The Oil Drum: Net Energy

Discussions about Energy and Our Future

The Energy Return of Nuclear Power (EROI on the Web-Part 4)

Posted by Nate Hagens on April 22, 2008 - 10:00am in The Oil Drum: Net Energy
Topic: Supply/Production
Tags: charles hall, eroei, eroi, nuclear [list all tags]

This is 4th in a continuing series of articles by Professor Charles Hall of the SUNY College of Environmental Science and Forestry and his students, describing the energy statistic, "EROI" for various fuels.

The concept of an energy theory of value has been around since (at least) the 1930s and net energy actually became part of law after Mark Hatfield petitioned Congress in 1970 regarding the importance of EROI. His efforts resulted in the passing of (now defunct) Public Law 93.577 which stipulated that all prospective energy supply technologies considered for commercial application must be assessed and evaluated in terms of their 'potential for production of net energy". However, insurmountable theoretical and practical difficulties arose when using the energy unit to understand, a) the conversion among disparate fuel types (energy quality), b) the contribution of the environment, and c) the boundaries of analysis. Despite these problems, energy analysis is grounded (largely) in physical principles, which gives it an important long term edge over financial analysis which may proximately be related to real things, but ultimately is related to the political will to print money.

Nuclear power is the logical step up in energy density from dung, wood, coal, oil..., but its scaling has been controversial and uncertain. Below is an overview of both the nuclear fuel cycle and its energy return. Please add your comments, links and expertise in a manner that Prof Goose is fond of saying, 'that would improve the silence'...;-)

Previous articles/commentary from this series:

At $100 Oil, What Can the Scientist Say to the Investor?
Why EROI Matters (Part 1 of 5)
EROI Post -A Response from Charlie Hall
EROI Part 2 of 5 - Provisional Results, Conventional Oil, Natural Gas
Unconventional Oil: Tar Sands and Shale Oil - EROI on the Web, Part 3 of 5

APPENDIX F. Nuclear

Nuclear Electricity: Potential, EROI and Social and Environmental Impacts

Robert Powers - SUNY-ESF, Syracuse NY

INTRODUCTION

Definition: Nuclear power refers to the controlled use of nuclear fission reactions to release energy captured for use in electricity generation.

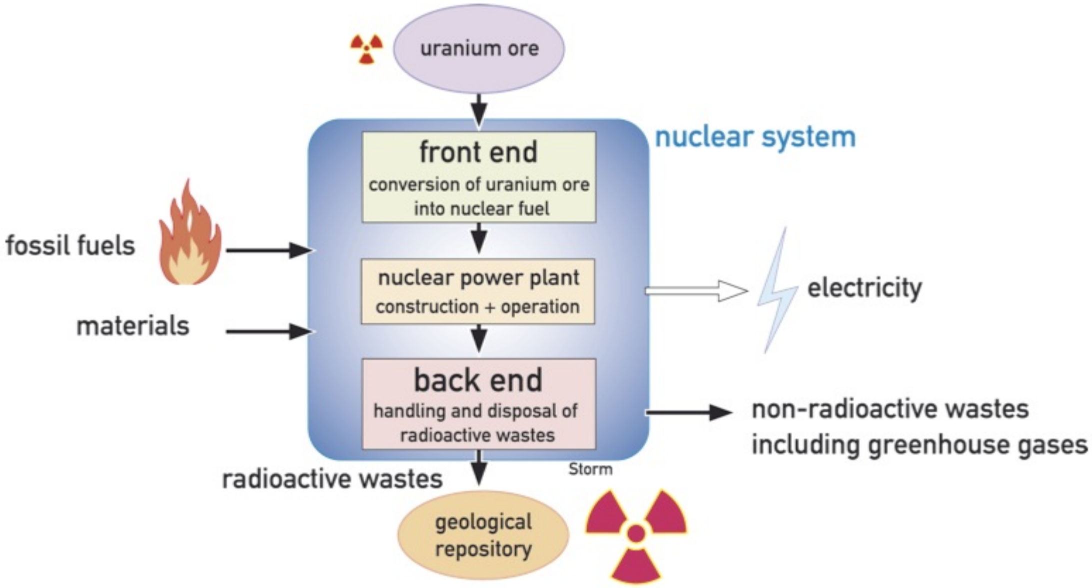

Figure 1 – Basic nuclear fuel cycle (Leeuwen 2005).
Click to Enlarge.

