Save the Planet: Eliminate CO_2 and Destroy Nuclear Waste

Introduction

Patrick Moore, cofounder of Greenpeace, wrote "nuclear energy may just be the energy source that can save our planet from another possible disaster: catastrophic climate change.... Nuclear energy is the only large-scale, cost-effective energy source that can reduce these emissions [of CO_2] while continuing to satisfy a growing demand for power."[a] Alternatives are far more expensive, and even with conservation none but solar, alone or together, can do the whole job, — and they don't do anything about the vexing problem of nuclear waste.

Essentially everything you've been told about civilian nuclear electric power is wrong. There are solutions to the problems of safety, waste, weapons proliferation, uranium supply, reliability, and cost.

The solutions are all embodied in one system, the brainchild of Leonard Koch and his colleagues at Argonne National Laboratory in 1964. A project to demonstrate it completely at realistic scale, leaving absolutely no loose ends, called the Integral Fast Reactor, or IFR [1][2], was funded by the Reagan administration in 1984. Hans Bethe said IFR was "the best fast reactor project that has ever been pursued." It was canceled by the Clinton administration in 1994, when it was an inch from completion [3], at more cost than finishing it.

A single complete and permanent solution to all energy, pollution, nuclear waste, and CO_2 emission problems is within our grasp. All obstacles to that solution are political, abetted and perpetuated by ignorance, intentional falsehoods, hysteria, and opportunistic demagoguery, not scientific, technological or engineering problems. Competition for energy resources is frequently blamed for wars. IFR would eliminate that excuse.

There is no time to waste. We really ought to get started.

What is IFR

IFR is an advanced liquid metal-cooled breeder reactor (ALMR), together with a fuel reprocessing system. The intent of the demonstration project was to "close the fuel cycle," so that actinides[b] go into a power plant, and the only waste that comes out is fission products. Actinides only come out to start a new IFR.

- IFR is inherently safe because of a negative temperature coefficient [4]. Above the design temperature, the hotter the reactor, the slower the reaction, reaching a safe equilibrium even in the absence of control, coolant circulation, or heat sink.
- IFR is simpler than light-water reactors (LWR), so construction and operating costs are lower.
- IFR can be fueled with 5%-used LWR fuel and waste from weapons production, thereby consuming a substance of which we are desperately eager to be rid: No need for Yucca Mountain.
- IFR uses 99% of the energy in the mined uranium instead of 0.6%. It creates its own fuel from abundant non-fissile actinides. There is enough uranium to power the entire world for at least one million years, or five million years if thorium is used in reactors of slightly different design.
- IFR produces 5% as much waste as LWR. The waste consists entirely of fission products, 80% of which are stable, have half-lives less than one year, or can be destroyed or used in the reactor, and the remainder are less radiotoxic than uranium in nature before only 200–300 years, instead of 300,000 years.
- IFR fuel is reprocessed on-site, reducing the opportunities for accidents and theft.

[a] http:// www.washingtonpost.com/wp-dyn/content/article/2006/04/14/AR2006041401209.html

[b] Actinides are elements from actinium to lawrencium. In a reactor they are thorium (in some reactors), uranium, neptunium, plutonium, americium and curium. Those from neptunium onward are called transuranics.

- Used IFR fuel is just about the most difficult substance from which to make weapons – more difficult than LWR waste. No nuclear state makes weapons from used civilian LWR fuel.

Electric power production

In 2006, the U.S. produced 787,219 gigawatt hours (GWh)[a], or roughly 90 gigawatt-electric years (GWe-years) of electric energy (roughly 20% of total energy demand) from light-water nuclear reactors, using about 2,000 tons (1,818 metric tons or tonnes) of nuclear fuel (mostly enriched uranium), yielding 433,000 watt hours per gram (Wh/gm), or 0.05 GWe-years per tonne.

Roughly 1,990,511 GWh, or 227 GWe-years (about 50% of total energy demand), were produced from 1,053,783,000 tons of coal, yielding 2.08 Wh/gm, or 2.37×10^{-7} GWe-years per tonne.

Approximately 64,000 GWh (an irrelevant 1.64% of total electricity demand) were produced from 110,634,000 barrels of petroleum (#1, #2, #4, #5, #6, C, converted coke, waste oil), yielding 3.93 Wh/gm, or 4.48×10^{-7} GWe-years per tonne.

About 816,441 GWh, or 93 GWe-years (21% of total energy demand) were produced from 6,461,615 million standard cubic feet of natural gas, yielding 4.87 Wh/gm, or 5.55×10^{-7} GWe-years per tonne.

To produce the same amount of electricity as 1 gram (0.001 kg) of LWR fuel, which is used with less than 5% efficiency, requires 208 kg of coal, 110 kg of petroleum, or 89 kg of natural gas.

About 54 GWe-years ($<$ 12% of demand) were produced from renewable sources, primarily hydro.

Total U.S. electric energy production was about 450 GWe-years, so average electric power demand was about 450 GW. Peak demand is about twice as much.

Total power demand

Total yearly-averaged U.S. power demand (electric and non-electric) is 3.75 terawatts (TW). Using the rule of thumb that it takes 3 GW thermal (GWth) to generate 1 GWe, current 450 GWe demand is equivalent to 1,350 GWth. Thus the non-electric demand is $3,750 - 1,350 = 2,400$ GWth.

Roughly 19% of non-electric demand, or 450 GWth, arises from the residential and commercial sectors.[b] Much of this demand is for space and water heating, which could be satisfied directly by electricity. Heat pumps would be between two and eight times more efficient than electrical resistance heating, or using heat from fossil fuels directly.[c] Using Mitsubishi's rating of 4.6 for its EcoDan/BRE model, those sectors would thus need about $450/4.6 \approx 100$ GWe additional electric power if converted completely to electricity.

Roughly one third of non-electric demand, or 800 GWth, arises from the industrial sector. Some of that can only be used in the form of higher-temperature heat than heat pumps can produce (for example, in cement manufacture). Guessing that 500 GWth must remain as heat, supplied by resistance or arc at about 100% efficiency, and the remaining 300 GWth could be replaced by 100 GWe, the industrial sector would need about $500 + 300/3 = 600$ GWe additional electric power.

Many industries need heat at temperatures that can be provided directly from reactors (up to about 1000°F or 550°C), without intermediate conversion to electricity. Examples include papermaking, food processing, plastic processing.... To the extent these facilities can be co-located with reactors, three times higher efficiency can be gained, thereby reducing required capacity below 800 GWth.

Roughly 48% of non-electric demand, or 1,150 GWth, arises from the transportation sector. About 85% of energy use in the transportation sector, or about 975 GWth, is for road, rail or pipeline transport.[d] Rail and pipeline transport could be immediately converted to electric supply, and work is in progress to convert

[a] http://www.eia.doe.gov/cneaf/electricity/epa/epates.html
[b] http://www.eia.doe.gov/energyexplained/index.cfm?page=us_energy_home
[c] http://www.fuelcells.bham.ac.uk/documents/review_of_domestic_heat_pump_cop.pdf
[d] http://www.ifp.com/content/download/57516/1274819/file/IFP-Panorama05%2009-ConsommationVA.pdf

road transport to electric supply. The remaining 15% is mostly for airplanes, ships, and heavy construction and farm equipment.

The efficiency of an electric vehicle, starting from the power plant, is about 73% (95% transmission efficiency × 88% battery charge efficiency × 88% battery discharge efficiency), while the efficiency of an internal-combustion engine is about 15%[a] (but in a series hybrid automobile it approaches 30%). Thus the efficiency of road transport would be increased by a factor of 4.9 (73%/15%) by conversion to electricity, while efficiency of rail and pipeline transport would be increased by a factor of 6.3 (95%/15%) because they don't need batteries. Thus the 975 GWth demand for road, rail and pipeline transport would be replaced by an increased electric power demand of about $975/4.9 \approx 200$ GWe. This leaves about 175 GWth supplied by liquid hydrocarbon fuels, primarily for airplanes, ships, and heavy construction and farm equipment. Liquid hydrocarbon fuels could ultimately be manufactured from energy + CO_2 + water using the Fischer-Tropsch process. An especially interesting possibility is to extract carbonates from seawater using the PARC process [5], direct reactor heat at 530° to produce hydrogen using the Cu-Cl process, and the Fischer-Tropsch process to produce alkanes.

Taking 450 GWe current demand together with 900 GWe new demands for electric power shows that we would have to expand our electric generating capacity by a factor of about $1350/450 = 3$ to cover all but 175 GWth of our power needs. Guessing 50% efficiency of converting electricity to liquid hydrocarbon fuels,[b] about 350 GWe would be required to displace the remaining 175 GWth transportation demand for liquid hydrocarbon fuels, for a total electric demand of 1,700 GWe, or about 3.75 times current capacity.

CO_2

About 2.344 billion tonnes of CO_2 were produced in 2006 by U.S. fossil-fueled power plants (1.938 from coal, 0.319 from natural gas). Total U.S. emissions were 5.894 billion tonnes (1.186 from residential, 1.035 from commercial, 1.658 from industrial, 2.014 from transportation).[c]

No CO_2 is produced from operation of nuclear reactors, although some CO_2 is produced by the mining, milling, refining, fabrication and transportation of uranium fuel, and in the construction (and eventual destruction) of a power plant (mostly from cement manufacture).

