	5.517 MeV	283.0 μW	26.82 W	23.05 Sv	2.185 MSv
^{229}Th	$^{233}_{92}$U	998.6 ng	4.360 nM	7.865 kBq	7.876 GBq	α $^{225}_{88}$Ra	7.340 ky	5.159 MeV	6.501 nW	6.510 mW	3.854 mSv	3.859 kSv
^{230}Th	$^{234}_{92}$U	6.672 mg	29.00 μM	4.985 MBq	747.2 MBq	α $^{226}_{88}$Ra	75.40 ky	4.774 MeV	3.813 μW	571.5 μW	1.047 Sv	156.9 Sv
^{231}Th	$^{235}_{92}$U	30.16 ng	130.5 pM	593.6 MBq	19.68 PBq	β $^{231}_{91}$Pa	1.063 d	94.65 keV	9.001 μW	298.4 W	201.8 mSv	6.692 MSv
^{232}Th	$^{236}_{92}$U	1.981 mg	8.537 μM	8.042 Bq	4.060 kBq	α $^{228}_{88}$Ra	14.05 Gy	4.083 MeV	5.261 pW	2.656 nW	1.850 μSv	933.7 μSv
^{234}Th	$^{238}_{92}$U	13.38 μg	57.17 nM	11.47 GBq	857.2 TBq	β $^{234m}_{91}$Pa	24.09 d	68.41 keV	125.7 μW	9.395 W	39.00 Sv	2.915 MSv
C $_{90}$Th		8.678 mg	37.65 μM	12.39 GBq	1.428 TBq				421.8 μW	48.60 mW	63.31 Sv	7.295 kSv
^{223}Ra	$^{223}_{87}$Fr	146.0 pg	≤ 1 pM	276.9 kBq	1.897 PBq	α $^{219}_{86}$Rn	11.43 d	6.005 MeV	266.4 nW	1.825 kW	27.69 mSv	189.7 MSv
^{224}Ra	$^{228}_{90}$Th	54.39 ng	242.8 pM	320.8 MBq	5.898 PBq	α $^{220}_{86}$Rn	3.640 d	5.789 MeV	297.5 μW	5.470 kW	20.85 Sv	383.4 MSv
^{225}Ra	$^{229}_{90}$Th	5.418 pg	≤ 1 pM	7.865 kBq	1.452 PBq	β $^{225}_{89}$Ac	14.80 d	118.3 keV	149.0 pW	27.50 W	778.6 μSv	143.7 MSv
^{226}Ra	$^{230}_{90}$Th	395.2 ng	1.748 nM	14.47 kBq	36.61 GBq	α $^{222}_{86}$Rn	1.600 ky	4.870 MeV	11.29 nW	28.57 mW	4.052 mSv	10.25 kSv
^{228}Ra	$^{232}_{90}$Th	≤ 1 pg	≤ 1 pM	3.506 Bq	8.663 TBq	β $^{228}_{89}$Ac	5.750 y	13.00 keV	≤ 1 pW	18.04 mW	2.419 μSv	5.978 MSv
E $_{88}$Ra		449.7 ng	1.992 nM	321.1 MBq	714.0 TBq				297.8 μW	662.1 W	20.88 Sv	46.44 MSv
^{231}Pa	$^{231}_{90}$Th	564.8 μg	2.445 μM	987.8 kBq	1.749 GBq	α $^{227}_{89}$Ac	32.76 ky	5.081 MeV	804.1 nW	1.424 mW	701.3 mSv	1.242 kSv
^{233}Pa	$^{237}_{93}$Np	22.23 μg	95.39 nM	17.08 GBq	768.3 TBq	β $^{233}_{92}$U	27.00 d	383.0 keV	1.048 mW	47.14 W	14.86 Sv	668.4 kSv
^{234}Pa	$^{234m}_{91}$Pa	201.5 pg	≤ 1 pM	14.92 MBq	74.04 PBq	β $^{234}_{92}$U	6.780 h	2.421 MeV	5.788 μW	28.72 kW	7.609 mSv	37.76 MSv
^{234m}Pa	$^{234}_{90}$Th	451.2 pg	1.928 pM	11.47 GBq	25.42 EBq	β $^{234}_{92}$U	1.170 m	833.7 keV	1.532 mW	3.395 MW		