Table 1 – Timeline of Major Events Related to Nuclear Power

Time	Event
1938	Hahn, Meitner and Strassman conduct the first successful fission experiments in Germany.
1942	Enrico Fermi obtained the first self-sustaining nuclear chain reaction at the University of Chicago on December 2, 1942. This reactor design was used to produce the plutonium used in the first US nuclear bombs.
1945	Atomic Bombs dropped by the US on Hiroshima and Nagasaki
1954	The Atomic Energy Act Amendments removed the government monopoly on owning and operating nuclear plants
1957	Price-Anderson Nuclear Industries Indemnity Act passed, serves to limit the liability of commercial nuclear power plant operators in the case of accidents
1963	First commercial nuclear plant ordered in the US (Oyster Creek Plant, NJ)
1968	Nuclear non-proliferation treaty signed
1971	Construction of last new plant in the US begun
1984	Nuclear replaces hydro as second largest source of electricity in the United States, after coal
1986	Chernobyl disaster in Ukraine, 57 official direct deaths, 300 thousand people relocated
1987	Congress selects Yucca Mountain as study site for first high level geological repository
2005	Energy Policy Act of 2005 signed, with large incentives to industry to create new nuclear plants in the US

Table 1 – Timeline of Major Events Related to Nuclear Power
Click to Enlarge.

TECHNOLOGY

Light Water Reactors (LWRs):