Nuclear is a lower carbon emitting option than wind, solar or hydroelectric, primarily because of the huge amounts of concrete, steel, aluminum, and plastic needed for those technologies.[d]

The net of nuclear energy produced less fossil fuel energy consumed is so large that life cycle emissions of CO_2 for the current generation of LWRs are only 3-6 grams of carbon per kilowatt hour (gC/kWh). As will be shown below, we have enough uranium, already mined and refined, to fuel IFR replacements for our LWR fleet for 10,000 years, to fuel IFR replacements for our entire electric generating capacity for 2,000 years, or to fuel IFR replacements for our entire energy economy for 530 years. Averaged over this time scale, with mined uranium used to 100% efficiency instead of 0.6%, life cycle CO_2 emissions for nuclear power plants are only 0.01-0.02 gC/kWh, or about 300,000 tonnes per year, a reduction of a factor of 50,000 from all sources in 2006. Once uranium mining, milling, and refining start again, they would presumably be powered by electricity from IFR, so the CO_2 emission rate would be even less.

For wind turbines it's 3–10 gC/kWh. For natural gas it's 105–163 gC/kWh. For coal it's 228–262 gC/kWh.[d,e]

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[a] http://www.electroauto.com/info/pollmyth.shtml

[b] Other fuels such as boron [3] might have higher total system efficiency.

[c] http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html

[d] "The Energy Challenge" page 117, published by DTI (now BERR http://http://www.berr.gov.uk/files/file31890.pdf) in 2007

[e] http://www.eia.gov/cneaf/electricity/page/co2_report/co2emiss.pdf

Wind

According to the National Renewable Energy Laboratory [6], the average total land use power density of wind projects is 3 MW/km^2. Utilities observe on average a 21% capacity factor for wind installations [3], giving an effective average wind project power density of 0.6 MW/km^2. Capacity factors will surely decrease, because high-potential sites are used first.

To supply 1.7 TWe would require 33% of the nation's land area (Alaska excluded) for wind farm projects.

W. Timothy Liu, recognized world wide as an expert on wind, says, however, that wind can never supply more than 15% of the world's current total energy needs. Professor Frank Shu of the University of California at San Diego estimates worldwide potential is 1.8 TWe.[a]

Solar photovoltaic

The global mean average peak power output of solar panels, as of 2014, is about 175 watts per square meter (W/m^2) – more at the equator, less at the poles, more in sunny locales, less in cloudy ones. Assuming a 15% capacity factor [3] leaves an effective power flux of 26.25 W/m^2, or .02625 GWe-yr/km^2 per year. So to generate all 4,064,702 gigawatt hours produced in the U.S. in 2007 would require $\approx 17,700$ square kilometers of cells. To provide 1,700 GWe-yr per year would require over 64,800 square kilometers of cells, plus perhaps 10% more for spaces between the racks of collectors. No problem! Just put solar panels on the roofs of homes. At 1000 ft^2 (90 m^2) per home, that's only 721 million homes.

By way of comparison, the San Onofre Nuclear Generating Station occupied 84 acres (0.34 km^2), and produced 2.3 GWe-yr per year, or 6.77 GWe-yr/km^2 per year. To produce 1,700 GWe-yr per year would require 251 km^2.

Human activity already uses 25% of the biological output of the land area of the earth, exclusive of Antarctica and Greenland. In parts of central and eastern Europe, and India, it is as high as 60%. Converting more land to solar power and biofuels would effectively increase this fraction, thereby depriving the non-human biosphere the use of this land.

Current photovoltaic cells have to produce energy for over four years to pay back the energy invested in producing and deploying them. As of 2013, photovoltaic and solar thermal sources contribute about 2.5% of our total electric power. Therefore, we would need exponential increase of 25% per year for 17 years to bring this to 100% of our electric power requirements, or 23 years to provide all of our power requirements, by which time photovoltaic cells would not have added one watt hour to our energy supply. The current annual growth rate is 5.7% [3], at which rate we could build enough capacity to supply all of our power needs in 92 years, but even more time would be needed to repay the energy investment.

Since the sun only shines during the day, energy would have to be stored for use at night, or transmitted from halfway around the world. At some latitudes it doesn't shine at all during winter, so long-distance distribution would be necessary.

Storage is a significant problem to which insufficient attention has been given. If all the batteries ever produced were fully charged at sundown (which is impossible because most have been recycled) they would not supply current demand for one night. An all-electric automobile fleet would use about 20% of energy output. An electric automobile can operate for about five hours at full power. If the entire electric automobile fleet were fully charged and connected to the grid at sundown, it could supply 20% of demand for five hours. Then nobody could drive to work because the batteries would be discharged.

Biofuels

The U.S. currently gets 1% of road transportation fuels, or about 9 GWth, from biofuels, using 10% of currently-harvested cropland, or about 1.3% of the nation's land area.

[a] http://www.physics.ucsd.edu/~tmurphy/phys239/shu_energy.pdf

To supply all road, rail, pipeline, ship, airplane, and heavy equipment fuels would require 1,270% of currently-harvested cropland area, or 130% of the nation's total land area.

Even providing only all ship, airplane, and heavy equipment fuels from biofuels would require 190% of currently-harvested cropland area, or about 18% of the nation's total land area (Alaska included). What would we eat?

Currently-harvested cropland area is about 75% of total farmland area. It is not possible to harvest 100% of farmland. Some must remain fallow each year to avoid depletion, and some is pasture.

Irrational hysteria about nuclear power regretted

Patrick Moore, a cofounder of Greenpeace, realizes that his view in the 1970's that nuclear power and nuclear weapons are the same thing was naïve. He now advocates nuclear power as "the energy source that can save our planet from another possible disaster: catastrophic climate change. . . ." "Nuclear energy is the only large-scale, cost-effective energy source that can reduce these emissions [of CO_2] while continuing to satisfy a growing demand for power. . . ." For his honesty, Greenpeace has kicked him out.[a] on page 1

He's not alone. James Lovelock, father of the Gaia theory, Stewart Brand, founder of the Whole Earth Catalog, the late Bishop Hugh Montefiore, founder and director of Friends of the Earth,[a] James Hansen, the outspoken NASA climate scientist, Mark Lynas, an outspoken critic of nuclear power before learning of IFR, and many other former critics of nuclear power, are now nuclear power advocates.

Safety of nuclear power in OECD countries

According to the Paul Scherrer Institute Nuclear Energy and Safety Research Division[b][c], nobody has died in any OECD or EU-27 country as a result of the operation of a civilian nuclear electric power generator.

Impressive as is the current perfect safety record, IFR is a more modern design that incorporates additional safety features. In particular, above the designed operating temperature, it has a negative temperature coefficient, meaning that the hotter the reaction gets, the slower it goes, ultimately settling down at an equilibrium temperature far below the "meltdown" temperature. This depends upon immutable laws of physics, not upon skill of operators, computers, pumps, or indeed on any moving parts at all, other than thermal expansion of the reactor core.

Seven years after the Three Mile Island accident, the prototype of IFR, called EBR-II, was compromised in the same way that the Three Mile Island reactor was compromised (loss of coolant flow). It shut down without any damage to the reactor, harm to the operators, or release of radioactive materials. A few hours earlier, it had been compromised in the other known way (loss of heat sink). Again, it shut down gracefully [3]. One month later, the Chernobyl reactor was compromised in the second way. According to Pete Planchon [7], who ran the tests for an invited international audience, "Back in 1986, we actually gave a small [20 MWe] prototype advanced fast reactor a couple of chances to melt down. It politely refused both times."

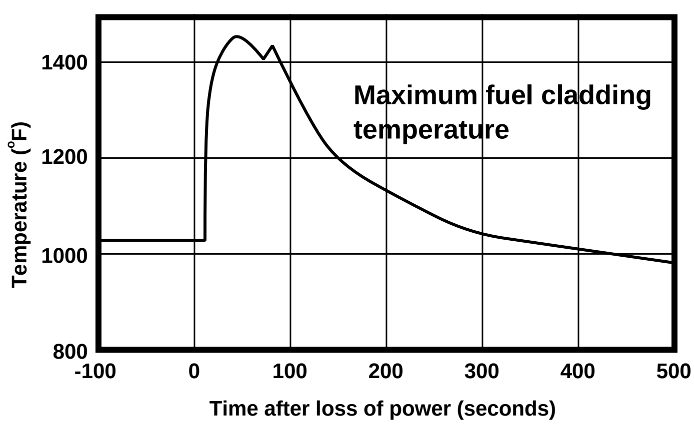

Figure 1: Core temperature after loss of cooling

[a]Friends of the Earth forced Bishop Montefiore to resign after he published a pro-nuclear article in a church magazine.
[b]https://www.psi.ch/nes/
[c]https://www.psi.ch/ta/RiskEN/SECURE_Deliverable_D5_7_2_Severe_Accident_Risks.pdf page 43

Three Mile Island

Notwithstanding the hysteria of Jack Lemmon, Jane Fonda and Michael Douglas in the movie "The China Syndrome," nobody, that is NOBODY, was injured by the Three Mile Island accident. It was a brilliant success story of careful design,[a] which has since been improved by lessons learned. Insurers paid out only $70 million. The owners spent a further $973 million on cleanup. Nobody has died of a radiation-related accident in the history of the U.S. civilian nuclear electric power reactor program,[f], or civilian nuclear electric power reactor programs in any OECD or EU-27 country.

