The Case for Nuclear Energy

R. Edward Craig, BS, MS, PE (Retired)

Viewpoint As the world's awareness of the threat of climate change grows and as people become more concerned over the environmental degradation caused by burning fossil fuels, more attention is being paid to nuclear-energy technology as a means of addressing both problems. Countries that depend on fuel imports are also viewing nuclear energy as a means of stabilizing their energy supplies and costs.

As a consequence, political groups that oppose nuclear energy are having to pose objections to it in order to persuade the public away from this potent energy solution. Discussions of these opponents' political motives and psychological inclinations are outside the scope of this paper. Instead, the paper will focus on factual information. In all cases, the information presented is the most authoritative the author was able to find.

The information presented here pertains specifically to conditions in the United States. Although the general considerations will apply to other countries, the author does not presume to know those countries' specific conditions or to offer advice.

Contents Page

Part 5. Safety

Part 7. Alternatives

Appendix B. Energy Storage

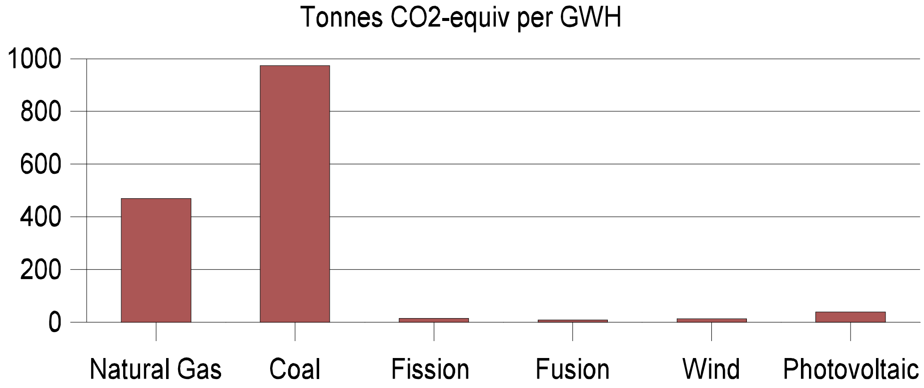
Part 1: Greenhouse-Gas Emissions

Emissions Comparisons

The most extensive study done on greenhouse-gas emissions was conducted at the University of Wisconsin in 2002. It is the only study that can be considered comprehensive and objective. Comparing the life-cycle CO2 emissions, which includes all the construction, mining, transport, manufacturing, fuel-processing, and decommissioning effects, the study's results are as follows [31]:

Tonnes CO2-equiv per GWH

Natural Gas	469
Coal	974
Fission	15
Fusion	9
Wind	14
Photovoltaic	39

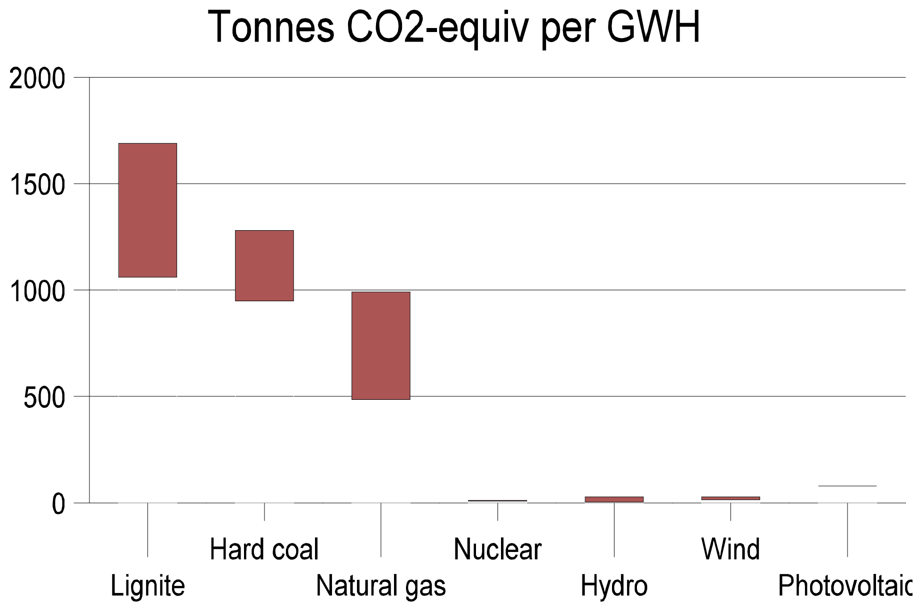


It is likely that the emissions from photovoltaic panels will drop due to higher efficiencies and improved manufacturing processes. The fairest conclusion that can be reached is that all the non-fossil energy sources are effective in avoiding greenhouse gases.

Similar studies have been done, which show virtually the same results. For example, a Swiss study showed the following [38]:

Tonnes CO2-equiv per GWH

Lignite	1060 - 1690
Hard coal	949 - 1280
Natural gas	485 - 991
Nuclear	8 - 11
Hydro	3 - 27
Wind	14 - 21
Photvoltaic	79



Anti-Nuclear Arguments

High-Grade vs. Low-Grade Ore

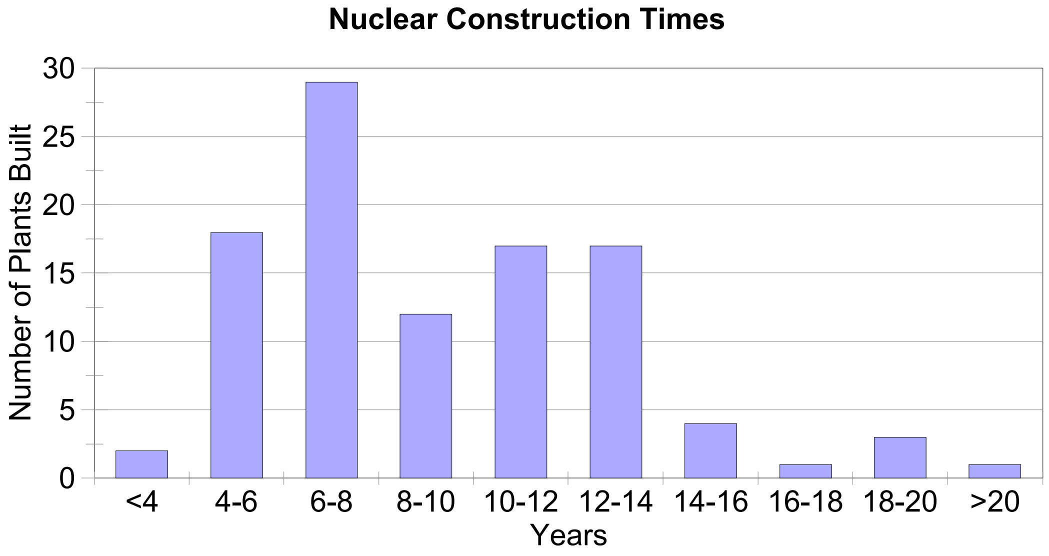
Opponents of nuclear energy have argued that the CO2 emissions from nuclear energy are much greater than those from renewable-energy sources. This argument is based on a study, known as Storm/Smith [33], which never was published in peer-reviewed literature and which is based on erroneous assumptions. In particular, the analysts assumed that all the uranium in the world has already been discovered. They also assumed that advanced reactors won't be used and, as a result, high-grade ores will be consumed in a few decades and so more CO2 will be emitted in mining and processing low-grade ores. As Part 3 of this paper shows, there are centuries' worth of high-grade ores. .

Indeed, new uranium deposits are found routinely. An example is a large deposit in Tanzania [34].

However, the Storm/Smith study does bring home the point that advanced reactors should be allowed to make steady progress to extend the supply of uranium.

Construction Times

Nuclear opponents argue that nuclear construction times are so long that they can't be built fast enough to forestall climate change. Actually, nuclear plants in the US have been built in less than four years. This is the breakdown of construction times:[54]



Since two of the plants were built in less than four years, clearly the long times for the others were caused by external factors. Whatever those factors were, this record shows that nuclear power plants can be built quickly if the regulatory conditions allow.

Another question that has to be addressed is the construction times for alternatives. Consider that commercial-size wind turbines currently being installed are rated at 1.5 MW. These are very large structures with rotor-tip heights of 450 feet that have to be spaced out at 50 acres each. Since their average output is less than 40% of their rating [47], it takes over 2500 of them to produce the same amount of electricity as one 1500 MW nuclear plant. The turbines would be spread over 200 square miles complete with maintenance roads, power lines, transformers, etc. The proposition that so many wind turbines could be installed faster than a nuclear power plant would be hard to defend.

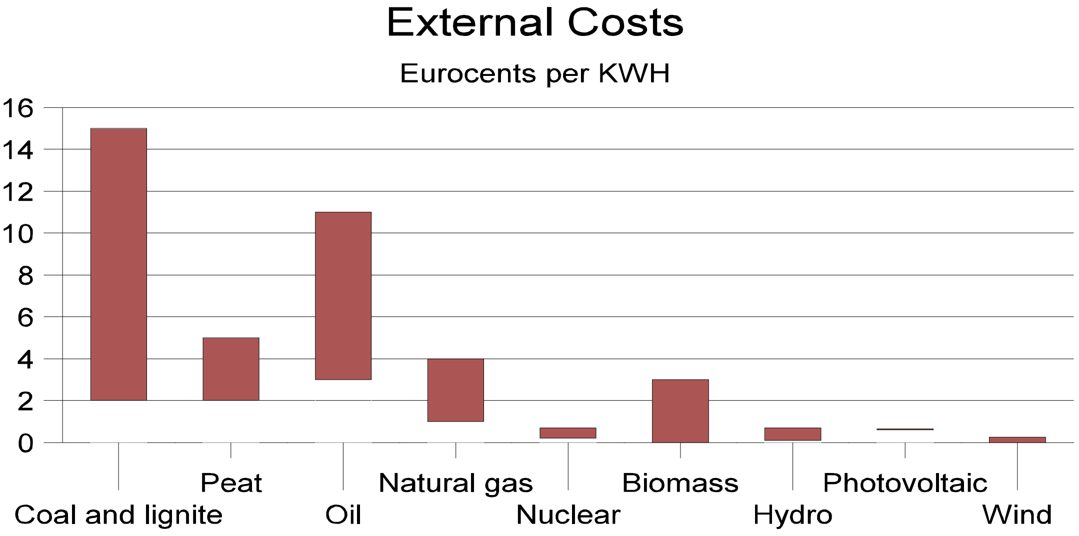
Part 2. Environmental Effects

External Costs

Comparing the environmental effects of energy sources always requires weighting the different effects. A widely-accepted method for comparing them is to calculate external costs in terms of monetary value. For that reason, calculated results should be considered approximate. Nonetheless, such results are the most practical comparison basis most people will accept.