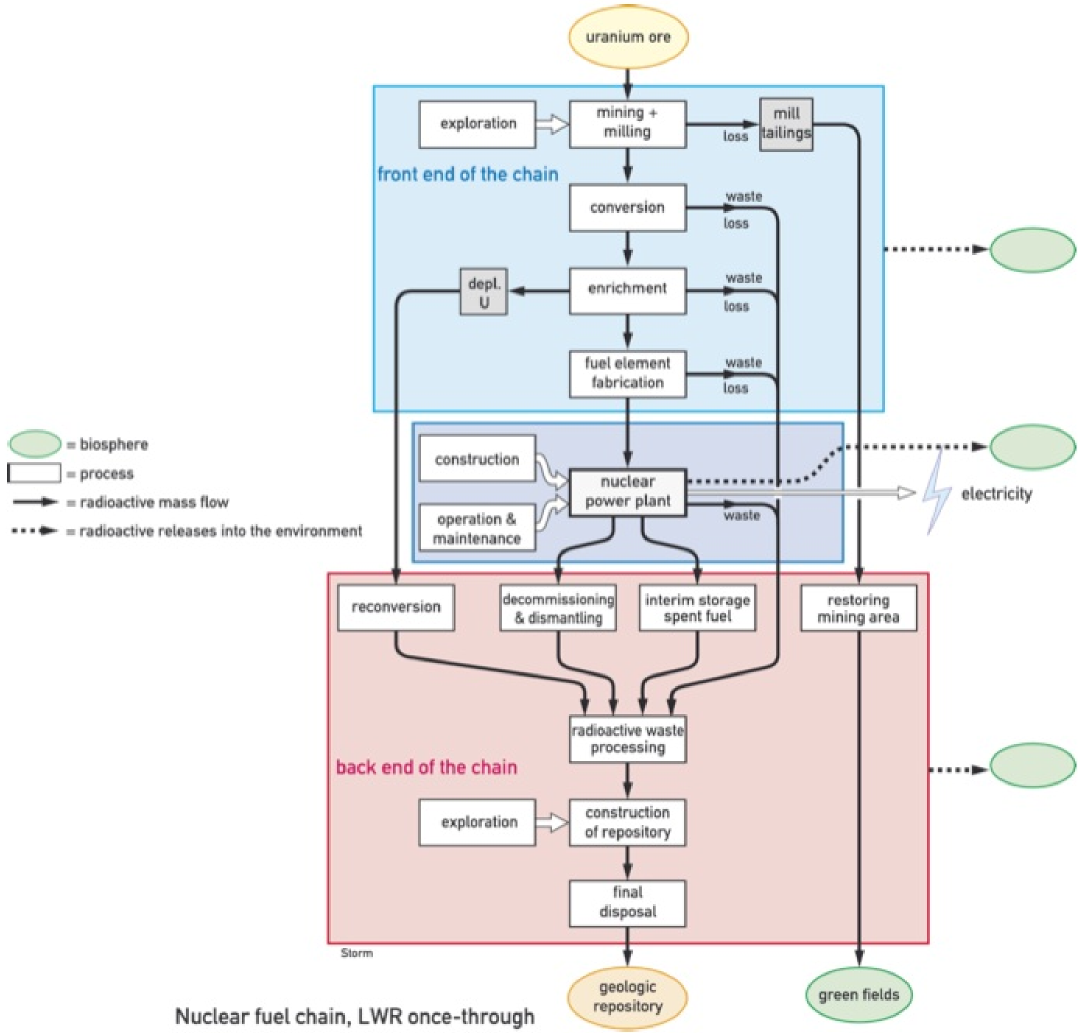

Figure 2 – Nuclear Fuel Chain (Leeuwen 2005).
Click to Enlarge.

All commercial reactors in the US are variants of light water reactors, either Pressurized Water Reactors, or Boiling Water Reactors, and are known as Generation II reactors (EIA 2007). Thus plants constructed in the short and medium term can only be incrementally different from current designs. Generation III and III+ reactors (which any new reactors built in the US will be) incorporate new safety features and standardized designs. It takes years to get regulatory approval for new reactor designs. Standardization, such as has been done in France, lowers costs substantially. Passive safety features activate through physical means, with little or no electricity and no human operators are necessary, increasing reliability in extreme traumas.

Breeders

Breeders are plants that use excess radiation to generate new fuels, with the combination of new LWR reactors could increase the amount of energy extracted from fissionable resources by 100 times (Martinez-Val 2007).

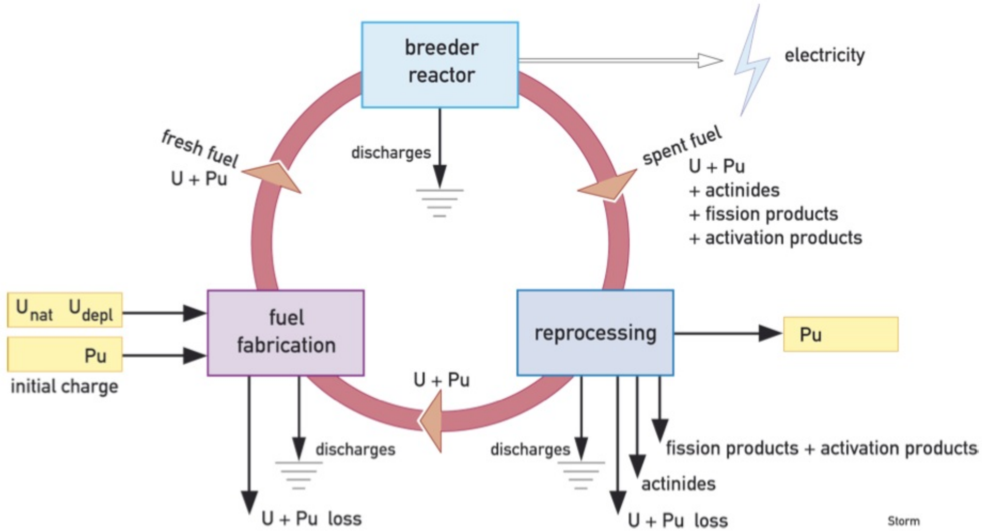

Figure 3 – General breeder cycle (Leeuwen 2005).
Click to Enlarge.

RESOURCE BASE

As noted in Proops (2001) and elsewhere, and shown in Figure 2, the nuclear fuel cycle is simple, and basically similar to the fossil fuel cycle. As can be the case with coal, the EROI and energy and economic balances in general seem to be highly dependent on ore-quality.