Chernobyl

Chernobyl was an accident waiting to happen. The reactor had an inadequate containment structure, it was an inherently unsafe design[b] (nobody plans to build another 3 GWth reactor out of charcoal and surround it with a tin-foil containment shed), and the operators literally (but unintentionally) blew it up by bypassing safety interlocks and already-inadequate shutdown mechanisms, ironically in a rush to get a safety check done. The 173-page report of the United Nations Scientific Committee for the Effects of Atomic Radiation (UNSCEAR)[cd][8] concludes that

- 134 plant workers and emergency workers suffered Acute Radiation Syndrome (ARS) from high doses of radiation. Two workers were killed by falling debris. One died from coronary thrombosis.
- In the first few months after the accident, 28 ARS victims died.
- Although another 19 ARS sufferers had died by 2006, those deaths had different causes not usually associated with radiation exposure.
- Skin injuries and cataracts were among the most common consequences in ARS survivors.
- Although several hundred thousand people, as well as the emergency workers, were involved in recovery operations, there is no consistent evidence of health effects that can be attributed to radiation exposure, apart from indications of increased incidence of leukemia and of cataracts among those who received higher doses.
- 6,000 cases of thyroid cancer were reported between 1991 and 2005 in affected areas. It is not possible to state scientifically that radiation caused a particular cancer in a particular individual. By 2005, only fifteen of those cases had been fatal.
- Radiation doses to the general public in the three most affected countries (Ukraine, Belarus, Russia) were relatively low and most residents "need not live in fear of serious health consequences." In the most affected areas, the average additional dose over the period 1986-2005 is approximately equivalent to that of one computed tomography scan.
- There is no ongoing increased risk of solid tumors or blood cancers.

The World Nuclear Association attributes 30 deaths to the accident.[e] "Tragic as those deaths were, they pale in comparison to the more than 5,000 coal-mining deaths worldwide every year," says Moore.[f]

[a] http://www.world-nuclear.org/info/inf36.html

[b] The Soviet RBMK reactor design is based upon the design of a military reactor, which was in turn based upon design documents for the U.S. Hanford reactors, stolen from the Oak Ridge National Laboratory before the Hanford reactors were built, optimized for production of plutonium for weapons purposes, scaled up for civilian nuclear power production (http://www.world-nuclear.org/info/inf31.html).

[c] http://www.unscear.org/unscear/en/chernobyl.html

[d] http://www.unis.unvienna.org/unis/en/pressrels/2011/unisinf398.html

[e] http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Chernobyl-Accident/ – see Appendix 1: Sequence of events.

[f] http://www.washingtonpost.com/wp-dyn/content/article/2006/04/14/AR2006041401209.html

More to the point, Chernobyl was a steam explosion, followed by a hydrogen explosion,[a] followed by a graphite fire. Although a test reactor at Idaho National Laboratory was intentionally destroyed by prompt criticality,[b] it is impossible for a municipal nuclear reactor licensed in an OECD or EU-27 country to generate a nuclear explosion. IFR, being liquid-metal cooled, has no water in the core, and is not graphite moderated. A steam explosion, a hydrogen explosion, or a graphite fire, is impossible in the core of an IFR.

Fukushima

Despite widespread hysteria, a report[c] from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), presented to the UN General Assembly in October 2013 [9], shows that nobody was killed, injured, or made ill by the destruction of the reactors at Fukushima by the earthquake and tsunami, and nobody will be.

From Page 9, section 2 "Dose Assessment," ¶ 29: "The Japanese people receive an effective dose of radiation from naturally occurring sources of, on average, about 2.1 millisieverts (mSv) annually and a total of about 170 mSv over their lifetimes."

From page 11, section 3 "Health Implications" ¶ 38 "No radiation-related deaths or acute diseases have been observed among the workers and general public exposed to radiation from the accident."

¶ 40 "For adults in Fukushima Prefecture, the Committee estimates [the increase in] average lifetime effective doses to be of the order of 10 mSv or less... a discernible increase in cancer incidence in this population that could be attributed to radiation exposure from the accident is not expected."

For comparison, the dose from an abdominal and pelvic CT scan repeated with and without contrast would be about 30 mSv, or about ten years' worth of average normal background radiation. This increases lifetime cancer risk from 1 in 5 to 1.005 in 5. Yearly dose on the Tibetan plateau is 13-20 mSv. In areas of monazite deposits in Brazil and India, doses exceed 36 mSv/year.

Nuclear power reactor waste

Foremost among the benefits of IFR, beyond enhanced inherent safety, the amount of waste is a factor of 20 less than the amount produced by LWRs. Most IFR waste is dangerously radioactive for five years, and the remainder for a few hundred years, instead of a few hundred thousand years [1].

The 2000 tons of used fuel removed from U.S. LWRs per year are currently considered waste, but are actually a valuable resource because only 5% of their energy content has been extracted.

Used fuel has a density of about 11 grams/cm^3, or about 8 tons/yd^3. As of 2006, total U.S. commercial fuel discharges amounted to about 59,160 tonnes,[d] or about 7,400 cubic yards of accumulated "waste." This is already enough for 8–10 Yucca Mountains. If piled on a 3,000 square yard football field, it would be 7.4 feet deep (but it would melt). The 100,000,000 tons of eternally-toxic solid waste[e] from operation of U.S. coal-fired power plants in 2006 alone would be about 74,000 feet, or about 14 miles, deep,[f] amounting to 740 miles in fifty years.

[a] Steam reacted with zirconium fuel pin cladding to produce hydrogen.

[b] Nuclear fission produces two populations of neutrons, those emitted within about ten nanoseconds (prompt neutrons), and those emitted up to several seconds later (delayed neutrons). If critical neutron flux arises from prompt neutrons, it is not possible to control the reaction.

[c] http://www.unscear.org/docs/GAreports/A-68-46_e_V1385727.pdf

[d] http://www.eia.doe.gov/cneaf/nuclear/spent_fuel/ussnfdata.html reports LWR waste of 42,750 tonnes through 2002; http://www.eia.doe.gov/emeu/aer/txt/stb0902.xls reports 631 GWe-yr nuclear production 2003–2009 and 1.6 TWe-yr from 1957–2002. Assuming the same 26,718 tonnes/TWe-yr 1957–2002 rate for 2003–2009 gives 16,860 additional tonnes.

[e] According to http://www.ornl.gov/info/ornlreview/rev26-34/text/colmain.html, there is 16.3 times more energy in the waste from coal-fired power plants than in the coal that was burned: 4.7 tonnes of uranium and 11.6 tonnes of thorium per GWe-yr, about 0.036% of a coal-fired power plant's solid waste. Power plants account for only 74% of coal combustion.

[f] According to http://www.tfhrc.gov/hnr20/recycle/waste/cbabs1.htm, density is 1.0125–1.35 tons/yd^3.

In addition to the 5%-used-fuel "waste" there are about 900,000 tons of depleted-uranium "waste" left over from the enrichment process, containing more than 90% of the energy in the uranium that was mined.

The rate at which waste generates heat is a more important factor than its volume. With transuranics present – as in what we currently call "waste" – the long-term capacity of a repository is determined by the heat those transuranics will generate millennia hence. With them removed, the primary determining factor becomes heat generated by ^{137}Cs and ^{90}Sr. With transuranics removed but ^{137}Cs and ^{90}Sr remaining, the capacity of a repository is increased by a factor of about five compared to the current technology. With only ^{137}Cs and ^{90}Sr remaining, the capacity is enormously increased [1].

A reactor (IFR or otherwise) produces about 1 tonne of fission products per GWe-year. The current U.S. LWR fleet produces about 90 GWe-year per year, thereby generating about 90 tonnes of fission products per year, about 5% of the total "waste," or about 300 milligrams per American. Radioactive ^{137}Cs and ^{90}Sr amount to about 39 kg per GWe-year. Not all isotopes of caesium and strontium are radioactive, and isotopic separation is costly, so it makes more sense to consider total caesium and strontium fission products, which amount to 92 kg/GWe-year, about 8.3 Tonnes/yr, or about 24 milligrams per American per year. If all those fission products within the 59,160 tonnes of "waste" accumulated from 1957 until 2006 were spread on a football field, the pile would be about 0.44 inches deep. A pile of all fission products, including those that are nonradioactive or have very short half lives, would be 4.8 inches deep (but it would melt).

If the current American supply of LWRs were replaced by IFRs, the stream of "waste" would be reduced from 1,818 to 90 tonnes per year, and if left mixed instead of separated those 90 tonnes would be less radiotoxic than mined uranium before 200–300 years instead of 300,000 years as for LWR "waste."

The nonradioactive, short-lived, and long-lived fission products could be separated. Strontium and caesium constitute 9% of fission products. 6% of fission products (^{99}Tc and ^{129}I) have very long half lives but can be transmuted to short-lived isotopes (15.46 seconds and 12.36 hours) by neutron absorption within the reactor, thereby effectively destroying them. ^{93}Zr, another 2% of fission products, can be recycled into fuel pin cladding or alloying (where it doesn't matter that it's radioactive, and the radioactivity is low-energy beta – electron – emission anyway). The remaining 89% are less radiotoxic than mined uranium before five to ten years. The stream requiring long-term storage (strontium and caesium) would thereby be substantially reduced, to about 92 kg/GWe-yr. The specific activity (heat generation per kilogram) of the remainder would be reduced. Other fission products (primarily ^{137}Cs and ^{90}Sr) could in principle be destroyed by neutron transmutation, but it takes longer than their normal decay. Even if they are simply stored, however, their specific activity is so low that storage is not a significant problem. At an average of $16 million/tonne (some much higher), the appreciable commercial value of many fission products[a] reduces the storage problem even further.