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
					0.15% →	γ $^{234}_{91}$Pa						
C $_{91}$Pa		587.0 μg	2.540 μM	28.57 GBq	48.66 TBq				2.587 mW	4.406 W	15.57 Sv	26.52 kSv
^{206}Pb	$^{210}_{84}$Po	71.93 pg	≤ 1 pM									
^{207}Pb	$^{207}_{81}$Tl	17.43 ng	84.21 pM									
^{208}Pb	$^{208}_{81}$Tl	30.50 μg	146.7 nM									
^{209}Pb	$^{209}_{81}$Tl	≤ 1 pg	≤ 1 pM	7.865 kBq	168.2 PBq	β $^{209}_{83}$Bi	3.253 h	194.0 keV	244.4 pW	5.228 kW	448.3 nSv	9.589 MSv
^{210}Pb		685.2 pg	3.263 pM	1.937 kBq	2.827 TBq	β $^{210}_{83}$Bi	22.16 y	39.06 keV	12.12 pW	17.69 mW	1.337 mSv	1.951 MSv
^{211}Pb	$^{215}_{84}$Po	≤ 1 pg	≤ 1 pM	276.9 kBq	914.2 PBq	β $^{211}_{83}$Bi	36.10 m	505.4 keV	22.42 nW	74.02 kW	49.84 μSv	164.5 MSv
^{212}Pb	$^{216}_{84}$Po	6.236 ng	29.42 pM	320.8 MBq	51.44 PBq	β $^{212}_{83}$Bi	10.64 h	321.1 keV	16.50 μW	2.646 kW	1.925 Sv	308.7 MSv
^{214}Pb	$^{218}_{84}$Po	≤ 1 pg	≤ 1 pM	14.47 kBq	1.214 EBq	β $^{214}_{83}$Bi	26.80 m	537.5 keV	1.246 nW	104.5 kW	2.026 μSv	169.9 MSv
A $_{82}$Pb		30.52 μg	146.8 nM	321.1 MBq	10.52 TBq				16.52 μW	541.3 mW	1.926 Sv	63.10 kSv
^{249}Cf	$^{249}_{97}$Bk	10.48 μg	42.08 nM	1.590 MBq	151.7 GBq	α $^{245}_{96}$Cm	351.0 y	7.804 MeV	1.988 μW	189.7 mW	556.5 mSv	53.10 kSv
^{250}Cf	$^{250}_{97}$Bk	1.206 μg	4.823 nM	4.882 MBq	4.048 TBq	α $^{246}_{96}$Cm	13.08 y	6.264 MeV	4.899 μW	4.062 W	781.1 mSv	647.7 kSv
^{251}Cf		976.6 ng	3.890 nM	57.33 kBq	58.70 GBq	α $^{247}_{96}$Cm	898.0 y	6.028 MeV	55.36 nW	56.69 mW	20.64 mSv	21.13 kSv
^{252}Cf		47.81 ng	189.7 pM	951.9 kBq	19.91 TBq	α $^{248}_{96}$Cm	2.645 y	12.04 MeV	1.836 μW	38.40 W	85.67 mSv	1.792 MSv
^{254}Cf		≤ 1 pg	≤ 1 pM	≤ 1 pBq	314.7 TBq	SF	60.50 d	199.3 MeV	≤ 1 pW	10.05 kW	≤ 1 pSv	125.9 MSv
					0.309% →	α $^{250}_{96}$Cm						
C $_{98}$Cf		12.71 μg	50.98 nM	7.481 MBq	588.6 GBq				8.778 μW	690.6 mW	1.444 Sv	113.6 kSv
^{225}Ac	$^{225}_{88}$Ra	3.660 pg	≤ 1 pM	7.865 kBq	2.149 PBq	α $^{221}_{87}$Fr	10.00 d	5.891 MeV	7.423 nW	2.028 kW	188.8 μSv	51.57 MSv
^{227}Ac	$^{231}_{91}$Pa	103.2 ng	454.6 pM	276.4 kBq	2.678 TBq	β $^{227}_{90}$Th	21.77 y	81.68 keV	3.617 nW	35.05 mW	304.0 mSv	2.946 MSv
					1.38% →	α $^{223}_{87}$Fr						
^{228}Ac	$^{228}_{88}$Ra	≤ 1 pg	≤ 1 pM	3.507 Bq	83.03 PBq	β $^{228}_{90}$Th	6.150 h	1.458 MeV	≤ 1 pW	19.39 kW	1.508 nSv	35.70 MSv
E $_{89}$Ac		103.2 ng	454.6 pM	284.3 kBq	2.754 TBq				11.04 nW	107.0 mW	304.2 mSv	2.948 MSv
^{208}Bi		≤ 1 pg	≤ 1 pM	119.3 nBq	172.9 MBq	ϵ $^{208}_{82}$Pb	368.0 ky	2.653 MeV	≤ 1 pW	73.51 μW		
^{209}Bi	$^{209}_{82}$Pb	1.009 ng	4.828 pM	≤ 1 pBq	3.331 μBq	α $^{205}_{81}$Tl	19.00 Ey	3.137 MeV	≤ 1 pW	≤ 1 pW		
^{210}Bi	$^{210}_{82}$Pb	≤ 1 pg	≤ 1 pM	1.937 kBq	4.593 PBq	β $^{210}_{84}$Po	5.012 d	389.0 keV	120.7 pW	286.2 W	2.518 μSv	5.971 MSv
^{210m}Bi		≤ 1 pg	≤ 1 pM	90.34 nBq	21.01 MBq	α $^{206}_{81}$Tl	3.000 My	5.295 MeV	≤ 1 pW	17.82 μW	≤ 1 pSv	315.1 mSv
^{211}Bi	$^{211}_{82}$Pb	≤ 1 pg	≤ 1 pM	276.9 kBq	15.50 EBq	α $^{207}_{81}$Tl	2.170 m	6.727 MeV	298.4 nW	16.70 MW		
					0.273% →	β $^{211}_{84}$Po						
^{212}Bi	$^{212}_{82}$Pb	591.5 pg	2.790 pM	320.8 MBq	542.3 PBq	β $^{212}_{84}$Po	1.009 h	2.868 MeV	147.4 μW	249.2 kW	83.41 mSv	141.0 MSv
					0.014% →	β α $^{208}_{82}$Pb						
					35.93% →	α $^{208}_{81}$Tl						
^{213}Bi	$^{217}_{85}$At	≤ 1 pg	≤ 1 pM	7.865 kBq	716.3 PBq	β $^{213}_{84}$Po	45.59 m	709.0 keV	893.3 pW	81.36 kW	1.573 μSv	143.3 MSv
					2.16% →	α $^{209}_{81}$Tl						
^{214}Bi	$^{214}_{82}$Pb	≤ 1 pg	≤ 1 pM	14.47 kBq	1.635 EBq	β $^{214}_{84}$Po	19.90 m	2.161 MeV	5.009 nW	566.1 kW	1.592 μSv	179.9 MSv
A $_{83}$Bi		1.601 ng	7.621 pM	321.1 MBq	200.6 PBq				147.7 μW	92.26 kW	83.41 mSv	52.10 MSv
^{210}Po	$^{210}_{83}$Bi	10.40 pg	≤ 1 pM	1.730 kBq	166.3 TBq	α $^{206}_{82}$Pb	138.4 d	5.405 MeV	1.498 nW	144.0 W	2.076 mSv	199.6 MSv