The most comprehensive study done to date is from the European Commission, which determined external costs of energy sources in member countries. They include global warming, public health, occupational health, and material damage. The results in eurocents per KWH are as follows [32]:

Coal and lignite	2 - 15
Peat	2 - 5
Oil	3 - 11
Natural gas	1 - 4
Nuclear	0.2 - 0.7
Biomass	0 - 3
Hydro	0.1 - 0.7
Photovoltaic	0.6
Wind	0 - 0.25



As would be expected, natural gas has lower environmental effects than coal or oil. The non-fossil sources all have lower effects than the fossil fuels and are about equally effective in reducing environmental harm.

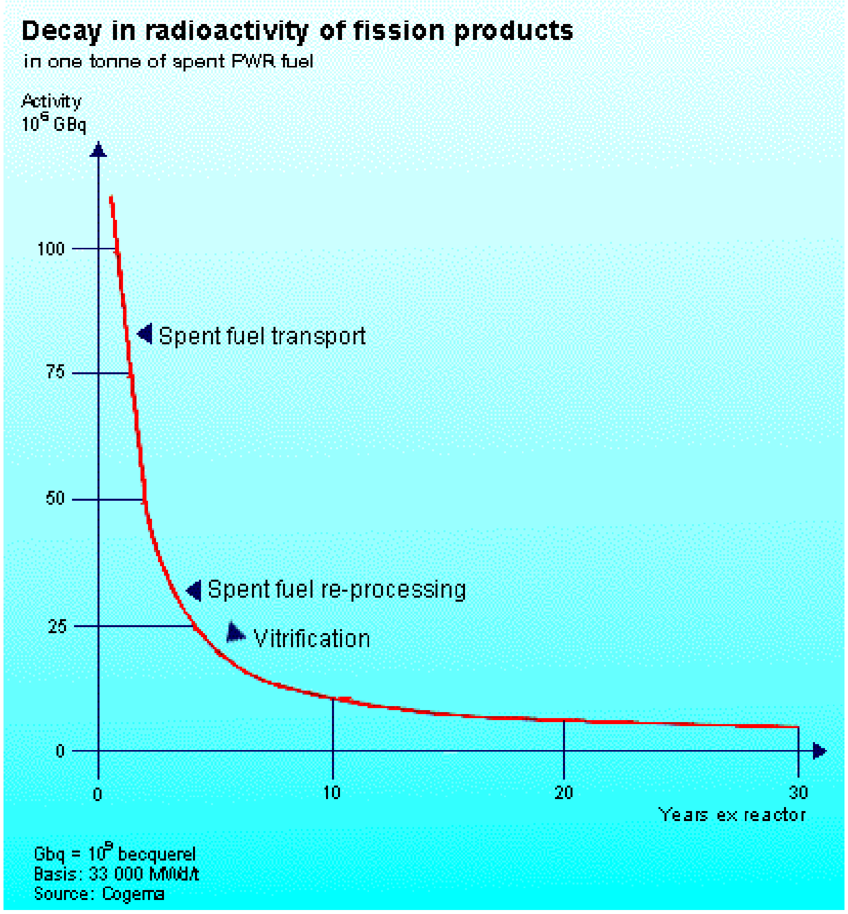
Anti-Nuclear Arguments

Spent Fuel and Waste

Opponents of nuclear energy argue that the waste from nuclear plants presents a high risk of environmental harm in the future. They point to certain constituents that last for very long times, even many thousands of years.

What they neglect to say is that the long-lived constituents give off a very small portion of the total radioactivity. Nearly all of the radioactivity comes from other constituents that decay away on much shorter time-scales. At one year, the radioactivity is 6% of what it was when the fuel was taken from the reactor and in 100 years it's 0.03%.[39]

Years after Removal	% Radioactivity
0	100
1	6
10	0.3
100	0.03



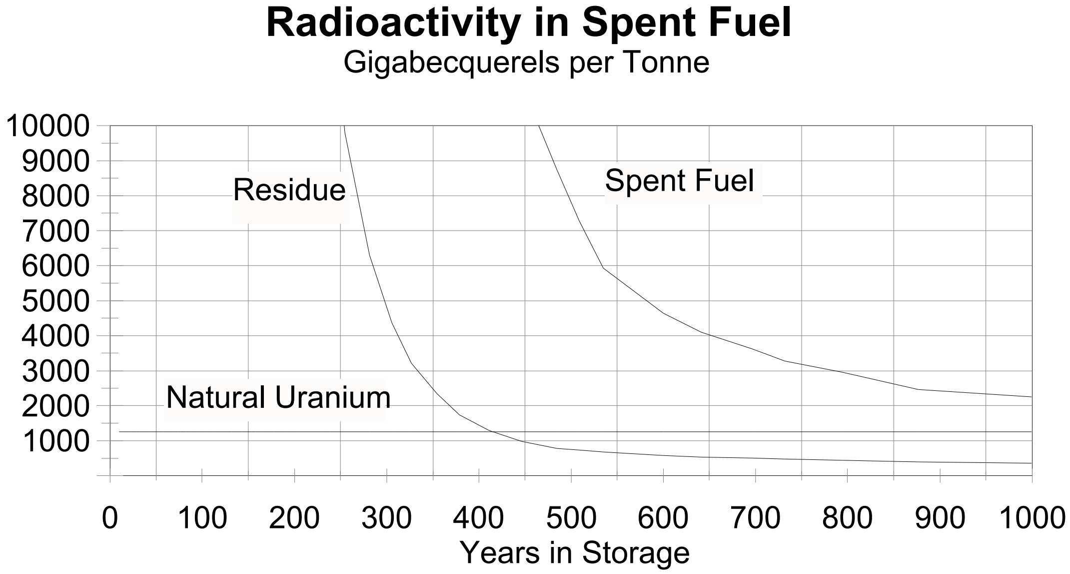
Decay in radioactivity of fission products

in one tonne of spent PWR fuel

Gbq = 10^9 becquerel
Basis: 33 000 MWd/t
Source: Cogema

Another thing nuclear opponents neglect to say is that no person has ever been harmed by spent fuel from nuclear power plants. The reason for this perfect record is that the amount of spent fuel is very small. For example, a 1000-MW coal-burning plant produces 300,000 tons of toxic waste every year, not counting the material released to the atmosphere. In contrast, a nuclear plant that generates the same amount of electricity produces only 23 tons, enough to partly fill a railroad boxcar.[40] The quantity is so small that the cost of keeping it safe is low.

The US is pursuing two strategies for dealing with the spent fuel. The first strategy is to reprocess it, separating out the valuable fuel, which makes up 96% of the volume. In 400 years the residue's radioactivity will decline to the level of the natural uranium ore that was used to produce the fuel, as shown here:[39]



Many options are open for securing the fuel for such a time period.

The second strategy is to isolate the spent fuel from reactors without processing it. A large repository is being constructed inside Yucca Mountain in Nevada, for which plans are currently being reviewed. The waste material is to be encapsulated and secured in a reinforced, below-ground structure. The risk of escape is remote at most, and the consequences of any release would be highly localized.

This second strategy is facing strong political opposition. Meanwhile, an international framework for reprocessing spent fuel is developing. The US is participating in the Global Nuclear Energy Partnership. Part of that program focuses on implementing techniques that lower the cost, improve energy efficiency, and prevent weapons proliferation.[36] Researchers are even gathering data to enable incinerator reactors that will consume nuclear waste and yield smaller amounts of waste that lose their radioactivity even sooner.[37]

Waste Heat

On occasion opponents of nuclear energy will raise the subject of waste heat. All thermal power plants---nuclear, fossil-fired, geothermal, or solar-thermal---release heat as part of the energy-conversion process. Nonetheless, the opponents argue that it counts against nuclear power's claim to environmental benefit. Some go so far as to contend that it makes nuclear power plants unacceptable.

The rebuttal is simple enough. Thermal-waste effects can be mitigated to whatever extent is desired. If sufficient water is available, wet cooling towers can cool the discharge water; if it isn't then dry cooling towers can, instead. In the future, the heat will be used productively for industrial processes or for heating buildings. The heat can even drive absorption-type air conditioners.

Uranium Mining

During the 1940's and 1950's unregulated mining activities related to the weapons program exposed miners to toxic dust and gases and left radioactive tailings on the ground surface which harmed the health of people nearby.[42][43][44] Nuclear opponents argue that this past negligence proves uranium mining is inherently harmful to the point of unacceptability.