If all current U.S. electric power generating capacity were replaced with IFR, the stream of fission products would amount to 450 tonnes per year, of which 41 tonnes require long-term custody. This is less than one quarter the quantity of 5%-used fuel that is generated by the LWRs that supply about 20% of our present electric power needs.

A 1.7 TWe energy economy powered by IFRs would produce 1,700 tonnes of fission products per year, or about 6.5% less than the 1,818 tonnes of 5%-used fuel removed from the LWRs that currently supply only about 5.3% of our energy needs. Long-lived fission products (mostly ^{93}Zr and ^{135}Cs) amount to about 131 kg per GWe-year, or 223 tonnes (730 milligrams per American) altogether per year. ^{93}Zr could be recycled into fuel-pins, so it needn't be stored. ^{93}Zr and ^{135}Cs would occupy about 121 yd^3, or about 1.4 inch if spread on a football field. They have such low specific activity that they are not considered to be dangerous. If ^{133}Cs (stable), ^{134}Cs (2.065y) and ^{137}Cs (30.08y) are not removed, the amount is 269 yd^3 per year.

Fission products with half-lives less than thirty years are less radiotoxic than mined natural uranium before 200–300 years so custody is simple for them. Production and radioactive decay offset each other, exponentially approaching an asymptote of about 5.84 tonnes of radioactive material per GWe (not GWe-year). If stable decay products are continuously removed, a constant capacity is needed for radioactive material storage, preferably co-located with each IFR.

That is, storage and disposal are not problems, and therefore IFR waste is not a problem.

[a] http://brc.gov/e-mails/August10/Commercial Value of 1 Metric ton of used fuel.pdf.

Refer to the appendices for more details.

Availability of nuclear fuel

For LWRs, the concentration of ^{235}U, the fissile isotope, is typically enriched from the natural 0.71% to about 4.2%, leaving behind a supply of uranium, depleted in ^{235}U, that is about 5.7 times the amount of "reactor grade" enriched uranium. Combining this and the 4-5% fuel efficiency of LWR, we extract less than 0.6% of the energy in mined uranium. In a reactor, some of the ^{238}U is transmuted into ^{239}Pu and other transuranics, which are directly usable as IFR fuel. In an IFR energy economy, once started, those transuranics rather than ^{235}U provide much of the fission energy, and the neutrons needed to transmute ^{238}U into more transuranics. That is, (a) enrichment is not necessary, and (b) the currently left-behind depleted uranium is valuable as future fuel.

Using a rule of thumb that fissioning 0.9 kg of actinides yields 1 GWth-day of energy, and generating 1 GWe requires 3 GWth to be expended, 1 GWe-yr requires $365.25 \times 3 \times 0.9 = 981$ kg ≈ 1 tonne of actinides to be converted to fission products. If mined uranium were used to 100% capacity instead of 0.6%, total U.S. power demand of about 1,700 GWe would require about 1,700 tonnes of new uranium per year.

IFRs could use the current U.S. supply of LWR "waste," a substance of which we are desperately eager to be rid, as fuel. If nothing is done other than to build an IFR to replace each LWR as it reaches the end of its useful life,[a] about 50 tonnes of start-up fuel per IFR, plus one tonne per year of make-up uranium thereafter[b] would be needed. That is, assuming there are 900,000 tonnes of LWR "waste" on hand (used fuel plus depleted uranium), there is enough fuel from that alone for about 10,000 years, without mining, milling, refining, or enriching any new uranium.

If all current U.S. electric generating capacity were replaced with IFRs, about 450 tonnes of makeup fuel would be needed per year, that is, there is enough fuel for about 2,000 years. If the entire energy economy were powered by IFR about 1,700 tonnes per year would be needed; that is, there is enough fuel from current LWR "waste" alone for almost 530 years. Is it really "waste?"

Uranium is four times more common than tin, and ten times more common than silver. Currently known reserves of uranium in ore of current commercial grade contain about five million tonnes of the metal.[c] That is, enough for about 4,300 years if used in 90 GWe capacity of U.S. LWRs, or about 4,800 years if all 1,700 GWe U.S. power demand were supplied by IFRs. Current total worldwide energy demand is about four times U.S. energy demand, so if the entire world were to be powered by IFRs, at current demand there is enough uranium, counting only known reserves profitably recoverable at \$138/kgU, for about 1,200 years.

The picture isn't so bleak, however, because the efficiency of use of uranium by IFRs means the fuel cost per kWh would be the same as for LWRs at \$138/0.006 ≈ \$23,000/kgU, or about 0.001¢/kWh. This makes it economically feasible to use lower grade ores, or more importantly to extract uranium from seawater, where there is estimated to be about 4.5 billion tonnes; this is enough for more than a million years of current worldwide energy demand. Even this, however, is a substantial under-estimate because uranium is continuously flowing into the oceans from rivers. That is, uranium alone is an essentially inexhaustible resource. Thorium, which could in principle serve as fertile future fuel, is four times more common than uranium, so even without river inflow, all current worldwide power needs could be supplied for about five million years using nuclear fission. Nuclear fission is an effectively inexhaustible energy resource.

Weapons proliferation

The "Integral" in IFR means that the entire system, including fuel reprocessing, is integrated in one facility. Actinides go into an IFR; none come out, except to start a new IFR. Opportunities for theft of partly-used

[a] We wouldn't replace LWRs prematurely because the IFR system functions symbiotically with the current fuel cycle.

[b] IFR fuel has to be ≈ 20% fissile (mainly PU-239) and 80% fertile (U-238). Once an IFR has been loaded it can generate its own fissile material from fertile material, so all it would need to keep running is one tonne of unenriched uranium per GWe-year.

[c] http://www.world-nuclear.org/info/inf75.html.

fuel would be reduced because it would not be transported to a separate facility for processing.

Unlike LWRs, an IFR power economy, once started, does not need its uranium fuel to be enriched in ^{235}U. This means that it is not necessary to have any facility to enrich uranium for other than military purposes. A reactor owner does need, however, either ironclad international guarantees of assured fuel supply, or the ability to reprocess partly used fuel.

The ability to reprocess fuel implies the presence of a cadre of professionals who are familiar with most of the techniques for making weapons-grade materials. The mixture of actinides taken out of IFR for reprocessing presents more difficult radiation, thermal, chemical, and metallurgical problems to would-be weaponeers than those taken from LWR. It is unsuitable for direct use in weapons, primarily because of the presence of ^{243}Am, ^{241}Pu, and non-fissionable ^{238}Pu, ^{240}Pu, and ^{242}Pu, but is admirably suited as IFR fuel. ^{241}Pu emits 50 times more heat, 5,000 times more neutrons, and 100 times more gamma radiation than ^{239}Pu. This could damage a weapon or cause predetonation, and makes maintenance of fine mechanical tolerances difficult. Expensive remote assembly is mandatory. Separating ^{239}Pu from nearby isotopes is more difficult than separating ^{238}U from ^{235}U, first because the mass difference is smaller, and second because synthesizing the gaseous compound PuF_6, needed for centrifugal or gas diffusion isotope separation, is difficult. Even though the problem of extracting weapons-grade materials from LWR is easier than for IFR, nobody has done so. Every nuclear weapons program has depended upon enriched uranium, or upon purpose-built reactors optimized to produce ^{239}Pu, and these have been nation-scale projects, not backyard garage-scale projects that a terrorist cell might successfully undertake. The simple conclusion is that used LWR fuel is just about the most difficult material from which to produce nuclear weapons [3]. A Lawrence Livermore National Laboratory study [10] concluded that spent IFR fuel cannot be used to make a nuclear weapon without significant further processing.

Even if the difficulties of producing weapons from used reactor fuel could be overcome, IFR presents no new problems of weapons proliferation because reprocessing and enrichment are not substantially different from the standpoint of international oversight. No country's desire or ability to produce nuclear weapons has ever been affected by any other country's decision to reprocess or not to reprocess used municipal reactor fuel. Every advanced industrial country could, in principle, produce nuclear weapons, independently of any other country's decision to reprocess or not to reprocess used municipal reactor fuel. If a country cannot be trusted with this technology, do not sell reactors or fuel reprocessing systems to them. The same long-distance transmission that would be required for solar power would serve their needs.

Costs

GE estimates their version of IFR, known as S-PRISM[a], can be built for about \$1.5-2/W, or \$2.2W after a 90% capacity factor is incorporated [11]. A GE/Hitachi consortium estimates they could produce IFR for \$1.2-1.4/W [3]. The Diablo Canyon generating station produces electricity for 5¢ per kWh. The Palo Verde station was constructed for \$1.79/W and produces electricity for 4.3¢ per kWh.

T. Boone Pickens proposed to build a 4 GWe wind farm. The estimated cost ballooned to \$3/W, or \$15/W after incorporating a 21% capacity factor [3]. The project was abandoned. The Sacramento Municipal Utility District (SMUD) reports a 15% capacity factor for solar photovoltaic. "No system with capacity factors this low is a viable energy producing system" [11]. After incorporating these capacity factors, the effective construction costs increase to \$4,000-\$8,500/kWe for wind, and \$16,000-\$60,000/kWe for solar. SMUD estimates a 69-year financial payback for solar photovoltaic.[b] Because wind and solar are diffuse sources, \$1.1-1.3 trillion would be needed for grid upgrades [3], adding another \$750/kWe to the construction cost. Because they are diffuse and erratic sources, additional costs for storage would be necessary.