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
^{211}Po	$^{211}_{83}$Bi	≤ 1 pg	≤ 1 pM	775.4 Bq	3.536×10^{12}	α $^{207}_{82}$Pb	516.0 ms	7.589 MeV	942.7 pW	4.299 GW		
^{215}Po	$^{219}_{86}$Rn	≤ 1 pg	≤ 1 pM	276.9 kBq	1.091×10^{15}	α $^{211}_{82}$Pb	1.780 ms	7.529 MeV	334.0 nW	1.317×10^{12}		
^{216}Po	$^{220}_{86}$Rn	≤ 1 pg	≤ 1 pM	320.8 MBq	1.289×10^{13}	α $^{212}_{82}$Pb	150.0 ms	6.904 MeV	354.8 μW	14.26 GW		
^{218}Po	$^{222}_{86}$Rn	≤ 1 pg	≤ 1 pM	14.47 kBq	10.47 EBq	α $^{214}_{82}$Pb	3.098 m	6.113 MeV	14.17 nW	10.25 MW		
A $_{84}$Po		10.43 pg	≤ 1 pM	321.1 MBq	30.80 EBq				355.2 μW	34.06 MW	2.076 mSv	199.1 MSv
^{249}Bk		3.356 ng	13.47 pM	203.6 kBq	60.67 TBq	β $^{249}_{98}$Cf	320.0 d	125.0 keV	4.077 nW	1.215 W	197.5 μSv	58.85 kSv
					0.001% →	α $^{245}_{95}$Am						
^{250}Bk	$^{254}_{99}$Es	≤ 1 pg	≤ 1 pM	1.108 Bq	144.0 PBq	β $^{250}_{98}$Cf	3.217 h	1.172 MeV	≤ 1 pW	27.04 kW	155.1 pSv	20.16 MSv
C $_{97}$Bk		3.356 ng	13.47 pM	203.6 kBq	60.67 TBq				4.077 nW	1.215 W	197.5 μSv	58.85 kSv
^{221}Fr	$^{225}_{89}$Ac	≤ 1 pg	≤ 1 pM	7.865 kBq	6.565 EBq	α $^{217}_{85}$At	4.900 m	6.509 MeV	8.201 nW	6.846 MW		
^{223}Fr	$^{227}_{89}$Ac	≤ 1 pg	≤ 1 pM	3.816 kBq	1.432 EBq	β $^{223}_{88}$Ra	21.80 m	437.9 keV	267.7 pW	100.5 kW	9.158 μSv	3.438 GSv
C $_{87}$Fr		≤ 1 pg	≤ 1 pM	11.68 kBq	3.025 EBq				8.469 nW	2.193 MW	9.158 μSv	2.371 GSv
C $^{254}_{99}$Es		≤ 1 pg	≤ 1 pM	1.106 Bq	69.04 TBq	α $^{250}_{97}$Bk	275.7 d	6.620 MeV	1.173 pW	73.22 W	30.97 nSv	1.933 MSv
$^{250}_{0}$Sf		45.96 μg										
G $^{4}_{2}$He		2.317 gm	578.9 mM									
^{207}Tl	$^{211}_{83}$Bi	≤ 1 pg	≤ 1 pM	276.1 kBq	7.051 EBq	β $^{207}_{82}$Pb	4.770 m	495.3 keV	21.91 nW	559.5 kW		
^{208}Tl	$^{212}_{83}$Bi	10.57 pg	≤ 1 pM	115.2 MBq	10.90 EBq	β $^{208}_{82}$Pb	3.053 m	3.971 MeV	73.29 μW	6.934 MW		
^{209}Tl	$^{213}_{83}$Bi	≤ 1 pg	≤ 1 pM	169.9 Bq	15.14 EBq	β $^{209}_{82}$Pb	2.200 m	2.802 MeV	76.26 pW	6.797 MW		
A $_{81}$Tl		10.61 pg	≤ 1 pM	115.5 MBq	10.88 EBq				73.31 μW	6.910 MW		
A $^{217}_{85}$At	$^{221}_{87}$Fr	≤ 1 pg	≤ 1 pM	7.865 kBq	5.958×10^{13}	α $^{213}_{83}$Bi	32.30 ms	7.197 MeV	9.068 nW	68.70 GW		
^{219}Rn	$^{223}_{88}$Ra	≤ 1 pg	≤ 1 pM	276.9 kBq	481.7 EBq	α $^{215}_{84}$Po	3.960 s	6.997 MeV	310.4 nW	540.0 MW		
^{220}Rn	$^{224}_{88}$Ra	9.394 pg	≤ 1 pM	320.8 MBq	34.15 EBq	α $^{216}_{84}$Po	55.80 s	6.403 MeV	329.1 μW	35.03 MW		
^{222}Rn	$^{226}_{88}$Ra	2.541 pg	≤ 1 pM	14.47 kBq	5.695 PBq	α $^{218}_{84}$Po	3.823 d	5.586 MeV	12.95 nW	5.096 kW		
G $_{86}$Rn		11.94 pg	≤ 1 pM	321.1 MBq	26.90 EBq				329.4 μW	27.60 MW		
Total		947.9 kg	3.983 kM	4.730 PBq	4.990 GBq				458.1 W	483.3 μW	21.05 MSv	22.21 Sv