Today, uranium mining in the US is tightly regulated to minimize harm to the miners and to the environment.[43] The US Government has taken responsibility for the abandoned mines and is progressing on a long-term remediation program.[45]

Part 3: Fuel Supply

CONSUMPTION AND RESOURCES

	US				World			
Fuel	**Consumption /Year**	**Heat Equiv Quadrillion BTU/Yr**	**Known Reserves**	**Projected Resource**	**Consumption /Year**	**Heat Equiv Quadrillion BTU/Yr**	**Known Reserves**	**Projected Resource**
Coal	1129 million tons [1]	22.829 [4]	270,718 million tons [5]	1,731,000 million tons [2]	6483 million tons [3]	122.6 [4]	1,000,912 million tons [5]	6,400,000 million tons [12]
Oil	7548 million barrels [6]	43.78 [8]	20,972 million barrels [7]	3,500,000 million barrels [13]	31,007 million barrels [6]	179.84 [8]	84,949 million barrels [7]	20,800,000 million barrels [13]
Nat Gas	27,160 billion cu ft [9]	27.959 [10]	211,085 billion cu ft [11]	1,190,620 billion cu ft [15]	104,425 billion cu ft [9]	107.998 [10]	6,395,050 billion cu ft [11]	10,139,000 billion cu ft [14]
Uranium	18,000 tonnes U [16]	8.34 [18]	316,600 tonnes U [16]	2,097,000 tonnes U [22]	64,000 tonnes U [16]	27.5 [19]	3,192,500 tonnes U [16]	35,000,000 tonnes U [21]
Thorium	Not used for fuel presently	N/A	720,000 tonnes Th [24]	2,097,000 tonnes Th [26]	Not used for fuel presently	N/A	4,500,000 tonnes Th [25]	35,000,000 tonnes U [26]

YEARS OF SUPPLY AT CURRENT USAGE RATES

	US		World	
Fuel	**Known Reserves**	**Projected Resource**	**Known Reserves**	**Projected Resource**
Coal	240	1533	154	987
Oil	2.8	464	2.7	671
Gas Nat	7.8	43.8	61	97
Uranium	17.6	116	50	547
Advanced Uranium Fuel Cycle [23]	528	3495	600	16,410
Advanced Uranium and Thorium Fuel Cycle	1728	6990	3605	32,800

ELECTRICITY GENERATION, MILLION KWH

	Coal	Petroleum	Natural Gas	Other Gases	Nuclear	Hydro-electric Conven-tional	Other Renew-ables	Hydro-electric Pumped Storage	Other	Total
US [27]	1,990,926 49%	64,364 1.5%	813,044 20%	16,060 0.4%	787,219 19%	289,246 7.1%	96,423 2.3%	-6,558	13,977	4,064,702
World [28]	7,755,000 41%	1,096,000 5.8%	3,807,000 20%		2,793,000 15%	3,121,000 16%				18,930,000

ELECTRICITY FROM RENEWABLE ENERGY, MILLION KWH - US

Total	351,301	8.6%
Biomass	55,400	1.4%
Waste	16,885	0.4%
Landfill Gas	6,200	0.15%
Landfill Biogenic	8,568	0.2%
Other Biomass	2,117	0.05%
Wood and Derived Fuels	38,515	0.95%
Geothermal	14,839	0.4%
Hydroelectric Conventional	248,312	6.1%
Solar/PV	606	0.015%
Wind	32,143	0.8%
Source: EIA 2007 <http://www.eia.doe.gov/cneaf/alternate/page/renew_energy_consump/table3.html>		

EIA puts the world total energy for geothermal, solar, wind, and wood and waste electric power generation at 369,710 million KWH, or 2%. [46]

Anti-Nuclear Arguments

Opponents of nuclear energy argue that nuclear fuel is in such short supply new reactors will just run out of fuel. Or they argue that refueling the reactors will require using low-grade ore so that the environmental effects are greater than shown in Part 2.

This argument pretends that proven reserves are all that exist. If that were the case, the world would run out of oil in three years. Clearly, it is not the case. There are hundreds of years' supplies of both oil and high-grade uranium ore. Current nuclear power plants use only a few percent of the energy in the fuel. Advanced fuel cycles can use nearly all the energy, and then nuclear fuels will last over a thousand years, even if all the world's electricity comes from nuclear energy and even if electricity consumption triples.

Part 4. Costs

Cost Comparison

Every responsible study has shown that nuclear electricity is as cheap as any of the non-fossil alternatives and is competitive with fossil-fired electricity. For example, the International Energy Agency and the Organisation for Economic Co-operation and Development's Nuclear Energy Agency determined the costs as follows [29]:

COST PER MWH IN US DOLLARS

Discount Rate	5%	10%
Coal	25-50	35-60
Nat Gas	37-60	40-63
Nuclear	21-31	30-50
Wind	35-95	45-140
Micro Hydro	40-80	65-100
Solar PV	~150	200+

The University of Chicago compared several detailed calculations with a range of discount rates and summarized the results thus [30]:

COST PER MWH IN US DOLLARS

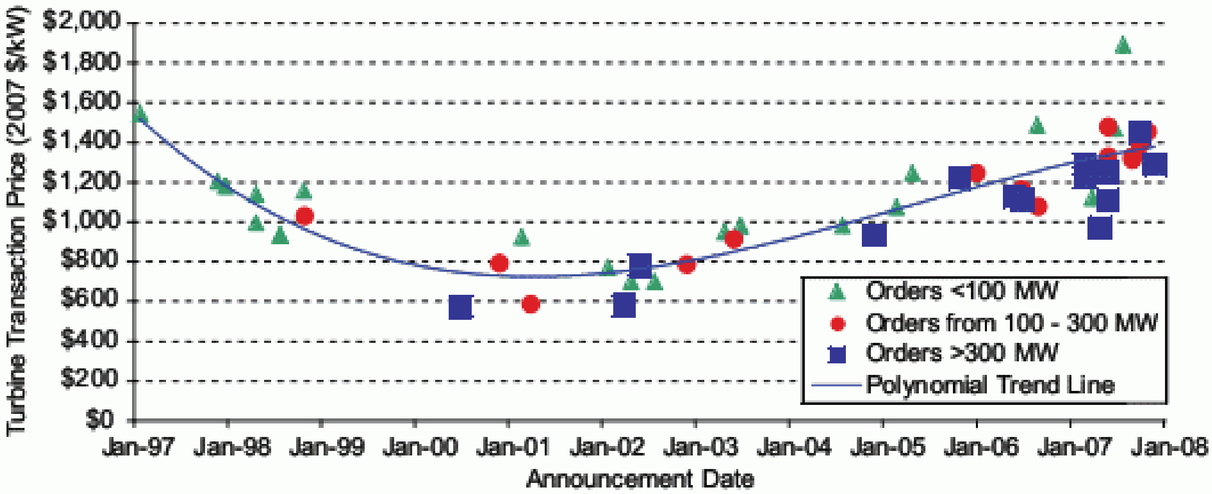
Coal	37-49
Nat Gas	56-68
Nuclear (assuming old designs)	65-77
Nuclear (assuming new designs)	36-55
Nuclear (assuming advanced-fuel designs)	57-64
Wind	55-77
Solar PV	202-308
Solar Thermal	158-235

A question that immediately presents itself is, why do the two studies give different numbers? The answer is that every study depends on assumptions, such as interest rates and fuel costs.

Both these factors, and other factors such as taxes, pollution controls, and equipment lifetimes, vary in time and place. This introduces an opportunity to do mischief, since a motivated commentator can pick-and-choose results to bolster his intended conclusion. These numbers only have significance if they're calculated on equal terms and only if they're read relatively, not absolutely.

Anti-Nuclear Arguments

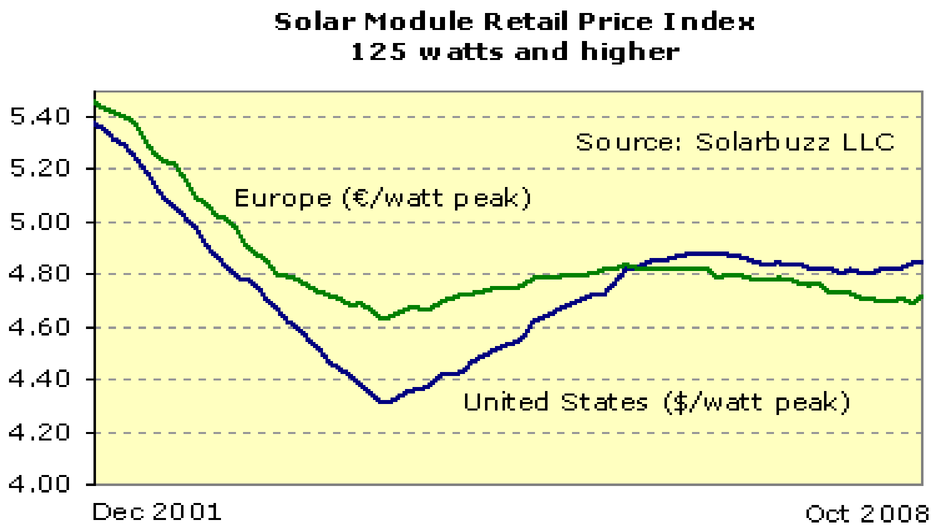
An argument being made sometimes is that nuclear construction costs have risen so fast they have rendered nuclear plants too expensive to build. This argument is anchored on a Reuters report about some calculations made by Cambridge Energy Research Associates (CERA) that allegedly show a cost increase of 185% between 2000 and 2007.[41] Imagine, an almost tripling of costs in seven years! However, CERA doesn't publish the results in a public forum; nor does it show the calculations so they can be verified. Indeed, there's no way even to know what methods it used. It is true, though that costs have risen strongly since China and India began their notable advances in material progress. These cost rises apply to all kinds of construction and, in particular, apply to alternative energy sources. Here is some information on the cost of windpower construction, which has doubled: [47]