Uranium

Uranium can come in several types of deposits, with different energy requirements for extraction from each.

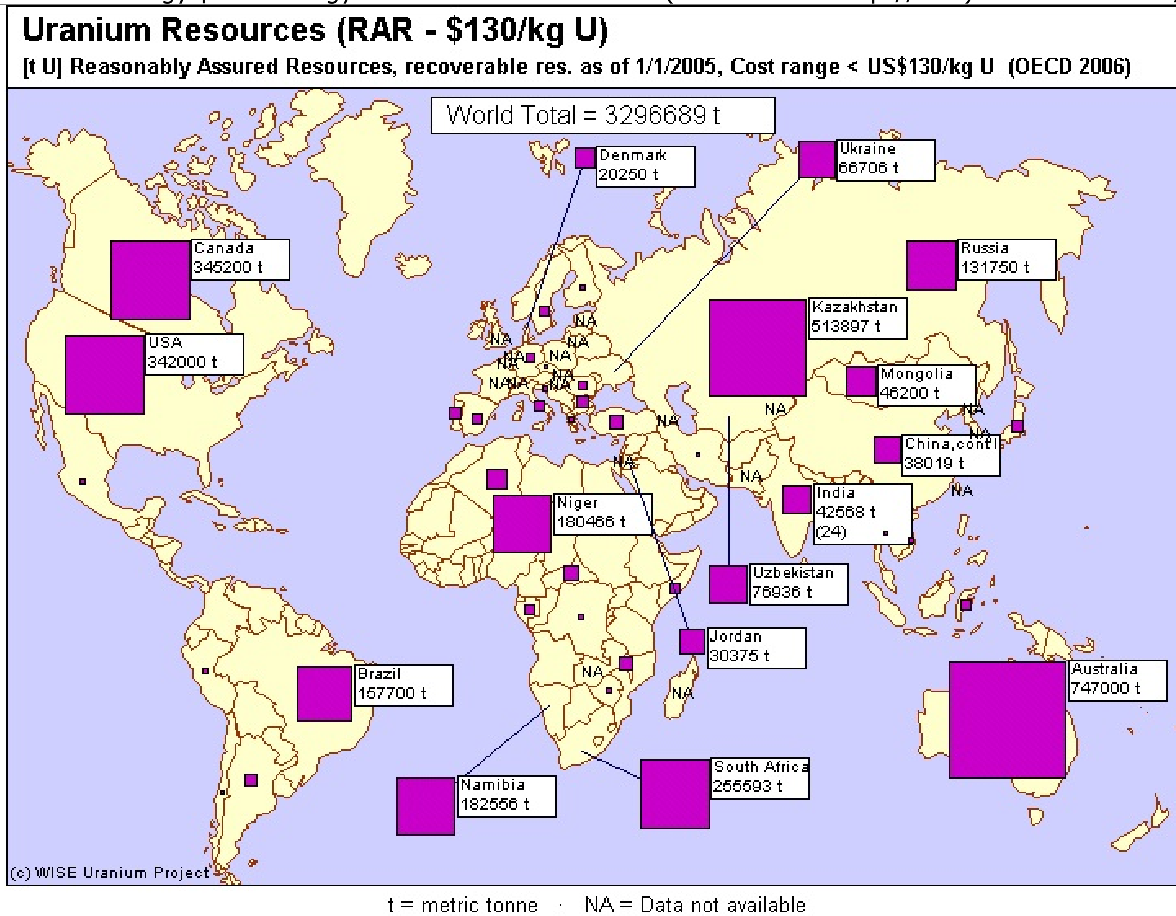

Figure 4 – Available uranium in the world (WISE 2007).

Click to Enlarge.

At current use rates, the known resources are enough to last for 70 years, although changes in price and technology can affect the economically recoverable resources available (Hore-Lacy 2006). As with other mineral resources the average grade of uranium has declined substantially over time as the best reserves have been depleted. The average grade mined also is very sensitive to the mining rate, and the mean grade declines substantially when the rate of extraction increases for society (Hall et al. 1986). Not much research, with the exception of Leeuwen (2005), has been done on the effect of net energy with regards to these decreasing quality deposits, which will be used when uranium increases in price.