In 2017, the lowest-price solar cells cost \$1.80 per peak watt. With 15% capacity factor, this is \$12 per average watt. Amortized over 25 years at 5%, and deducting the four-plus year energy payback, capital cost alone is 11.7¢ per kWh (18.1¢ at 10%). The GVEA 40 battery, in Fairbanks, Alaska is the largest utility-scale

[a] Super Power Reactor Inherently Safe Modular

[b] Lifetime is only 30–40 years. See http://www.osti.gov/bridge/servlets/purl/755637-oDWEJR/webviewable/755637.pdf or http://www.globalspec.com/LearnMore/Optics_Optical_Components/Optoelectronics/Photovoltaic_Cells.

storage battery. It weighs 1,200 tonnes, provides 10 MWh storage, and cost \$3.50/Wh. Amortized over five years, this is 5.7¢kWh[a]. To have constant output, the panel capacity needs to be twice the demand – half for immediate use and half to charge batteries, so the capital cost for cells plus storage is 29.1¢ per kWh. This does not include mounting, transportation, operation, maintenance, land, recycling, or grid upgrades. The equation used to calculate amortized cost is

$$A(n) = rA(n-1) - p$$

where $A(0)$ is the initial cost per watt, and $A(n)$ is the amount remaining to be paid after n payments of p dollars, at an interest rate of $100(r-1)\%$ per payment period. Solving this equation for $A(n)$, setting $A(n) = 0$, and solving for p gives

$$p = A(0)\, r^n \frac{r-1}{r^n - 1} .$$

The cost per watt hour is p/H where H is hours per payment period. If the payment period is one year, and power is provided continuously, H is 8766 (365.25×24). Because solar panels have a 4.5 year energy payback period, the final value needs to be multiplied by $n/(n-4.5)$, where n is years.

The following table compares construction costs for eight renewable sources [3]. Costs are per peak kWe, not average kWe. The capacity factor is not included.

Source	Cost \$/kWe	Source	Cost \$/kWe	Source	Cost \$/kWe	Source	Cost \$/kWe
Wind (onshore)	800	Wind (offshore)	1,700	Hydro	2,000	Geothermal	2,100
Biomass	2,300	Solar (thermal)	2,400	Tidal	2,800	Solar (PV)	5,900

The following table compares operating and construction costs for six electric power technologies [3], [12], [13]. External, grid upgrade, and storage costs are not included. Since 1981, nuclear power utilities have been paying 0.1¢/kWh into the Federal Nuclear Waste Fund, so LWR decommissioning and "waste" handling costs are included as internal costs.

Fuel	Operating Cost ¢/kWh	Construction Cost \$/kWe	Average Capacity Factor	Effective Construction Cost \$/kWe†	Life (yrs)	Delivered ¢/kWh‡	Federal Subsidy ¢/kWh*
LWR Nuclear	4.9	1,000-2,000	> 90%	1,111-2,222	50	5.15–5.41	0.210
Coal	6.0-6.3	1,000-1,500	> 90%	1,111-1,667	50	6.25–6.68	0.056
Hydro	4.0-8.0	2,000	≈ 33%	6000	100	4.69–8.69	0.136
Gas	7.6-9.2	400-800	> 90%	444-888	30	7.77–9.54	0.060
Wind	4.9-10.0	1,000-2,000	≈ 21%	4,762-9,524	20	7.62–15.43	3.533
Solar PV	15.0-30.0	6,000-9,000	≈ 15%	40,000-60,000	30	30.21–52.82	23.131

†Construction cost / capacity factor.
‡Operating cost + construction cost / (capacity factor × lifetime). Amortization not included.
*http://www.eia.gov/analysis/requests/subsidy/, tables ES4 and ES5, for 2013

Particulate emissions alone from coal-fired power plants cost \$165 billion [3], and cause 30,100 premature deaths, 603,000 asthma attacks, and 5,130,000 lost work days, per year in the United States alone [14].

Nuclear power has the lowest delivered costs in ten of twelve countries studied [15] (India, China and Russia were not included). The two that did not have the lowest costs were the United States and Korea. The report did not address the significant costs in the United States of protracted litigation and continuously revised regulations, and slow licensing of individual reactors. It would be helpful if the Nuclear Regulatory Commission were to adopt the French system of licensing reactor designs instead of individual reactors. IFRs

[a]Prof. Nate Lewis, in a private seminar **Where will we get our energy?** at Caltech Jet Propulsion Laboratory estimated 40-50¢/kWh

would be less expensive to build and operate than current technology because they are simpler standardized designs instead of complicated one-off designs [3]. The system is further substantially simplified because the coolant operates at atmospheric pressure instead of 160 atmospheres, and it absorbs essentially all neutrons that escape the core, so special alloys and over-designing are not needed to compensate for containment vessel embrittlement caused by neutron damage, and there are much fewer radioactive structural neutron activation products.

When external costs are included, nuclear costs are estimated [16] to be about one tenth as much as coal. CO_2 emissions are explicitly excluded from costs of fossil-fuel systems. Nuclear utilities have been paying 0.1¢/kWh into the Federal Waste Disposal Fund since 1981 for used nuclear fuel disposal and reactor decommissioning; these costs are included as internal costs for LWR. The radiological cost of mining is included, but for IFR that would be irrelevant, since there is already enough uranium above ground for several centuries. For IFR, fuel would be cheaper than free for a few hundred years, because it would consume the LWR "waste" of which we are desperately eager to be rid, and disposal of IFR waste would be far less expensive than disposal of 5%-used LWR fuel, so IFR must have much lower than one tenth the operating cost of coal.

The United States has already invested $8 Billion in the Yucca Mountain repository. It is estimated to cost $43.6 Billion to complete [3], and current waste would require about 8-10 times more capacity than Yucca Mountain would have at completion. IFR would make Yucca Mountain irrelevant, and is even more important now that the Obama administration has canceled Yucca Mountain. Why is the Nevada Congressional delegation not insisting that the IFR demonstration project be restarted?

Tony Blair's government commissioned a study by Sir Nicholas Stern, former vice president and chief economist for the World Bank. He recommended committing 1% of global GDP to reduce CO_2 emissions to 25%-70% below current levels by mid century, and that increased extreme weather costs alone could reach 1% of GDP [3]. For the United States, that amount of today's GDP would be $290 billion per year. In the next section, we estimate that producing an energy economy entirely powered by IFR could be accomplished in fewer than 65 years. Spending $290 billion per year on CO_2 remediation during that interval would cost $18.8 trillion (in today's dollars). At $2.2B/GWe for IFR, 1.7 TWe would cost $3.74 trillion[a] – 20% as much – and would essentially eliminate CO_2 emissions, not reduce them by 25%-70%.

What can be done

As admirable as they are, conservation, biofuels, wind, geothermal, tides, waves, ocean currents, and hydro, alone or together, cannot power any economy, nor can they destroy the 59,160 tonnes of "waste" from the first 53 years of U.S. LWR operations, and more accumulated since 2006. Wind and solar are much more expensive than IFR. There are no good hydro sites that have been exploited. A 2017 study [17] concluded that a 100% renewable-electricity system might not be physically feasible, let alone economically viable. Coal is terrible (and more expensive as well). Natural gas is more benign than coal, but still produces CO_2. Oil produces CO_2, and importing it and protecting access to overseas sources is expensive in both blood and national treasure. Solar is much more expensive than IFR, and wouldn't destroy waste. That leaves IFR as the only alternative that is both sufficient and economically viable.

There are no serious plans for electric airplanes, ships, or heavy construction or farm equipment, so some liquid hydrocarbon fuels will be needed for the foreseeable future. Hydrogen is at present a nonstarter because of the storage problem. Fortunately, we know how to make hydrocarbon fuels from energy + water + CO_2.[b] Using such fuels, or hydrogen if the storage problem is solved (or maybe boron [3]), it is possible, therefore, to convert the entire U.S. energy economy to electricity, provided mostly by IFR, with hydro, wind, solar, geothermal, or biofuels where appropriate.

The current U.S. economy could be powered by about 1.7 TWe. Each 1 GWe reactor needs 8–10 tonnes of startup fissile material, which would, at first, largely be actinides from used LWR fuel, and plutonium and enriched uranium from decommissioned weapons. The current U.S. inventory of fissionable actinides is

[a] GE/Hitachi estimates $2.1-2.4 trillion – 11-13% of $18.8 trillion.

[b] The Fischer-Tropsch process.

about 900 tonnes, plus about 225 tonnes of weapons-grade ^{235}U,[a] or enough to start up only about 110-140 GWe of capacity using IFR. With breeding, that IFR fleet could have a sustained growth rate of 5% per year, or maybe more. After startup, the deployment rate would gradually accelerate from 5–7 per year, helped along by actinides from still-operating LWRs, and reach the desired 1.7 TWe goal within about 40–50 years, or sooner to the extent renewable sources are appropriate, or if uranium enrichment is continued.

A single complete and permanent solution to all energy, pollution, nuclear waste, and CO_2 emission problems is within our grasp. All obstacles to that solution are political, abetted and perpetuated by ignorance, intentional falsehoods, irrational hysteria, and opportunistic demagoguery, not scientific, technological or engineering problems. Competition for energy resources is frequently blamed for wars. IFR would eliminate that excuse.