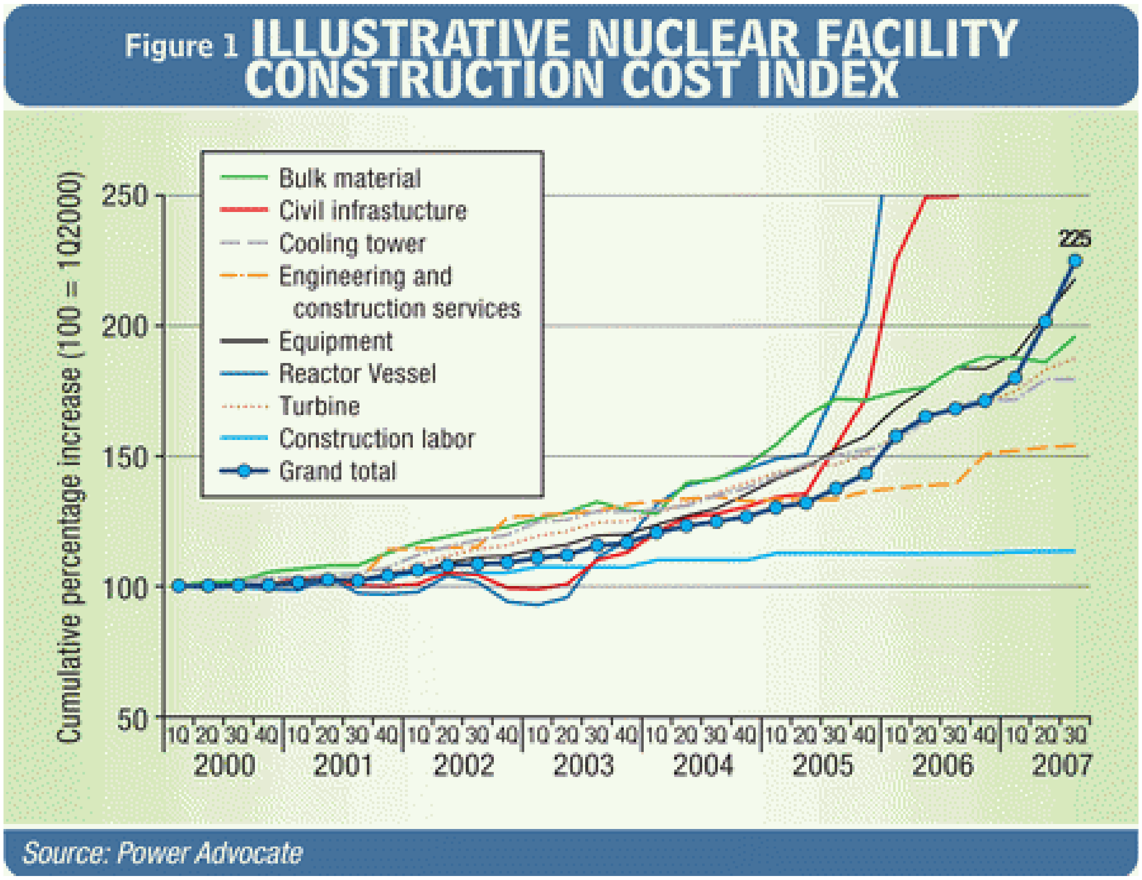
Source: Berkeley Lab database.

Figure 25. Reported U.S. Wind Turbine Transaction Prices Over Time

And some data on solar-electric construction. It has essentially held constant, but at US$4700 per KW rated power or over US$20,000 per average KW, it still is hopelessly expensive. What this shows is that the pressure on material prices has kept solar energy from getting cheaper.[48]



Finally, here is some information from Power Engineering International on nuclear construction costs, which shows a cost increase of 125%, not much different from the increase for windpower.[49]



What all these numbers show is what energy analysts have been telling us right along. Nuclear energy is as cost-effective as any non-fossil energy source, even ignoring the intermittency problem of part-time energy sources. But if intermittency is considered, then the comparison widens. There aren't any practical ways to overcome intermittency, as shown in Part 6 of this paper. But if there were some way, the economic and environmental costs would drive the total cost out of sight.

As the world grapples with this issue, one other point has to be considered. A new generation of nuclear power plants is being born. These new plants use passive safety systems so the active systems can be simpler, thereby reducing costs. Furthermore, they operate at higher efficiencies, lowering fuel costs. As shown in the University of Chicago data, these improvements make nuclear energy cheaper than any alternative.

Part 5. Safety

The most comprehensive information on the subject of nuclear safety can be found at Prof. Bernard Cohen's site, "The Nuclear Energy Option."[50]

This paper will present information at a more elementary level.

The subject of nuclear safety can be covered very simply. The dominating fact is that US nuclear power plants have a perfect safety record.

Accidents

What makes nuclear power plants safe are the multiple layers of safety. Each safety system has multiple backups.

Only one plant has ever done harm to any member of the public. That was a Soviet monstrosity which had literally no safety features. It was made of graphite, a flammable material, and covered by a sheet-metal shed to keep the rain off. Western reactors are made of steel and are built below ground and are encased in layers of steel and concrete. The Chernobyl reactor had instability built into it and at the time of the accident its emergency shutdown system and its emergency core cooling system were both disabled. No one in the world is planning to build that type of reactor in the future. In contrast, the accident at Three Mile Island destroyed the reactor but didn't harm anyone. No one was injured or made ill by that accident.[55] The difference was the layers of safety.

Radioactive Emissions

Measurements near nuclear power plants show that people living there receive between three and six additional millirems of exposure.[51] In comparison, people in the US on average receive about 300 millirems from natural sources and another 60 from artificial sources. But living or working in a masonry building or living at a high elevation can increase a person's exposure by hundreds of millirems. Studies show that these much larger variations have no effect on people's health.[52]

Terrorism

Nuclear opponents argue that suicidal saboteurs could invade a nuclear plant and damage enough equipment to cause a core meltdown. It's true that terrorists could cause expensive damage, which is the reason nuclear plants have extensive security. But the layers of safety surrounding reactors will prevent any harm to the surroundings. Even the accident at Three Mile Island, which did as much harm as terrorists could, caused no harm to the people living nearby.[55]

The possibility of terrorists flying a jet airliner into a reactor was analyzed by the Electric Power Research Institute, which concluded that such an incident would not cause a breach in the reactor's containment structure.[56]

Another possibility considered is that terrorists could steal spent-fuel shipments and explode them in a populated area. This is a threat that has to be taken seriously. Spent fuel currently isn’t being transported but when it is the shipments will have major security. In the worst case, if the theft were successful and the containers were exploded, the consequences would be localized and short-term. Any individuals who were contaminated would be cleaned up by emergency teams. Contaminated areas would be cleaned up by trained crews with the proper equipment and safety gear. So spent fuel ranks with many other dangerous substances that could be terrorist targets. Compared with ammonia, chlorine, and agricultural pesticides, spent fuel is harder to steal and less effective as a terrorist weapon.

Part 6. Weapons Proliferation

In the popular media nuclear energy and weapons proliferation are often treated as Siamese twins. Actually, they are not connected. Having nuclear energy does not enable a country to make weapons, and not having nuclear energy does not prevent a country from making weapons.

The confusion comes from the existence of production reactors, which are built and operated in special ways to produce the right isotopes of plutonium.

In either type of reactor, the uranium isotope U238 is transmuted into Pu239, which is a bomb material. But if the fuel stays in the reactor more than a few weeks some of the Pu239 turns into Pu240. Pu240 prevents the bomb from going off by predetonating before a critical mass is achieved. To make bomb material from plutonium from power reactors requires isotope separation and enrichment. If a country has the capability of doing separation and enrichment, it can make a bomb from uranium, which is an easier material to work with.[63]

Hans Blix was head of IAEA, the UN agency responsible for preventing proliferation. Here’s what he has to say [64]:

“A phasing out of nuclear power in some or all states would not lead to the scrapping of a single nuclear bomb.

“States can have nuclear weapons without nuclear power though it is not common today. Israel is a case in point. It has no nuclear power but is assessed to have some 200 nuclear warheads. For a long time China had only the weapons. Indeed, most nuclear weapons states, including the US, had weapons before they had power. ”

Part 7. Alternatives

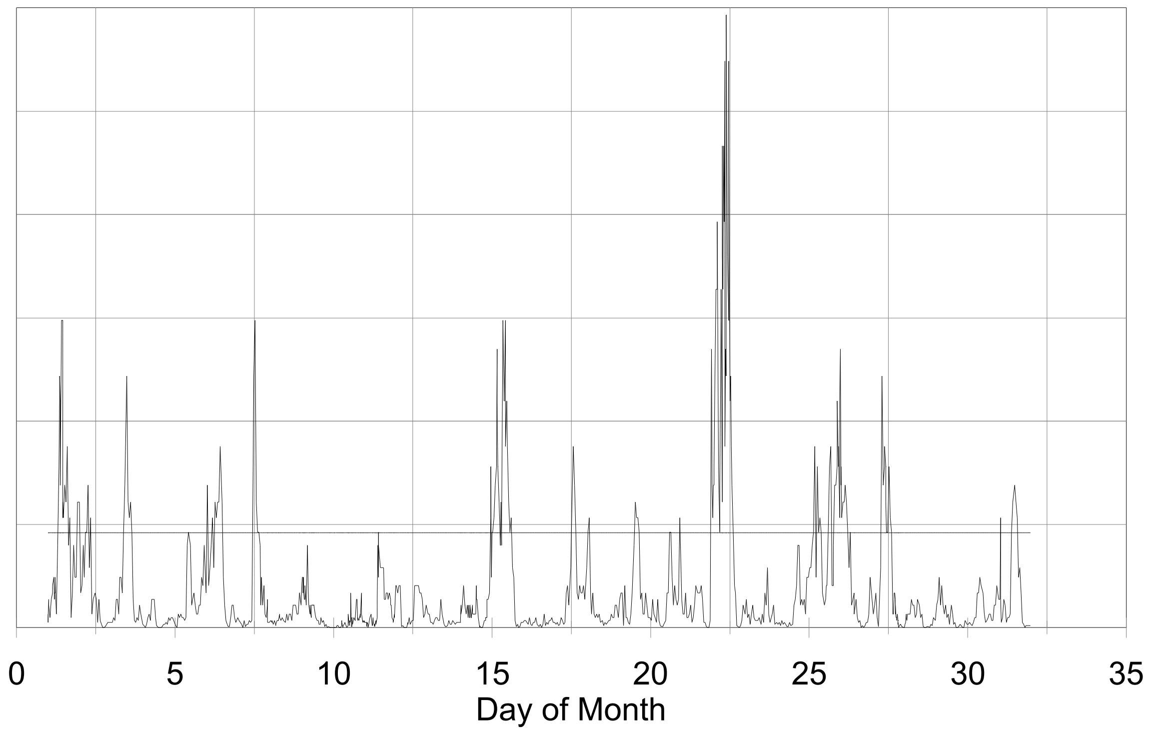
The reliability of electricity supplies is a central focus in this debate. Fossil fuels have a high level of reliability. Nuclear plants have to be shut down periodically for refueling and occasionally are shut down because of equipment malfunctions. Fortunately, refueling is flexible so any plant's refueling can be scheduled to adjust for the requirements of other plants and it's never necessary to take many of them offline at any time.