ICRP Publication 119 does not report dose factors for isotopes with half lives less than ten minutes or greater than 10^9 years.

Total radiotoxicity is not the sum of the “Sv” column because ICRP Publication 119 includes radiotoxicity of daughter in radiotoxicity of parent.

Dose factors for gases are given as Sv/day per Bq/m^3. Radiotoxicity is not computed for gases.

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Decay Chains

$$\begin{array}{llll} {}^{210}_{82}\mathrm{Pb} \rightarrow & {}^{210}_{83}\mathrm{Bi} \rightarrow & {}^{210}_{84}\mathrm{Po} \rightarrow & {}^{206}_{82}\mathrm{Pb} \\ & \searrow & {}^{206}_{81}\mathrm{Tl} \rightarrow & {}^{206}_{82}\mathrm{Pb} \\ \searrow & {}^{206}_{80}\mathrm{Hg} \rightarrow & {}^{206}_{81}\mathrm{Tl} \ldots & \end{array}$$

${}^{208}_{83}\mathrm{Bi} \to {}^{208}_{82}\mathrm{Pb}$

${}^{210m}_{83}\mathrm{Bi} \to {}^{206}_{81}\mathrm{Tl} \ldots$

${}^{236}_{93}\mathrm{Np} \to {}^{236}_{94}\mathrm{Pu} \to {}^{232}_{92}\mathrm{U} \to {}^{228}_{90}\mathrm{Th} \to {}^{224}_{88}\mathrm{Ra} \to {}^{220}_{86}\mathrm{Rn} \to {}^{216}_{84}\mathrm{Po} \to {}^{212}_{82}\mathrm{Pb} \to {}^{212}_{83}\mathrm{Bi} \to {}^{212}_{84}\mathrm{Po} \to {}^{208}_{82}\mathrm{Pb}$
$\searrow {}^{208}_{82}\mathrm{Pb}$
$\searrow {}^{208}_{81}\mathrm{Tl} \to {}^{208}_{82}\mathrm{Pb}$
$\searrow {}^{236}_{92}\mathrm{U} \to {}^{232}_{90}\mathrm{Th} \to {}^{228}_{88}\mathrm{Ra} \to {}^{228}_{89}\mathrm{Ac} \to {}^{228}_{90}\mathrm{Th} \ldots$
$\searrow {}^{232}_{91}\mathrm{Pa} \to {}^{232}_{92}\mathrm{U} \ldots$
$\searrow {}^{232}_{90}\mathrm{Th} \ldots$

${}^{240m}_{93}\mathrm{Np} \to {}^{240}_{94}\mathrm{Pu} \to {}^{236}_{92}\mathrm{U} \ldots$
$\searrow {}^{240}_{93}\mathrm{Np} \to {}^{240}_{94}\mathrm{Pu} \ldots$