Fast breeder reactors with fuel recycling will be developed. There is no credible alternative. There is an 800 MWe reactor in service in Russia[b] and a 1200 MWe reactor is under development. China has contracted to buy a BN-800 reactor from Russia. South Korea has announced a 400 GWe fast-neutron reactor will be available for sale in 2020. India is building a prototype fast-neutron reactor to exploit their vast reserves of thorium. China and Japan are making progress on their own designs. American experts are retiring or dying far faster then younger ones are being prepared. The United States will soon be a third-world country in energy technology.

Should the United States spend \$18.8 trillion on CO_2 reduction and mitigation, \$10.75 trillion on coal soot damage, \$68–102 trillion on solar cells, \$25 trillion on wind turbines, \$4.75 trillion on grid upgrades – about \$130−170 trillion altogether (and none of those would destroy one gram of nuclear waste), and suffer 2 million unnecessary deaths due to coal emissions, or spend \$2.4 trillion on IFR (and render all nuclear waste harmless)?

For me the answer is obvious. There is no time to waste. We really ought to get started.

Acknowledgment

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Appendix – Fission product yields from light-water reactors

See http://en.wikipedia.org/wiki/Fission_product_yield. Sorted by half life.

Number fraction†	Isotope decay path and half life	Mass per GWe-year	Comment
2.8336%	$^{131}\mathrm{I} \xrightarrow{8.02d} {}^{131}\mathrm{Xe}$	31.50 kg	Reduced by 1.95×10^{-14} per year – 0.6 ng after one year.
55.4478%	Various < 1y	541.1 kg*	Decay to stable products.
0.3912%	$^{106}\mathrm{Ru} \xrightarrow{373.6d} {}^{106}\mathrm{Rh}$	3.519 kg	
≈ 0.35%	$^{134}\mathrm{Cs} \xrightarrow{2.065y} {}^{134}\mathrm{Ba}$	3.980 kg	Created in the reactor from ^{133}Cs by neutron capture.
2.2713%	$^{147}\mathrm{Pm} \xrightarrow{2.62y} {}^{147}\mathrm{Sm}$	28.33 kg	
0.0297%	$^{125}\mathrm{Sb} \xrightarrow{2.76y} {}^{125}\mathrm{Te}$	315 g	
<0.0330%	$^{155}\mathrm{Eu} \xrightarrow{4.76y} {}^{155}\mathrm{Gd}$	434 g	Mostly destroyed by neutron capture in the reactor.
0.2717%	$^{85}\mathrm{Kr} \xrightarrow{10.78y} {}^{85}\mathrm{Rb}$	1.960 kg	Currently released to the atmosphere.
<0.0003%	$^{113m}\mathrm{Cd} \xrightarrow{14.1y} {}^{113m}\mathrm{In}$	2.88 g	Mostly destroyed by neutron capture in the reactor.
5.7518%	$^{90}\mathrm{Sr} \xrightarrow{28.9y} {}^{90}\mathrm{Y} \xrightarrow{3.19h} {}^{90}\mathrm{Zr}$	43.93 kg	Principal medium-term radiation and heat source.
6.0899%	$^{137}\mathrm{Cs} \xrightarrow{30.08y} {}^{137}\mathrm{Ba}$	70.80 kg	Principal medium-term radiation and heat source.
<0.4203%	$^{151}\mathrm{Sm} \xrightarrow{90y} {}^{151}\mathrm{Eu} \xrightarrow{1e18y} {}^{147}\mathrm{Pm} \xrightarrow{2.62y} {}^{147}\mathrm{Sm} \xrightarrow{1e11y} {}^{143}\mathrm{Nd}$	5.385 kg	Mostly destroyed by neutron capture in the reactor. ^{151}Eu is essentially stable.
6.0507%	$^{99}\mathrm{Tc} \xrightarrow{211ky} {}^{99}\mathrm{Ru}$	50.83 kg	Dominant radiation source among fission products in the range of $10^4 \rightarrow 10^6$ years; candidate for transmutation to $^{100}\mathrm{Tc} \xrightarrow{15.46s} {}^{100}\mathrm{Ru}$.
0.0236%	$^{126}\mathrm{Sn} \xrightarrow{230ky} {}^{126}\mathrm{Sb} \xrightarrow{12.35d} {}^{126}\mathrm{Te}$	252 g	
0.0508%	$^{79}\mathrm{Se} \xrightarrow{295ky} {}^{79}\mathrm{Br}$	341 g	
6.2856%	$^{93}\mathrm{Zr} \xrightarrow{1.53my} {}^{93}\mathrm{Nb}$	49.60 kg	
<6.3333%	$^{135}\mathrm{Cs} \xrightarrow{2.3my} {}^{135}\mathrm{Ba}$	72.55 kg	
0.1629%	$^{107}\mathrm{Pd} \xrightarrow{6.5my} {}^{107}\mathrm{Ag}$	1.479 kg	
0.6576%	$^{129}\mathrm{I} \xrightarrow{15.7my} {}^{129}\mathrm{Xe}$	7.198 kg	Candidate for transmutation to $^{130}\mathrm{I} \xrightarrow{12.36h} {}^{130}\mathrm{Xe}$.
≈ 6.44%	^{133}Cs stable	72.68 kg	A few percent converted by neutron capture to ^{134}Cs.
<1.0888%	^{149}Sm stable	13.77 kg	
<0.0065%	^{157}Gd stable	86.59 g	

†The number fraction is the fraction of the atoms of fission products that are the specified isotope, not the mass fraction. The mass is computed by multiplying the number fraction by the atomic mass, and normalizing the total to one tonne per GWe-year.

*Assumes average mass number of 115.

Thermal neutron transmutation of ^{90}Sr, ^{137}Cs, ^{126}Sn, ^{79}Se, ^{93}Zr, ^{135}Cs and ^{107}Pd is not practical due to low neutron absorption cross section at the neutron temperature in LWRs.

The amount of an isotope at a particular time can be calculated by solving the differential equation

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = k - \frac{\ln 2}{\tau} N(t)$$

where $N(t)$ is the amount at time t in years, k is the production rate per year, and τ is the half-life in years. The solution (assuming $N(0) = 0$) is

$$N(t) = \frac{\tau k}{\ln 2}\left(1 - 2^{-t/\tau}\right) .$$

From this, when $t >> \tau$, the amount of each radioactive fission product, is exponentially asymptotic to a constant, approximately $\tau k/\ln 2$: decay compensates for production. The amount of these materials is proportional to the power capacity, not the total amount of energy produced. If stable decay products are continuously removed, the size of the repository is roughly constant.

The following table shows asymptotic fractions and asymptotic masses per GWe (not GWe-year) of short and medium half-life fission products. The fraction is measured in terms of the annual number of fission product atoms, which is twice the number of actinide atoms consumed.

Asymptotic number fraction and mass per GWe

Isotope	Fraction	Mass kg	Isotope	Fraction	Mass kg
$^{137}\mathrm{Cs} \xrightarrow{30.08\mathrm{y}} {}^{137}\mathrm{Ba}$	264.3%	3,072*	$^{90}\mathrm{Sr} \xrightarrow{28.9\mathrm{y}} {}^{90}\mathrm{Y} \xrightarrow{2.671\mathrm{d}} {}^{90}\mathrm{Zr}$	239.8%	1,831
Various $\tau < 1$y	79.99%	<780.6†	$^{147}\mathrm{Pm} \xrightarrow{2.62\mathrm{y}} {}^{147}\mathrm{Sm}$	8.5852%	107.1
$^{85}\mathrm{Kr} \xrightarrow{10.78\mathrm{y}} {}^{85}\mathrm{Rb}$	4.226%	30.48‡	$^{134}\mathrm{Cs} \xrightarrow{2.065\mathrm{y}} {}^{134}\mathrm{Ba}$	1.043%	11.85*
$^{106}\mathrm{Ru} \xrightarrow{373.6\mathrm{d}} {}^{106}\mathrm{Rh}$	0.5773%	5.192	$^{155}\mathrm{Eu} \xrightarrow{4.76\mathrm{y}} {}^{155}\mathrm{Gd}$	0.2266%	2.981
$^{125}\mathrm{Sb} \xrightarrow{2.76\mathrm{y}} {}^{125}\mathrm{Te}$	0.1183%	1.254	$^{131}\mathrm{I} \xrightarrow{8.02\mathrm{d}} {}^{131}\mathrm{Xe}$	0.0898%	0.998

*Assumes isotope separation of ^{133}Cs, ^{134}Cs, ^{135}Cs, and ^{137}Cs. Total caesium accumulates at 220 kg/GWe-yr.
†The unclassified components are assumed to have an average mass number of 115, and to have a one year half life. Since they are a mixture of products with half lives under one year, the true asymptotic fraction and mass are less.
‡ ^{85}Kr is currently vented to the atmosphere.

The total mass of these products exponentially approaches an asymptote of less than 5,844 kg per GWe, or 9,934 tonnes for a 1.7 TWe economy. If their decay products are continuously removed, storage is not a problem. If not reprocessed, they are diluted by their decay products and therefore their specific activity declines sufficiently that they are not radioactively dangerous after 200–300 years, but the volume is proportional to kt, not k. In 200 years of a 1.7 TWe economy the amount is less than 250,000 tonnes, less than 130,000 cubic yards, or less than 44 feet deep on a football field. Separating the streams according to half life reduces the 200-year stream by 85%.