Wind Energy

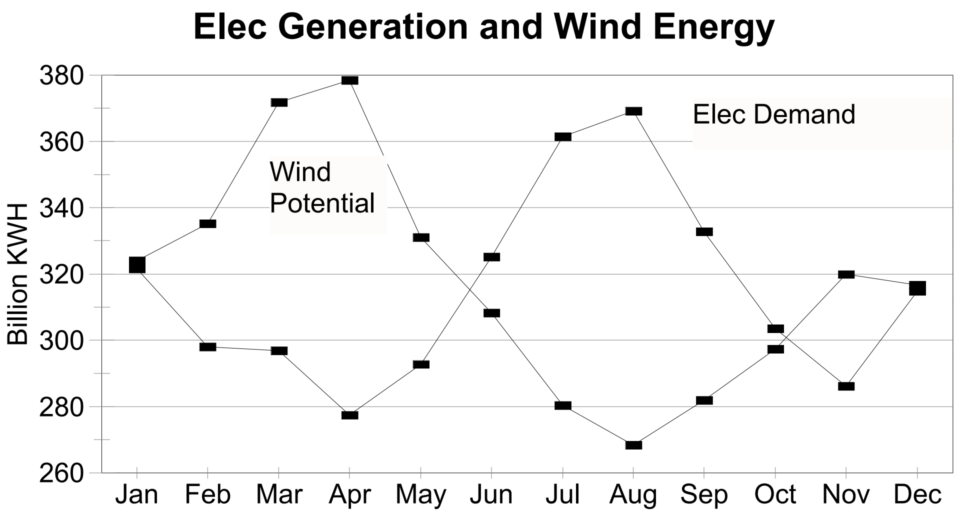
Wind energy is the cheapest of the "renewable" sources, so naturally it has seen the greatest development. However, it suffers the most in the area of reliability. As an example, the graph below shows wind power for the month of December in Amarillo, Texas.[57] Amarillo is a prime wind area, with decent winds all year and much less seasonal variation than most places, and December is a good month because it avoids both the gusts of Spring and the doldrums of late Summer.[58]

Even so, we see a few gusty days with intervals up to a week where the power level barely reaches the mean-power level for a few hours Wind advocates argue that interconnecting large regions together and storing energy can make up for this deficiency.

Windpower for December 2007
Amarillo, Texas



Neither of these nostrums works. First, here is a plot of wind supply and electricity demand for the US, assuming that the entire country is interconnected, except Alaska. The details are given in Appendix A.



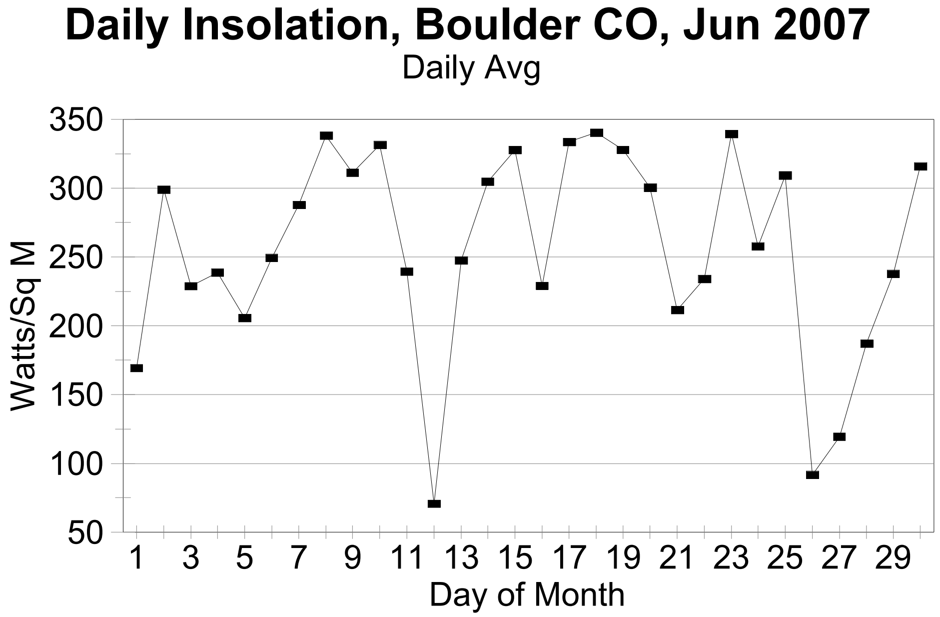
We see that electricity demand is highest in late summer, when wind power is lowest, and vice versa.

Calculations given in Appendix A show that for windpower to provide all the US's electricity an amount of storage equal to 386 billion MWH is required. There are no prospects of storing that much energy. As a point of reference, if all of Lake Mead were drained through Hoover Dam, the energy yield would be less than 14 billion MWH. Some 28 Lake Meads would be required together with 28 Hoover Dams and 28 other Lake Meads to catch the water below the dams. The details are shown in Appendix B.

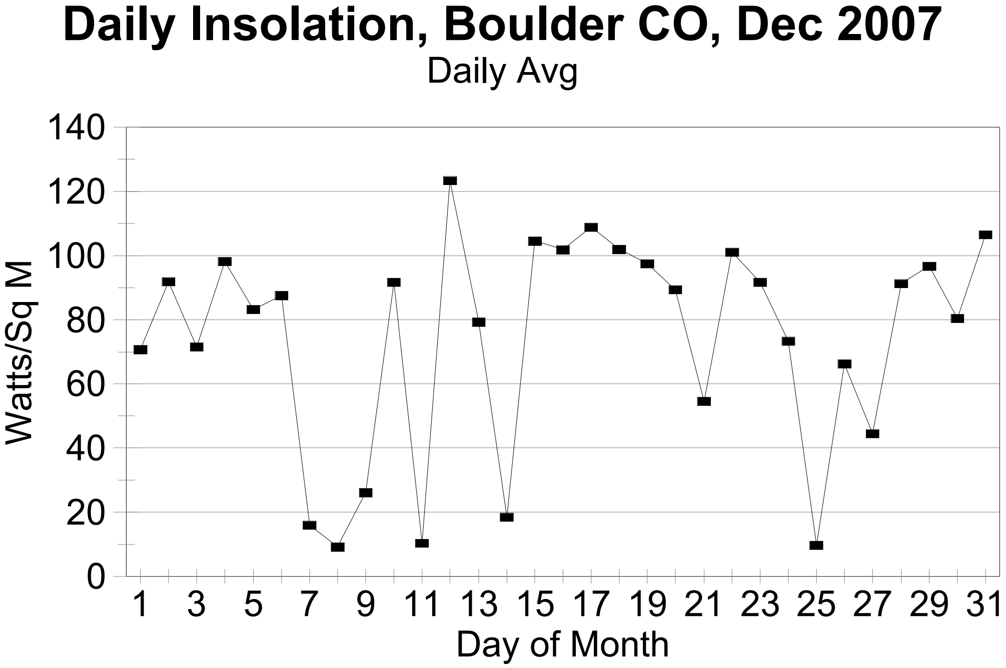
Serious wind advocates don't argue for 100% wind electricity, but for more realistic amounts. The American Wind Energy Association calls for 20% of the country's electricity to come from wind, which DOE considers to be reasonably achievable.[60]

Solar Energy

Boulder, Colorado is a better-than-average location for solar energy, with an annual insolation of 1936 KW/sq meter, compared to the average 1700.[61] Still, there are large day-to-day fluctuations.

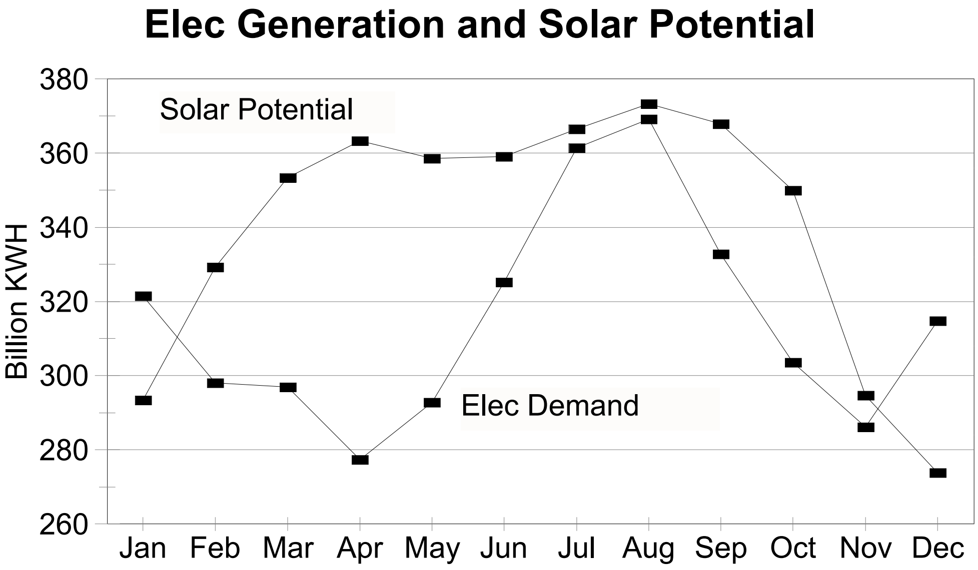

Daily Insolation, Boulder CO, Jun 2007

Daily Avg


Daily Insolation, Boulder CO, Dec 2007

Daily Avg

These fluctuations make matching load to demand a challenge. Still, if we look at the monthly data for the entire country, we see that solar energy matches demand better than wind. The details are given in Appendix A.