${}^{242m}_{95}\mathrm{Am} \to {}^{242}_{95}\mathrm{Am} \to {}^{242}_{96}\mathrm{Cm} \to {}^{238}_{94}\mathrm{Pu} \to {}^{234}_{92}\mathrm{U} \to {}^{230}_{90}\mathrm{Th} \to {}^{226}_{88}\mathrm{Ra} \to {}^{222}_{86}\mathrm{Rn} \to {}^{218}_{84}\mathrm{Po} \to {}^{218}_{85}\mathrm{At} \to {}^{218}_{86}\mathrm{Rn} \to {}^{214}_{84}\mathrm{Po} \to {}^{210}_{82}\mathrm{Pb} \ldots$
$\searrow {}^{214}_{83}\mathrm{Bi} \to {}^{214}_{84}\mathrm{Po} \ldots$
$\searrow {}^{210}_{81}\mathrm{Tl} \to {}^{210}_{82}\mathrm{Pb} \ldots$
$\searrow {}^{209}_{82}\mathrm{Pb} \to {}^{209}_{83}\mathrm{Bi} \to {}^{205}_{81}\mathrm{Tl}$
$\searrow {}^{214}_{82}\mathrm{Pb} \to {}^{214}_{83}\mathrm{Bi} \ldots$
$\searrow {}^{242}_{94}\mathrm{Pu} \to {}^{238}_{92}\mathrm{U} \to {}^{234}_{90}\mathrm{Th} \to {}^{234m}_{91}\mathrm{Pa} \to {}^{234}_{92}\mathrm{U} \ldots$
$\searrow {}^{234}_{91}\mathrm{Pa} \to {}^{234}_{92}\mathrm{U} \ldots$
$\searrow {}^{238}_{93}\mathrm{Np} \to {}^{238}_{94}\mathrm{Pu} \ldots$

${}^{246}_{95}\mathrm{Am} \to {}^{246}_{96}\mathrm{Cm} \to {}^{242}_{94}\mathrm{Pu} \ldots$

${}^{241}_{96}\mathrm{Cm} \to {}^{241}_{95}\mathrm{Am} \to {}^{237}_{93}\mathrm{Np} \to {}^{233}_{91}\mathrm{Pa} \to {}^{233}_{92}\mathrm{U} \to {}^{229}_{90}\mathrm{Th} \to {}^{225}_{88}\mathrm{Ra} \to {}^{225}_{89}\mathrm{Ac} \to {}^{221}_{87}\mathrm{Fr} \to {}^{217}_{85}\mathrm{At} \to {}^{217}_{86}\mathrm{Rn} \to {}^{213}_{84}\mathrm{Po} \to {}^{209}_{82}\mathrm{Pb} \ldots$
$\searrow {}^{213}_{83}\mathrm{Bi} \to {}^{213}_{84}\mathrm{Po} \ldots$
$\searrow {}^{209}_{81}\mathrm{Tl} \to {}^{209}_{82}\mathrm{Pb} \ldots$
$\searrow {}^{237}_{94}\mathrm{Pu} \to {}^{237}_{93}\mathrm{Np} \ldots$
$\searrow {}^{233}_{92}\mathrm{U} \ldots$

${}^{243}_{96}\mathrm{Cm} \rightarrow {}^{243}_{95}\mathrm{Am} \rightarrow {}^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu} \rightarrow {}^{235}_{92}\mathrm{U} \rightarrow {}^{231}_{90}\mathrm{Th} \rightarrow {}^{231}_{91}\mathrm{Pa} \rightarrow {}^{227}_{89}\mathrm{Ac} \rightarrow {}^{227}_{90}\mathrm{Th} \rightarrow {}^{223}_{88}\mathrm{Ra} \rightarrow {}^{219}_{86}\mathrm{Rn} \rightarrow {}^{215}_{84}\mathrm{Po} \rightarrow {}^{215}_{85}\mathrm{At} \rightarrow {}^{211}_{83}\mathrm{Bi} \rightarrow {}^{211}_{84}\mathrm{Po} \rightarrow {}^{207}_{82}\mathrm{Pb}$
$\searrow {}^{207}_{81}\mathrm{Tl} \rightarrow {}^{207}_{82}\mathrm{Pb}$
$\searrow {}^{211}_{82}\mathrm{Pb} \rightarrow {}^{211}_{83}\mathrm{Bi} \ldots$
$\searrow {}^{223}_{87}\mathrm{Fr} \rightarrow {}^{223}_{88}\mathrm{Ra} \ldots$
$\searrow {}^{219}_{85}\mathrm{At} \rightarrow {}^{219}_{86}\mathrm{Rn} \ldots$
$\searrow {}^{215}_{83}\mathrm{Bi} \rightarrow {}^{215}_{84}\mathrm{Po} \ldots$
$\searrow {}^{235m}_{92}\mathrm{U} \rightarrow {}^{235}_{92}\mathrm{U} \ldots$
$\searrow {}^{239}_{94}\mathrm{Pu} \ldots$