For long-lived isotopes, i.e., $t << \tau$, on a human time scale decay does not compensate for production. Approximating $2^{-t/\tau} = \exp(-t \ln 2/\tau) \approx 1 - t \ln 2/\tau$, the solution is $N(t) \approx kt$, as expected. The amount of these fission products is in proportion to the total amount of energy produced, not the power capacity.

Long-lived isotopes accumulate at the rate of about 182 kg per GWe-year, or about 309 tonnes per year for a 1.7 TWe economy. ^{99}Tc and ^{129}I can be destroyed by transmutation, but the others, amounting to about 124 kg per GWe-year, are impractical to destroy by transmutation. If other isotopes of caesium (about 147 kg per GWe-year) are not separated from ^{135}Cs, the total long-term disposal stream increases to 271 kg per GWe-year (but its specific activity decreases). If stored for about 30 years before disposal, about 35 kg per GWe-year of ^{137}Cs will decay, leaving about 235 kg per GWe-year, or about 400 tonnes per year for a 1.7 TWe economy, if the resulting stable ^{137}Ba were removed. Surely disposal of 400 tonnes per year of these isotopes would not be a problem.

Value of one tonne of used LWR fuel
separated and reduced to metal

Substance	Mass (gr.)	Value $/gr	Value $/tonne of waste	Radioactivity (Mev/Bq-s) α	β	γ	Half life (years)	Heat W/gr
^{238}U	944,100	0.143	135,006	4.2		0.496	4.47×10^{9}	
^{236}U	3,971	0.143	568	4.5		0.494	2.34×10^{7}	
^{235}U	7,974	0.143	1,140	4.4		0.657	704	
^{234}U	225	0.143	32	4.8		0.0532	2.45×10^{5}	
^{237}Np	503	0.143	72	4.7		0.0294	2.14×10^{6}	
^{242}Pu	454	0.143	65	4.8		0.0449	3.76×10^{5}	
^{241}Pu	111	0.143	16	4.9		0.1485	14.35	
^{240}Pu	2,302	0.143	329	5.2		0.5424	6.56×10^{3}	
^{239}Pu	5,025	0.143	719	5.2		0.0516	2.41×10^{4}	
^{238}Pu	95	0.143	14	5.5		0.0435	87.74	1.56
^{241}Am	1,084	0.143	155	5.5		0.0595	432	
^{243}Am	85	0.143	12	5.3		0.0747	7.37	
^{244}Cm	4	0.143	1	5.8		0.0428	18.11	2.44
Actinides	965,933	0.143	138,129					
^{96}Zr	798	3.05	2,434				Stable	
^{94}Zr	741	3.05	2,260				Stable	
^{93}Zr	718	3.05	2,190		0.010	0.0305	1.61×10^{6}	
^{92}Zr	639	3.05	1,948				Stable	
^{91}Zr	590	3.05	1,799				Stable	
^{90}Zr	391	3.05	1,192				Stable	
Fuel cladding	3,877	3.05	11,822					
^{99}Tc for alloys	771	10.00	7,710		0.0846	weak	2.111×10^{5}	
^{90}Sr	391	2.00	782		0.1958		29	0.93
^{88}Sr	350	2.00	700				Stable	
^{137}Cs	377	2.00	754		0.187	0.479	30.17	0.42
^{135}Cs	300	2.00	600		0.0757	0.662	2.3×10^{6}	
^{133}Cs	1,125	2.00	2,250				Stable	
Heat sources	2,543	2.00	5,086					
Br	22	1.00	22				Stable	
Mo	3,345	0.257	860				Stable	
Ru	2,177	45.78	99,663				Stable	
Ag	76	2.00	152				Stable	
Cd	108	2.00	216				Stable	
Ba	2,311	0.560	1,295				Stable	
Tb	2.6	30.00	78				Stable	
Dy	1.4	5.00	7				Stable	
Rh	467	500.00	233,500				Stable	
^{87}Rb	365	11.78	4,300		0.0817		4.81×10^{10}	
^{123}Te	485	1.39	675		?		$> 9.2\times10^{16}$	
^{138}La	1,215	1.80	2,187		0.0329	1.44	1.02×10^{11}	
^{144}Nd	3,488	2.20	7,673	1.90			2.29×10^{15}	
^{115}In	2.6	10.00	26		0.1532		4.41×10^{14}	

(cont.)

Value of one tonne of used LWR fuel
separated and reduced to metal (cont.)

Substance	Mass (gr.)	Value $/gr	Value $/tonne of waste	Radioactivity (Mev/Bq-s) α	β	γ	Half life (years)	Heat W/gr
^{142}Ce	2,355	0.28	662	1.5?			$> 5.0 \times 10^{16}$	
^{152}Gd	142	5.48	778	2.15			$1.4{\times}10^{15}$	
^{147}Sm	200	2.00	400	2.25			$1.06{\times}10^{11}$	
^{148}Sm	167	2.00	334	1.9323			$7.0{\times}10^{15}$	
^{149}Sm	2.4	2.00	5				Stable	
^{151}Sm	8.8	2.00	17		0.0196	0.0216	90	
^{152}Sm + ^{154}Sm	419	2.00	838				Stable	
^{107}Pd	1,371	82.94	113,710		0.0093	0.1476	$6.5{\times}10^{6}$	
^{90}Y	456	10.00	4,560		0.9336	weak	64 hr	
^{152}Eu	0.35	60.00	21		0.0831	0.122	13.4	
^{154}Eu	109.5	60.00	6,570		0.221	0.123	8.601	
^{155}Eu	0.16	60.00	9		0.047	0.087	4.753	
Other solid	19,297		478,558					
^{3}H	0.0034	294,117	1,000		0.0156		12.5	
^{4}He	2.89	1.73	5				Stable	
^{85}Kr	308	2.00	616		0.687	0.514	10.72	
Xe	5,332	1.70	9,050				Stable	
Gases	5,643		10,671					
Total fission products	32,131	16.00	513,937					
Not counted	1,936							
Total	1,000,000	0.65	652,066					

http://brc.gov/e-mails/August10/Commercial Value of 1 Metric ton of used fuel.pdf with radioactivity data from http://www.nndc.bnl.gov/chart

Actinides can be recycled as fuel.

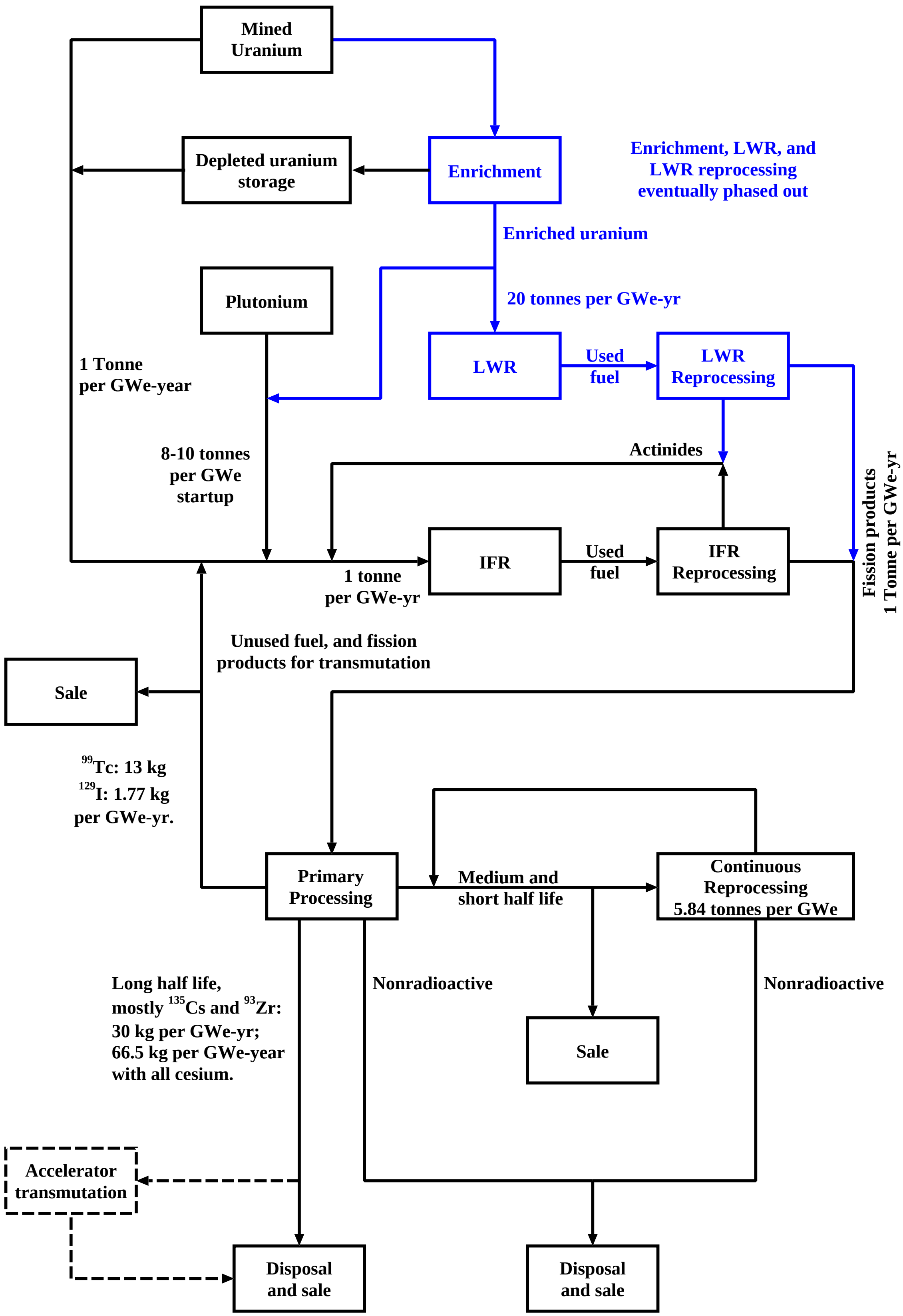
Zirconium from fuel pin alloys and cladding, and fission products, can be recycled into new fuel pin cladding and alloys.