The calculations, given in Appendix A, show that for solar energy to provide all the country's electricity, 141 billion MWH of storage would be required, or ten Lake Meads with their own Hoover Dams and collection lakes. The storage calculations are shown in Appendix B.

Geothermal Energy

Like other geologic energy sources, geothermal has a known or proven reserve and a much larger projected resource. The US Geological survey says the known potential is 9057 MW and the projected resource is 30,000 MW, with a wide uncertainty band. There could also be over 500,000 MW of dry thermal energy, but technology for exploiting it doesn't exist.[62]

As shown in Part 3, the US uses 4,064,702 million KWH per year. The known potential could generate 2% and the projected resource could generate 6.5%.

Other Energy Sources

The Federal Government has supported research into more exotic energy sources such as tidal, wave, or current machines. There aren't any indications that any of them will succeed.

Carbon Capture and Sequestration

CCS is popular among elected officials because it seems like a painless way to satisfy all the pressure groups. Unfortunately, no one has suggested a way of accomplishing it that even sounds like it could succeed. Under this scheme, CO2 would be pumped into the ground in hopes it would stay there. No one knows how to predict whether any geologic structure could hold the CO2 securely. Furthermore, tests would certainly take decades and proceeding with such a scheme without test data could never be considered responsible.

References and Suggested Reading

References

[1] EIA 2007 <http://www.eia.doe.gov/cneaf/coal/quarterly/html/t25p01p1.html>

[2] EIA 1997. Speculative judgement <http://www.eia.doe.gov/cneaf/coal/reserves/chapter1.html>

[3] EIA 2005 <http://www.eia.doe.gov/emeu/international/coalconsumption.html>

[4] EIA 2005 <http://www.eia.doe.gov/emeu/international/coalconsumption.html>

[5] EIA 2005 <http://www.eia.doe.gov/emeu/international/>

[6] EIA 2007 <http://www.eia.doe.gov/emeu/international/oilconsumption.html>

[7] EIA 2006 <http://www.eia.doe.gov/emeu/international/oilreserves.html>

[8] EIA <http://www.eia.doe.gov/kids/energyfacts/science/energy_calculator.html>

[9] EIA 2006 <http://www.eia.doe.gov/emeu/international/gasconsumption.html>

[10] EIA 2006 <http://www.eia.doe.gov/emeu/international/gasconsumption.html

[11] EIA 2007 <http://www.eia.doe.gov/emeu/international/oilreserves.html>

[12] None of the international agencies concerned with energy estimate the total available world coal resources. For this table, the projected resource is based on applying the ratio of projected-to-known reserves for the US (6.4) to the known world reserves.

[13] EIA 2008 <http://www.eia.doe.gov/oiaf/ieo/pdf/pettbl.pdf>

[14] EIA 2008 <http://www.eia.doe.gov/oiaf/ieo/nat_gas.html>

[15] EIA 2000 <http://www.naturalgas.org/overview/resources.asp>

[16] USGS 2002 <http://pubs.usgs.gov/bul/b2179-a/B2179-A-508.pdf>

[17] EIA 2007 <http://www.eia.doe.gov/emeu/aer/txt/ptb0902.html>

[18] 806.5 billion KWH [17], based on 33% average thermal efficiency [EIA <http://www.eia.doe.gov/cneaf/nuclear/page/uran_enrich_fuel/convert.html>]

[19] 2,660.26 billion KWH [20], based on 33% average thermal efficiency [EIA <http://www.eia.doe.gov/cneaf/nuclear/page/uran_enrich_fuel/convert.html>]

[20] EIA 2006 <http://www.eia.doe.gov/pub/international/iealf/table27.xls>

[21] IAEA 2006 <http://www.iaea.org/NewsCenter/News/2006/uranium_resources.html>

[22] Uranium 2005: Resources, Production, and Demand : a Joint Report. By OECD Nuclear Energy Agency, International Atomic Energy Agency. Published by OECD Publishing, 2006. ISBN 9264024255, 9789264024250

[23] Advanced fuel cycles extract more than 30 times the energy as conventional. [OECD 2005 <http://www.oecd.org/LongAbstract/0,3425,en_2649_34667_36910363_1_1_1_1,00.html>]

[24] USBM 1985 <http://www.iaea.org/inisnkm/nkm/aws/fnss/fulltext/0412_1.pdf>

[25] IAEA 2006 <http://www.nea.fr/html/general/press/2006/redbook/red_book_questions_and_answers.pdf>

[26] Based on a comparison of known reserves between uranium and thorium, it is apparent that projected resources of thorium will at least equal those of uranium. For estimating purposes, the energy output of thorium can be equated to that of uranium [Thorium Energy <http://www.thoriumenergy.com/index.php?option=com_content&task=view&id=28&Itemid=1> and ThinkQuest <http://library.thinkquest.org/3471/fission.htmlhttp://library.thinkquest.org/3471/fission.html>].

[27] EIA 2006 <http://www.eia.doe.gov/cneaf/electricity/epa/epat1p1.html>

[28] IEA 2008 <http://www.iea.org/textbase/nppdf/free/2008/key_stats_2008.pdf>

[29] IEA <http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1472>

[30] Univ of Chicago <http://www.ne.doe.gov/np2010/reports/NuclIndustryStudy-Summary.pdf>

[31] Meier, Paul J. Lifecycle Assessments of Electricity Generation Systems and Applications for Climate Change Policy Analysis. University of Wisconsin, UWFDM-1181. <http://fti.neep.wisc.edu/pdf/fdm1181.pdf>

[32] ExternE <http://europa.eu.int/comm/research/energy/pdf/externe_en.pdf>

[33] Storm/Smith <http://www.stormsmith.nl/>

[34] Reuters: Uranium Resources - Uranium Discoveries Fri Jan 18, 2008 <http://www.reuters.com/article/pressRelease/idUS117499+18-Jan-2008+RNS20080118>

[35] UIC data <http://www.uic.com.au/graphics/nefig16.gif>

[36] GNEP <http://www.gnep.gov/afci/advsepresearch.html>

[37] WNA <http://www.world-nuclear.org/info/inf35.html>

[38] Paul Scherrer Institut <http://gabe.web.psi.ch/pdfs/Annex_IV_Dones_et_al_2003.pdf>

[39] WNA <http://www.world-nuclear.org/info/inf04.html>

[40] DOE <http://www.eia.doe.gov/cneaf/nuclear/page/nuclearenvissues.html>

[41] Reuters <http://www.reuters.com/article/companyNews/idUSN1338924120080214>

[42] Utah <http://historytogo.utah.gov/utah_chapters/utah_today/uraniummininginutah.html>

[43] EPA <http://www.epa.gov/radtown/uranium-mines.html>

[44] DOL <http://www.dol.gov/oasam/programs/history/osha.htm#23>

[45] DOE <http://www.swhydro.arizona.edu/archive/V7_N6/feature5.pdf>

[46] EIA 2005 <http://www.eia.doe.gov/emeu/international/electricitygeneration.html>

[47] DOE <http://eetd.lbl.gov/ea/ems/reports/lbnl-275e.pdf>

[48] Solar Buzz <http://www.solarbuzz.com/> (Oct. 28, 2008)

[49] PEI
<http://pepei.pennnet.com/display_article/340641/140/ARTCL/none/none/1/Nuclear-New-Build-Precondition:-Cost-Visibility-and-Predictability/>

[50] Cohen <http://www.phyast.pitt.edu/~blc/book/BOOK.html>

[51] Scientific American
<http://www.sciam.com/article.cfm?id=coal-ash-is-more-radioactive-than-nuclear-waste>

[52] NRC
<http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/bio-effects-radiation.html>

[53] EIA <http://www.eia.doe.gov/cneaf/nuclear/page/nuc_reactors/reactsum.html>

[54] EIA <http://www.eia.doe.gov/cneaf/nuclear/page/nuc_reactors/reactsum.html>

[55] Hatch/Susser Study <http://aje.oxfordjournals.org/cgi/content/abstract/132/3/397>

[56] EPRI
http://www.nei.org/resourcesandstats/documentlibrary/safetyandsecurity/reports/epriplantstructuralstudy/

[57] NOAA <http://cdo.ncdc.noaa.gov/qclcd/QCLCD?randomnum=44240225W74261>

[58] NOAA <http://lwf.ncdc.noaa.gov/oa/climate/online/ccd/avgwind.html>

[59] <http://gwperplexed.niof.org/energystorage.htm>

[60] AWEA <http://www.newwindagenda.org/images/ico-brochure.jpg>

[61] Univ of Colorado <http://foehn.colorado.edu/weather/atoc1/daily_stats.grf>

[62] USGS ,http://www.usgs.gov/newsroom/article.asp?ID=2027&from=rss_home>

[63] DOE <http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=C007853D41625F9EF547619EA2A648F7?purl=/671863-dJ7rsp/webviewable/>

[64] Blix <http://www.dnva.no/c26889/nyheter/vis.html?tid=27367>

Suggested Reading

An authoritative analysis of nuclear energy, with emphasis on safety and environmental effects, can be found in *The Nuclear Energy Option*, by Bernard L. Cohen. Prof. Cohen has generously posted the manuscript at <http://www.phyast.pitt.edu/~blc/book/BOOK.html>. The information is necessarily technical, but the writing is clear enough for non-specialists.

Power to Save the World by Gwyneth Cravens recounts the journey of a professional writer who learned about nuclear energy by meeting experts on their own turf. Not a technical book, it’s still filled with relevant information people need to understand the issues. She has a descriptive web page at <http://cravenspowertosavetheworld.com/>.