${}^{244}_{96}\mathrm{Cm} \rightarrow {}^{240}_{94}\mathrm{Pu} \ldots$

${}^{249}_{97}\mathrm{Bk} \rightarrow {}^{249}_{98}\mathrm{Cf} \rightarrow {}^{245}_{96}\mathrm{Cm} \rightarrow {}^{241}_{94}\mathrm{Pu} \rightarrow {}^{241}_{95}\mathrm{Am} \ldots$
$\searrow {}^{237}_{92}\mathrm{U} \rightarrow {}^{237}_{93}\mathrm{Np} \ldots$
$\searrow {}^{245}_{95}\mathrm{Am} \rightarrow {}^{245}_{96}\mathrm{Cm} \ldots$

${}^{251}_{98}\mathrm{Cf} \rightarrow {}^{247}_{96}\mathrm{Cm} \rightarrow {}^{243}_{94}\mathrm{Pu} \rightarrow {}^{243}_{95}\mathrm{Am} \ldots$

${}^{252}_{98}\mathrm{Cf} \rightarrow {}^{248}_{96}\mathrm{Cm} \rightarrow {}^{244}_{94}\mathrm{Pu} \rightarrow {}^{240}_{92}\mathrm{U} \rightarrow {}^{240}_{93}\mathrm{Np} \ldots$

${}^{254}_{98}\mathrm{Cf}$

${}^{254}_{99}\mathrm{Es} \rightarrow {}^{250}_{97}\mathrm{Bk} \rightarrow {}^{250}_{98}\mathrm{Cf} \rightarrow {}^{246}_{96}\mathrm{Cm} \ldots$

Activation Products Per Tonne of Fuel

used for 50.68 GWth-day LWR burnup at power of 36.54 MWth and $3.14 \times 10^{14} N/\text{cm}^2/s$ neutron flux,
after ten years' storage, as calculated by ORIGEN2 version 2.1 on 9 October 2013.
Radiotoxicity in Sieverts computed for adult ingestion using dose factors from ICRP publication 119

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
^{90}Zr	$^{90}_{39}$Y	120.7 kg	1.343 kM									
^{91}Zr	$^{91}_{39}$Y	26.41 kg	290.5 M									
^{92}Zr		41.10 kg	447.2 M									
^{93}Zr		160.7 gm	1.730 M	14.95 GBq	93.03 MBq	β $^{93m}_{41}$Nb	1.530 My	19.59 keV	46.93 μW	292.0 nW	16.44 Sv	102.3 mSv
					2.5% →	β $^{93}_{41}$Nb						
^{94}Zr		42.60 kg	453.6 M	1.000 kBq	23.48 mBq	2β $^{94}_{42}$Mo	6.000 Py	1.144 MeV	183.2 pW	≤ 1 pW		
^{95}Zr		≤ 1 pg	≤ 1 pM	12.72 mBq	795.5 TBq	β $^{95}_{41}$Nb	64.03 d	854.3 keV	≤ 1 pW	108.9 W	12.08 pSv	755.7 kSv
					1.08% →	β $^{95m}_{41}$Nb						
^{96}Zr		6.957 kg	72.54 M	24.60 mBq	3.536 μBq	2β $^{96}_{42}$Mo	39.00 Ey	3.350 MeV	≤ 1 pW	≤ 1 pW		
A $_{40}$Zr		237.9 kg	2.608 kM	14.95 GBq	62.83 kBq				46.93 μW	197.2 pW	16.44 Sv	69.12 μSv
^{87}Sr		3.321 mg	38.21 μM									
^{88}Sr		325.3 mg	3.701 mM									
^{89}Sr		≤ 1 pg	≤ 1 pM	283.5 pBq	1.076 PBq	β $^{89}_{39}$Y	50.57 d	583.0 keV	≤ 1 pW	100.5 W	≤ 1 pSv	2.797 MSv
^{90}Sr		26.93 μg	299.5 nM	136.0 MBq	5.050 TBq	β $^{90}_{39}$Y	28.79 y	195.8 keV	4.266 μW	158.4 mW	3.808 Sv	141.4 kSv
E $_{38}$Sr		328.6 mg	3.739 mM	136.0 MBq	413.8 MBq				4.266 μW	12.98 μW	3.808 Sv	11.59 Sv
^{93}Nb	$^{93}_{40}$Zr	245.6 μg	2.644 μM									
^{93m}Nb	$^{93}_{40}$Zr	610.9 μg	6.575 μM	6.395 GBq	10.47 TBq	γ $^{93}_{41}$Nb	16.13 y	29.88 keV	30.61 μW	50.11 mW	767.4 mSv	1.256 kSv
^{94}Nb		63.41 ng	675.2 pM	439.7 Bq	6.934 GBq	β $^{94}_{42}$Mo	19.99 ky	1.719 MeV	121.1 pW	1.910 mW	747.5 nSv	11.79 Sv
^{95}Nb	$^{95}_{40}$Zr	≤ 1 pg	≤ 1 pM	28.24 mBq	1.448 PBq	β $^{95}_{42}$Mo	34.99 d	809.0 keV	≤ 1 pW	187.7 W	16.38 pSv	840.0 kSv
^{95m}Nb	$^{95}_{40}$Zr	≤ 1 pg	≤ 1 pM	94.34 μBq	14.10 PBq	γ $^{95}_{41}$Nb	3.608 d	234.4 keV	≤ 1 pW	529.4 W	≤ 1 pSv	7.896 MSv
					5.6% →	β $^{95}_{42}$Mo						
A $_{41}$Nb		856.6 μg	9.220 μM	6.395 GBq	7.466 TBq				30.61 μW	35.74 mW	767.4 mSv	895.9 Sv
^{89}Y	$^{89}_{38}$Sr	24.79 mg	278.8 μM									
^{90}Y	$^{90}_{38}$Sr	6.754 ng	75.12 pM	136.0 MBq	20.14 PBq	β $^{90}_{40}$Zr	2.671 d	935.4 keV	20.38 μW	3.017 kW	367.2 mSv	54.37 MSv
^{91}Y		≤ 1 pg	≤ 1 pM	686.2 nBq	907.9 TBq	β $^{91}_{40}$Zr	58.51 d	605.8 keV	≤ 1 pW	88.12 W	≤ 1 pSv	2.179 MSv
E $_{39}$Y		24.79 mg	278.8 μM	136.0 MBq	5.486 GBq				20.38 μW	822.1 μW	367.2 mSv	14.81 Sv
^{98}Tc		4.887 ng	49.91 pM	157.2 mBq	32.17 MBq	β $^{98}_{44}$Ru	4.200 My	1.532 MeV	≤ 1 pW	7.892 μW	314.4 pSv	64.33 mSv
^{99}Tc		1.152 mg	11.65 μM	722.8 kBq	627.4 MBq	β $^{99}_{44}$Ru	214.0 ky	84.60 keV	9.796 nW	8.503 μW	462.6 μSv	401.6 mSv
A $_{43}$Tc		1.152 mg	11.65 μM	722.8 kBq	627.4 MBq				9.796 nW	8.503 μW	462.6 μSv	401.6 mSv
^{1}H		12.73 mg	12.63 mM									
^{2}H		10.72 μg	5.322 μM									
^{3}H		4.054 pg	1.344 pM	1.449 kBq	357.4 TBq	β $^{3}_{2}$He	12.33 y	5.678 keV	1.318 pW	325.1 mW	60.86 nSv	15.01 kSv