Some radioactive elements produce sufficient heat to be usable as energy sources, for example in radioisotope thermal generators for space applications. These would not be isotopically separated. ^{90}Sr is 53% of the total strontium in fission products, so heat production for all strontium is 0.49 W/gr. ^{137}Cs is 21% of the total caesium in fission products, so heat production for all caesium is 0.088 W/gr.

Technetium is valuable for alloying with rhenium, and has medical applications.

Gases would be separated first, then actinides, then highly radioactive products. This would reduce the cost of separating and reducing the stable and less radioactive products.

Appendix – Fuel and waste cycles



Appendix – Partitioning and Transmutation

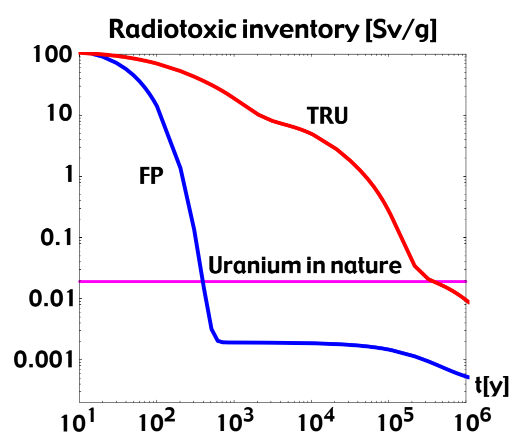
Medium- and long-lived fission products could in principle be destroyed, by transmuting them to isotopes that are stable or have short half lives, which decay to stable isotopes.

The following table[a] shows that ^{99}Tc, ^{129}I, ^{93}Zr, ^{107}Pd and ^{135}Cs, can be transmuted much faster than their natural decay (i.e., $T^J_{\text{trans}} << T^J_{1/2}$). The radiotoxicity of ^{107}Pd and ^{135}Cs is so small it is not worth the bother to transmute them. ^{93}Zr can be recycled into fuel pin cladding or fuel alloying. If ^{99}Tc and ^{129}I were destroyed, there could be very few remaining objections to nuclear power. For ^{90}Sr and ^{137}Cs, $T^J_{\text{trans}} >> T^J_{1/2}$, so transmuting them is not interesting. They are biologically active, but can simply be stored for about six half lives (180 years), after which the remaining amounts (0.69 and 1.1 kg/GWe-yr) can be discarded or sold. If they are initially deposited in "deep geological" storage, the containment duration requirement for the repositories is significantly shorter, by a factor of 1,500, than for used LWR fuel. For ^{79}Se and ^{126}Sn, $T^J_{\text{trans}} << T^J_{1/2}$, but T^J_{trans} is not sufficiently small to be interesting. Although the radiotoxicity per gram of ^{126}Sn and ^{79}Se is large, they are produced in such small amounts that their total radiotoxicity per GWe-yr is comparable to that of the others.

Isotope J decay mode and $T^J_{1/2}$	Radiotoxicity		$\sigma^J_{(n,\gamma)}$ (barns)		T^J_{trans} (years)		Mass per GWe-yr	Transmuted decay mode
	Sv/g	Sv/GWe-yr	Thermal	Fast	Thermal	Fast		
$^{90}\text{Sr}\xrightarrow{28.9\text{y}}{}^{90}\text{Y}$	141.1k	1.664M	.014	0.01	1,600	2,200	11.79 kg	$^{91}\text{Sr}\xrightarrow{9.63\text{h}}{}^{91}\text{Y}$
$^{137}\text{Cs}\xrightarrow{30.08\text{y}}{}^{137}\text{Ba}$	41.87k	1.152M	0.02	0.01	11,000	2,200	27.52 kg	$^{138}\text{Cs}\xrightarrow{33.41\text{m}}{}^{138}\text{Ba}$
$^{99}\text{Tc}\xrightarrow{211\text{ky}}{}^{99}\text{Ru}$	0.4	8.708	4.3	0.2	51	110	21.77 kg	$^{100}\text{Tc}\xrightarrow{15.46\text{s}}{}^{100}\text{Ru}$
$^{126}\text{Sn}\xrightarrow{230\text{ky}}{}^{126}\text{Sb}$	4.936	4.019	0.05	0.005	4,400	4,400	0.814 kg	$^{127}\text{Sn}\xrightarrow{2.1\text{h}}{}^{127}\text{Sb}$
$^{79}\text{Se}\xrightarrow{295\text{ky}}{}^{79}\text{Br}$	7.478	1,271	0.1	0.03	2,200	7,300	0.170 kg	^{80}Se is stable
$^{93}\text{Zr}\xrightarrow{1.53\text{my}}{}^{93}\text{Nb}$	0.102	2.097	0.28	0.03	790	730	20.56 kg	^{94}Zr is stable
$^{135}\text{Cs}\xrightarrow{2.3\text{my}}{}^{135}\text{Ba}$	0.085	1.009	1.3	0.07	170	310	11.87 kg	$^{136}\text{Cs}\xrightarrow{13.04\text{d}}{}^{136}\text{Ba}$
$^{107}\text{Pd}\xrightarrow{6.5\text{my}}{}^{107}\text{Ag}$	0.0007	8.309	0.3	0.5	730	44	6.922 kg	^{108}Pd is stable
$^{129}\text{I}\xrightarrow{15.7\text{my}}{}^{129}\text{Xe}$	0.718	4.921	4.3	0.14	51	160	8.853 kg	$^{130}\text{I}\xrightarrow{12.36\text{h}}{}^{130}\text{Xe}$

T^J_{trans} is the transmutation half-time for isotope J.
Amounts and radioactivity from ORIGEN 2.2. Radiotoxicity dose factors from ICRP publication 119.

This graph from the Swedish Radiation Safety Authority[b][29] shows that most of the radiotoxicity of used nuclear fuel arises from the transuranics, which IFR would consume, and that the radiotoxicity of fission products is below the radiotoxicity of uranium ore within 200-300 years. Transmuting ^{99}Tc and ^{129}I would reduce the long-term tail of the fission product radiotoxicity from 300 years onward by 60%. The ordinate is radiotoxicity per gram *of the original fission products*, not the remaining fission products at the time specified by the abscissa. Fission products are stored together; stable ones are not continuously separated from radioactive ones.



[a]Data from http://users.ictp.it/~pub_off/lectures/lns005/Number_2/Slessarev_1.pdf
[b]http://www.stralsakerhetsmyndigheten.se/Global/Publikationer/Tidskrift/Nucleus/2007/Nucleus-4-2007.pdf

Appendix – Worldwide limitations of alternative energy sources

Details in http://www.physics.ucsd.edu/~tmurphy/phys239/shu_energy.pdf by Dr. Frank Shu.

Solar photovoltaic

Solar photovoltaic could in principle supply 15 TWe, enough to power the Earth's entire current energy economy, using about 0.2% of the land area of the Earth below 60° latitude.

Wind

Land-based wind cannot supply more than about 1.8 TWe, or about 12% of the current energy economy.

Ocean currents

The Kuroshio current, which flows northward in the western Pacific past Taiwan and Japan, has a power of about 100 GW. Assuming 50% efficiency of extraction allows about 50 GWe to be extracted. The gulf stream flows twice as fast, producing eight times as much power, allowing about 400 GWe to be extracted. Extracting significant power from ocean currents, anywhere in the world, would have profound effects on climate.

Coastal ocean waves

Assuming 50% efficiency of energy extraction, ocean waves impinging on all the shorelines of the Earth could provide about 0.24 TWe, or about 1.6% of the current energy economy.

Geothermal

Geothermal sources cannot provide more than about 0.4 TWe, or about 2.7% of the current energy economy.

Tides

Energy extractable from tidal sources amounts to about 3 GWe worldwide, or about 0.02% of the current energy economy. It is only economically feasible in bays, such as the Bay of Fundy, which concentrate tides to heights of as much as 5 meters. Damming such bays has effects on the resonant frequency of nearby bays and estuaries, profoundly altering currents and tides in nearby areas.

Hydroelectric

The Earth's land area is 148×10^{12} m^2. Average rainfall is 1.2 meters per year. Water density is 10^3 kg/m^3. Total rainfall is thus about 1.8×10^{17} kg. Dropping 100 meters releases 1.8×10^{17} kg $\times$ 9.8 m/s^2 $\times$ 100 m = 1.76×10^{20} joule. Spread out over a year, 3.15×10^7 s, gives 5.6 TW. Assuming 90% efficiency yields 5 TWe. The total available is less, perhaps 3.5 TWe, if polar regions are excluded. Hydroelectric installations observe about 30% capacity factor, yielding total worldwide availability of about 1 TWe-yr/yr, or about 6.7% of the current energy economy.

Total

Excluding solar photovoltaic and ocean currents, alternative electricity sources could yield about 3.443 TWe worldwide, or about 23% of the current energy economy.