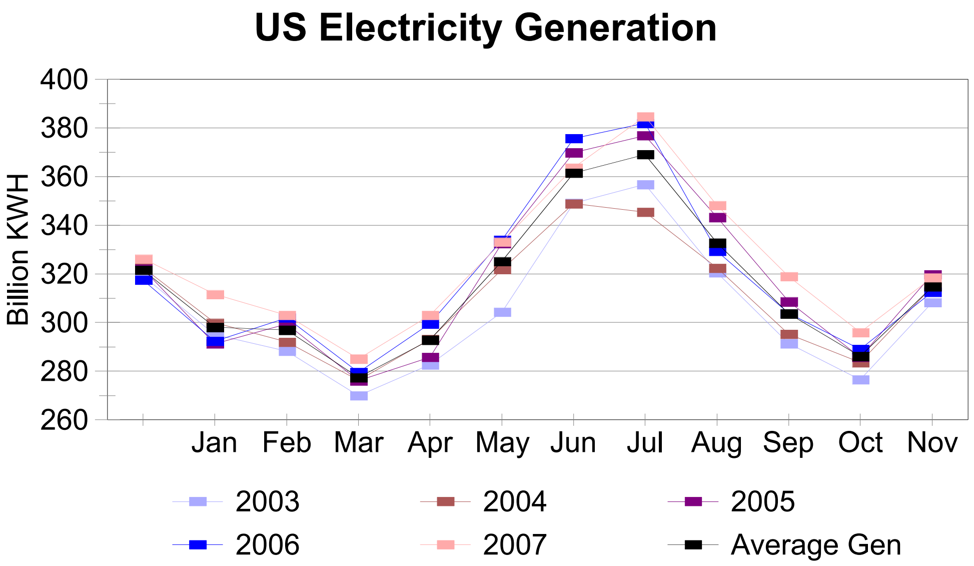
Appendix A

Solar Energy, Wind Power, Intermittency, and Storage

In ordinary conversations about renewable energy, the issue of energy storage is often overlooked. Renewable sources generate energy on their own schedules, not customers' schedules. The difference must be met either by backup energy supplies or by energy storage. This article describes some storage calculations in the absence of fossil-fired or nuclear sources. The calculations can be downloaded from <http://gwperplexed.niof.org/elec_gen.xls>.

This is a plot of electricity generation for the US. This writer doesn't have data for any other countries and wouldn't presume to offer advice if he did.

<http://tonto.eia.doe.gov/merquery/mer_data_ascii_display.asp?table=T07.01>

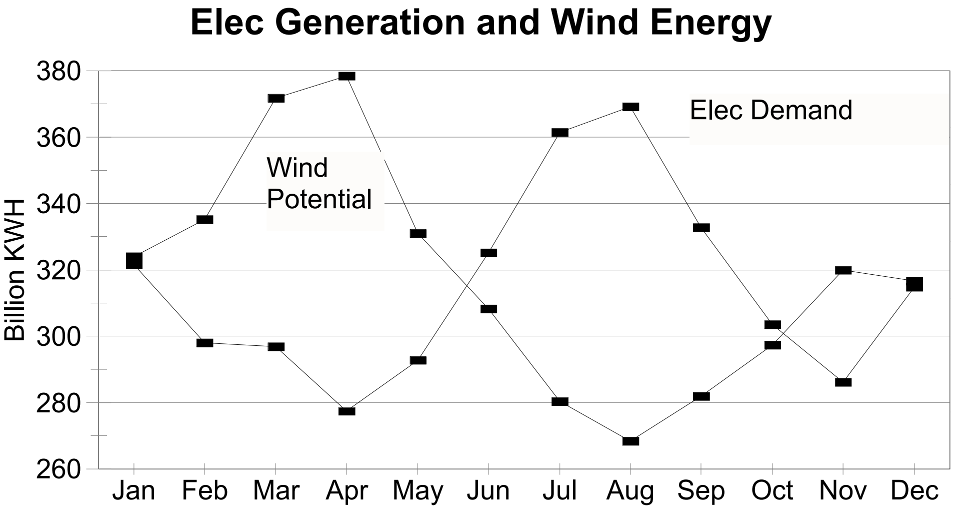


For the rest of this analysis, the average generation for the years 2003-2007 will constitute the model year.

First, compare the demand curve with the availability of wind energy. Wind energy is approximately proportional to the cube of wind speed. Density is also a factor, and there is considerable mismatch at very high and very low wind speeds, but those differences won't change the conclusions. This analysis is based on wind-speed cubed.

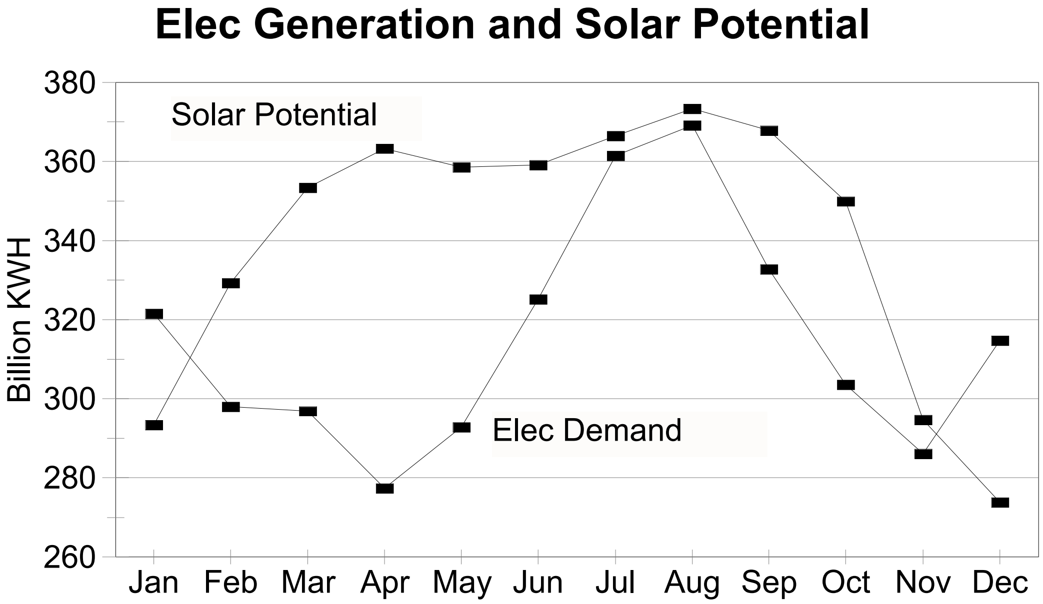
The data show wind speeds for 265 cities. We have deleted cities with low winds or high differences between high-wind and low-wind months. We also have deleted Alaska cities, owing to their unique characteristics and their separation from the US power grid. 244 cities are left.

<http://lwf.ncdc.noaa.gov/oa/climate/online/ccd/avgwind.html>



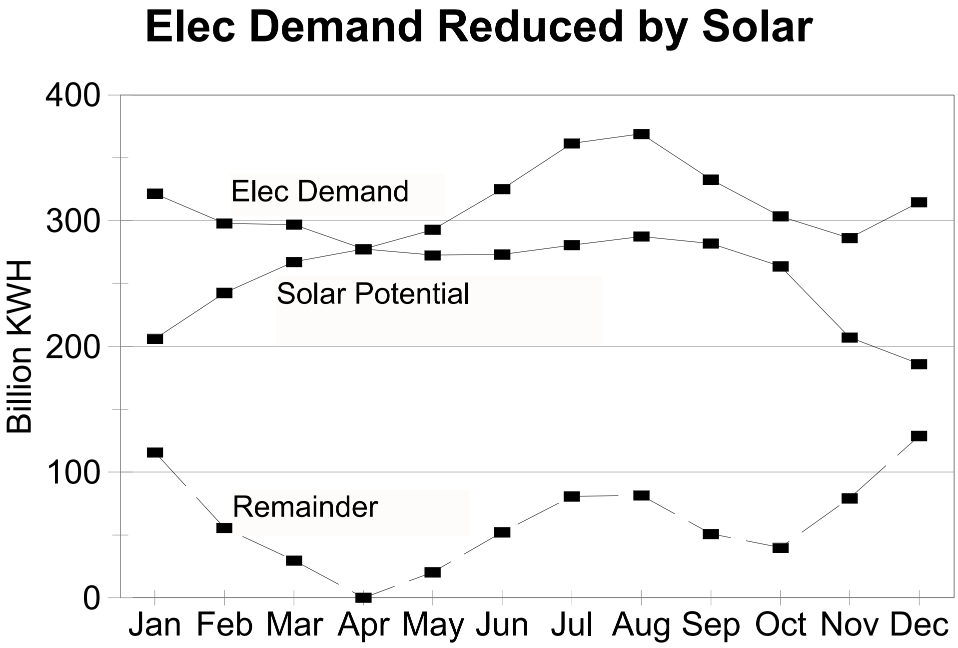
Clearly, wind energy doesn't match electricity demand well. Next, compare electricity generation with solar potential. Cities with poor solar characteristics were deleted from the data, leaving 221 out of 238.