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Isotope	Decay	Mass		Radioactivity		Decay	Half	Energy	Thermal Power		Radiotoxicity †	
‡	From	grams	Moles	GBq	GBq/gm	To	Life	per Bq-s	Watts	Watts/gm	Sv	Sv/gm
G $_{1}\mathrm{H}$		12.74 mg	12.64 mM	1.449 kBq	113.7 kBq				1.318 pW	103.4 pW	60.86 nSv	4.777 μSv
$^{102}\mathrm{Rh}$		$\leq$ 1 pg	$\leq$ 1 pM	2.251 μBq	44.76 TBq	ϵ $^{102}_{44}\mathrm{Ru}$	2.902 y	2.151 MeV	$\leq$ 1 pW	15.42 W	$\leq$ 1 pSv	53.71 kSv
$^{103}\mathrm{Rh}$		1.108 pg	$\leq$ 1 pM									
A $_{45}\mathrm{Rh}$		1.108 pg	$\leq$ 1 pM	2.251 μBq	2.032 MBq				$\leq$ 1 pW	700.1 nW	$\leq$ 1 pSv	2.438 mSv
$^{3}\mathrm{He}$	$^{3}_{1}\mathrm{H}$	3.120 pg	1.034 pM									
$^{4}\mathrm{He}$		16.30 mg	4.072 mM									
G $_{2}\mathrm{He}$		16.30 mg	4.072 mM									
$^{94}\mathrm{Mo}$	$^{94}_{40}\mathrm{Zr}$	23.39 pg	$\leq$ 1 pM									
$^{95}\mathrm{Mo}$	$^{95}_{41}\mathrm{Nb}$	29.03 gm	305.9 mM									
$^{96}\mathrm{Mo}$	$^{96}_{40}\mathrm{Zr}$	1.824 gm	19.02 mM									
$^{97}\mathrm{Mo}$		48.80 gm	503.6 mM									
$^{98}\mathrm{Mo}$		616.9 mg	6.301 mM	833.5 mBq	1.351 Bq	2β $^{98}_{44}\mathrm{Ru}$	100.0 Ty	112.0 keV	$\leq$ 1 pW	$\leq$ 1 pW		
$^{100}\mathrm{Mo}$		1.234 μg	12.35 nM	16.50 pBq	13.37 μBq	2β $^{100}_{44}\mathrm{Ru}$	9.900 Ey	3.034 MeV	$\leq$ 1 pW	$\leq$ 1 pW		
A $_{42}\mathrm{Mo}$		80.27 gm	834.8 mM	833.5 mBq	10.38 mBq				$\leq$ 1 pW	$\leq$ 1 pW		
$^{98}\mathrm{Ru}$	$^{98}_{42}\mathrm{Mo}$	$\leq$ 1 pg	$\leq$ 1 pM									
$^{99}\mathrm{Ru}$	$^{99}_{43}\mathrm{Tc}$	40.54 ng	409.9 pM									
$^{100}\mathrm{Ru}$	$^{100}_{42}\mathrm{Mo}$	99.42 μg	995.2 nM									
$^{101}\mathrm{Ru}$		500.4 ng	4.959 nM									
$^{102}\mathrm{Ru}$	$^{102}_{45}\mathrm{Rh}$	9.511 ng	93.33 pM									
$^{104}\mathrm{Ru}$		$\leq$ 1 pg	$\leq$ 1 pM									
A $_{44}\mathrm{Ru}$		99.97 μg	1.001 μM									
$^{104}\mathrm{Pd}$		$\leq$ 1 pg	$\leq$ 1 pM									
$^{105}\mathrm{Pd}$		$\leq$ 1 pg	$\leq$ 1 pM									
$^{106}\mathrm{Pd}$		$\leq$ 1 pg	$\leq$ 1 pM									
A $_{46}\mathrm{Pd}$		$\leq$ 1 pg	$\leq$ 1 pM									
Total		238.0 kg	2.609 kM	21.62 GBq	90.84 kBq				102.2 μW	429.4 pW	20.25 Sv	85.10 μSv

ICRP Publication 119 does not report dose factors for isotopes with half lives less than ten minutes or greater than 10^9 years.
Total radiotoxicity is not the sum of the "Sv" column because ICRP Publication 119 includes radiotoxicity of daughter in radiotoxicity of parent.
Dose factors for gases are given as Sv/day per Bq/m^3. Radiotoxicity is not computed for gases.

‡Electrorefiner destination: A = anode, C = cathode, E = electrolyte, G = gas; †Radiotoxicity of daughters is included in parents.

Decay Chains

$^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He}$

$^{89}_{38}\mathrm{Sr} \rightarrow {}^{89}_{39}\mathrm{Y}$
$\searrow {}^{89m}_{39}\mathrm{Y} \rightarrow {}^{89}_{39}\mathrm{Y}$

$^{90}_{38}\mathrm{Sr} \rightarrow {}^{90}_{39}\mathrm{Y} \rightarrow {}^{90}_{40}\mathrm{Zr}$

$^{91}_{39}\mathrm{Y} \rightarrow {}^{91}_{40}\mathrm{Zr}$

$^{93}_{40}\mathrm{Zr} \rightarrow {}^{93}_{41}\mathrm{Nb}$
$\searrow {}^{93m}_{41}\mathrm{Nb} \rightarrow {}^{93}_{41}\mathrm{Nb}$

$^{94}_{40}\mathrm{Zr} \rightarrow {}^{94}_{42}\mathrm{Mo}$

$^{95}_{40}\mathrm{Zr} \rightarrow {}^{95}_{41}\mathrm{Nb} \rightarrow {}^{95}_{42}\mathrm{Mo}$
$\searrow {}^{95m}_{41}\mathrm{Nb} \rightarrow {}^{95}_{42}\mathrm{Mo}$
$\searrow {}^{95}_{41}\mathrm{Nb} \ldots$

$^{96}_{40}\mathrm{Zr} \rightarrow {}^{96}_{42}\mathrm{Mo}$

$^{94}_{41}\mathrm{Nb} \rightarrow {}^{94}_{42}\mathrm{Mo}$

$^{98}_{42}\mathrm{Mo} \rightarrow ^{98}_{44}\mathrm{Ru}$ $^{100}_{42}\mathrm{Mo} \rightarrow ^{100}_{44}\mathrm{Ru}$ $^{98}_{43}\mathrm{Tc} \rightarrow ^{98}_{44}\mathrm{Ru}$ $^{99}_{43}\mathrm{Tc} \rightarrow ^{99}_{44}\mathrm{Ru}$ $^{102}_{45}\mathrm{Rh} \rightarrow ^{102}_{44}\mathrm{Ru}$

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There are many books about energy. There are many books about climate.

This book looks at both in a comprehensive, quantitative, system engineering way. Most other books look at individual components, without connecting them. This book connects the dots.

The conclusions might surprise you:

1. Human activity has an impreceptible effect on climate.
2. A warming climate is a good thing.
3. Eliminating CO_2 emissions is exactly the wrong thing to be doing if we want to preserve life on Earth.
4. If we must acquiesce in the demands of climate activists, the only physically feasible and economically viable energy source is nuclear fission – the safest thing humanity has ever done.