<http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/>

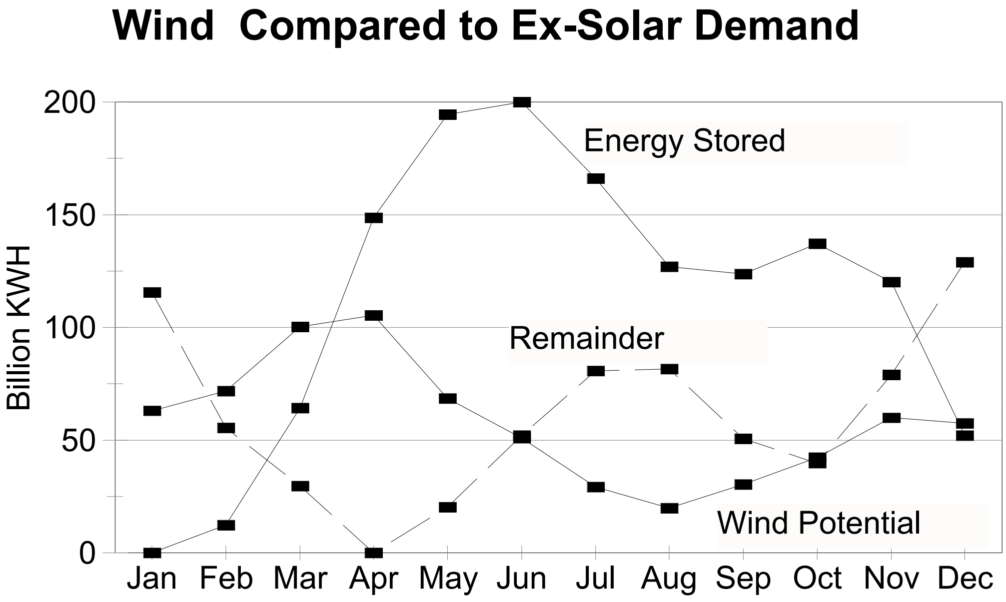


So we see that solar energy matches the electricity demand somewhat better. Our goal here is to calculate the amount of energy needed for a year, so we shall assume that storage exists for any one month. We have to make that assumption because we are using monthly data. For our first cut we shall calculate the maximum amount of solar energy that can be generated and used within a month, and we find that 80.6% of the yearly demand can be met with solar energy on these terms.

Now we can consider the remaining demand after all that solar energy is accounted for.

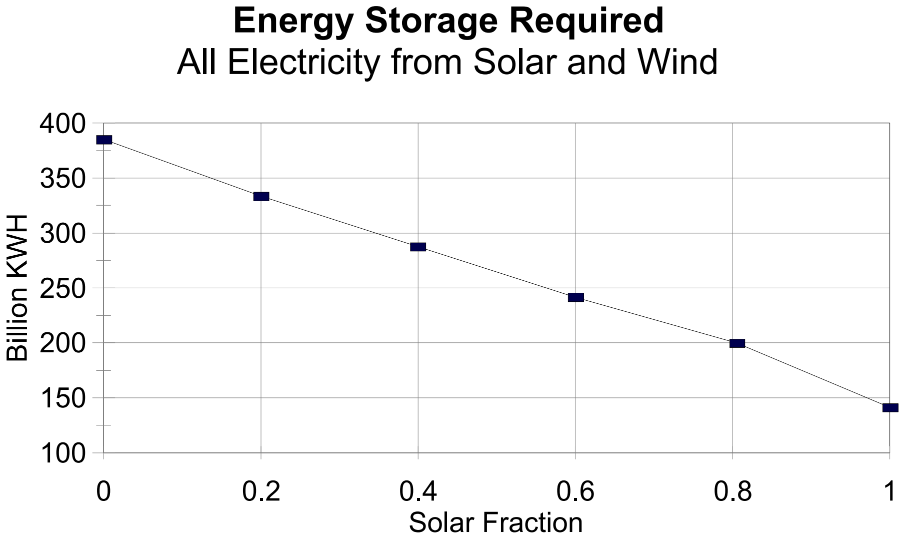


Now we can compare the remaining demand with available wind energy.



The calculations show that 200 billion KWH of storage is required.

We can do the same calculations for other shares of supply from solar energy, with the results shown here:



Our calculations show that the storage requirement ranges from 141 to 386 billion KWH.

Appendix B

Energy Storage

Appendix A shows that the storage requirement ranges from 141 billion KWH for 100% solar electricity to 386 billion KWH for 100% wind.

Pumped Storage

Imagine that a lake exists, named Upper Lake Fead, which is equal in size to Lake Mead. Lower Lake Fead is the same size and is located at the bottom of Foover Dam, which is identical to Hoover Dam. However, all the water in Upper Lake Fead can drain through the water turbines.

Lake Volume = 30,000,000 acre-feet [7]
Average head at dam = 520 feet [8]

If the efficiency were 100%, then

Energy = volume x pressure = volume x head x weight-density

= 30,000,000 acre-feet x 43560 sq-ft/acre x 520 feet x 62.4 lb/cu-ft

= 4.24 x 10^16 ft-lb

= 16 billion KWH

We'll set the turbine efficiency at 85% and account for pump inefficiency by upsizing where necessary. Thus, Upper Lake Fead is good for 13.6 billion KWH.

So we have calculated that the US would need between 10 and 28 Foover Dams, each with Upper and Lower Lake Feads, depending on how much electricity is generated with solar energy. There are, in fact, no Foover Dams and no locations for building any.

Alternatively, we can consider an existing installation. The Ludington Pumped Storage Plant [9] in Michigan is perhaps the world's largest, generating 1,872 megawatts at a flow rate of 33 million gallons per minute. The reservoir, which covers 842 acres, holds 27 billion gallons, so the capacity is

27 billion / 33 million x 1872 = 1.53 million MW-minutes = 25,500 MWH

This means we need between 5,500,000 and and 15,100,000 plants of the same size.

Compressed Air

Another scheme that sometimes is mentioned is storing compressed air in caves. There is a facility in Huntorf, Germany that we can use for an example.[5] It compresses air to 1000 pounds per square inch pressure.

The data show that it stores 3 x 290 = 870 MWH of energy and the cave volume is 310,000 cubic meters.

To store one billion KWH, the cave's volume would have to be 1,000,000 / 870 x 310,000 cubic meters = 356 million cubic meters. Suppose a cave averaged 20 meters wide and 20 meters high (65 feet x 65 feet); then the length required would be 356 million / 400 = 890,000 meters = 890 km = 552 miles. To save 141 to 386 billion KWH would require a total cave-length of 78,000 to 213,000 miles. Granted that most big caves have never been surveyed, it's still safe to say that there aren't tens of thousands of miles of caves in the US.

Batteries

As our reference battery, we shall use the vanadium-redox type of flow battery, which has an energy density of up to 40 watt-hour/Kg. This is the best battery currently available for bulk storage.

Let's say that batteries are limited to 10 meters diameter and 5 meters height. That's roughly the volume of a house. The volume of each is 393 cubic meters. Sulphuric acid, the main constituent, has almost twice the density of water, so the weight of each tank would be 786,000 Kg and its capacity is 31,440 KWH. To store 141 to 386 billion KWH would require 4,485,000 to 12,277,000 batteries, or one battery for every 25 to 69 persons. Another tank the same size is needed to hold the spent acid.

Sometimes people will suggest that the batteries of plug-in hybrid cars could store the energy needed. Let's overlook the problem that the cars are unavailable much of the time because they are being driven and have to be recharged according to the owners' needs, not according to when the energy for recharging them is available.

Toyota's intended battery has a storage capacity of 202 volts x 13 amp-hours, or 2.6 KWH [10]. Each battery costs around $10,000[11]. The number of plug-in batteries required would be 54 billion to 148 billion, in a country with 306 million people. Or, if each person owned one battery and used it only for energy storage, the combined capacity would be only 0.2% to 0.56% of what's needed. For the storage to provide 5% of the amount needed would require technological improvements that aren't even on the horizon.

Hot-Water Storage

A company called Ausra is proposing to build concentrated-solar power plants in the deserts of the American Southwest. They intend to get around the problem of night-time electrical demand by storing hot water.

It would be helpful if Ausra would provide some technical information. In its absence, we'll have to make some assumptions. To avoid accusations of unfairness, we'll make all the assumptions favorable to the solar plant.

We don't know, for example, what the storage temperature will be. Higher temperatures allow more energy storage but require thicker container walls because of the higher pressure. We'll assume 600ºF because density starts dropping off quickly at higher temperatures, and pressure rises quickly. Even at that temperature the collector efficiency will be very low and the pressure would be about 1550 pounds per square inch. At that temperature, a pound of water holds 618 BTU, compared to 70 BTU at 100º.[6]

A modest thermal plant would be rated at 1000 MW of electricity. Imagine we wished to average that power over 16 hours, for a total of 16000 MWHe. Assuming a generous 45% efficiency, the energy required would be 16000 x 3,413,000 / 0.45 = 121 billion BTU of heat. Each pound of water can give up 618 - 70 = 548 BTU, so that means the storage has to be 221 million pounds. Density at 600º is about 42 lbs / cubic foot, so the volume required would be 5,262,000 cubic feet. Suppose the tanks were 20 feet in diameter, so their area would be 3.14 x 20 ft x 20 ft / 4 = 314 sq feet. To hold the required amount of water would require a total tank length of 16,750 feet, or 3.2 miles. By the way, if we say steel is good for 50,000 psi stress, the tank thickness would have to be 1550 / 50000 x 20 ft / 2 = 0.31 feet or 3.7 inches.[6]

So we need 3.2 miles of tank for 16 hours of storage. But what if the sky is cloudy for one day? Then we need 40 hours of storage, or 8 miles of tank. And that's for just one smallish thermal plant. In fact, there could be weeks of cloudy days, or days with only a few hours of sunshine, even in Arizona.

References

[1] http://www.eia.doe.gov/cneaf/electricity/epa/epat1p1.html

[2] http://www.nypa.gov/facilities/niagara.htm

[3] http://www.great-lakes.net/lakes/ref/eriefact.html

[4] http://www5.ncdc.noaa.gov/documentlibrary/pdf/wind1996.pdf

[5] http://www1.ceit.es/asignaturas/tecener1/Lesson6.pdf

[6] Baumeister and Marks, Standard Handbook for Mechanical Engineers

[7] http://www.crwua.org/coloradoriver/riveruses/index.cfm?action=reclamation

[8] http://www.usbr.gov/lc/hooverdam/faqs/powerfaq.html

[9] http://www.consumersenergy.com/apps/pdf/LudingtonPumpedStorage.pdf

[10] http://www.japancorp.net/Article.Asp?Art_ID=14929

[11] http://www.bloomberg.com/apps/news?pid=20601101&sid=arvp1GgT74o8&refer=japan