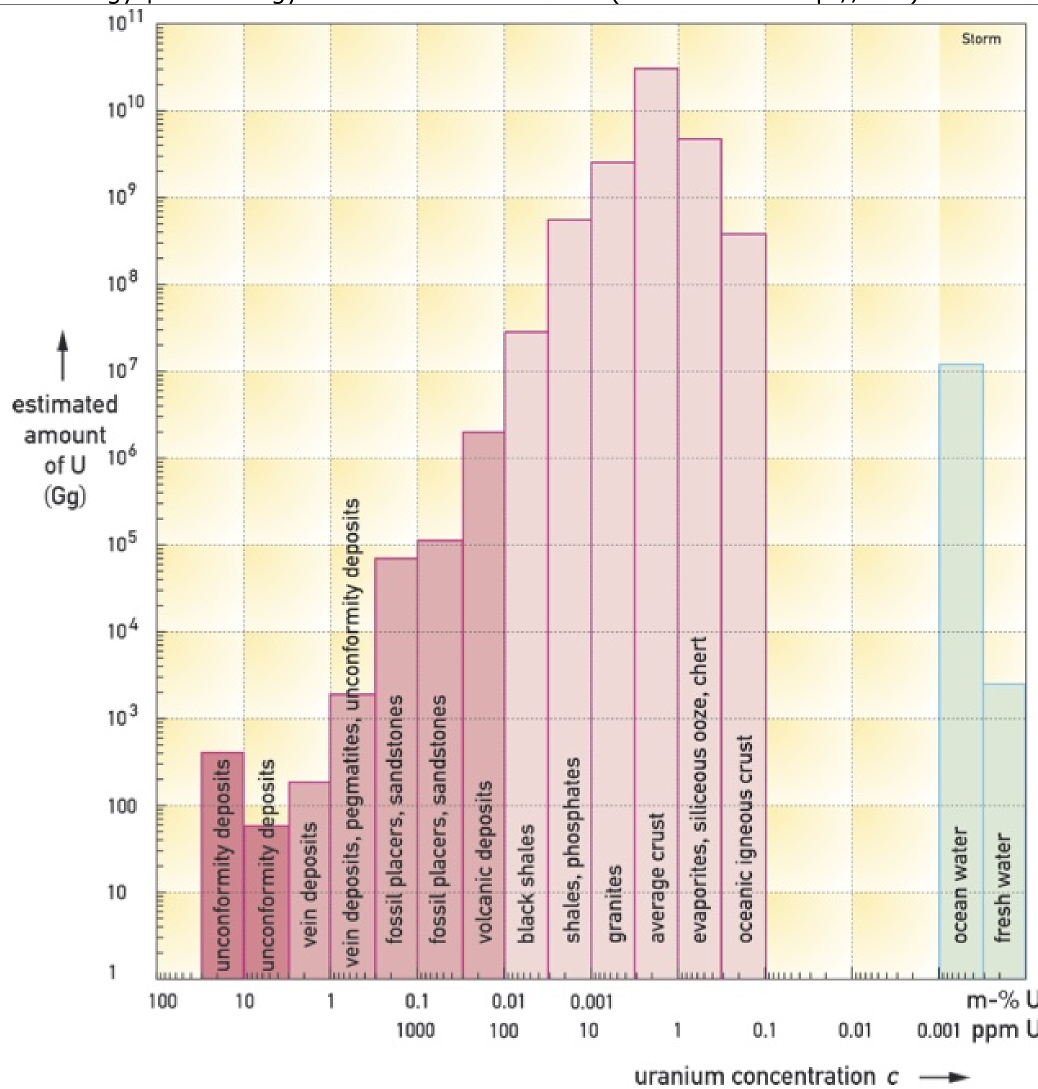

Figure 5 – Available uranium as a function of resource/ore type (Leeuwen 2005).
Click to Enlarge.

As extraction and depletion have operated over time, the average ore grade has decreased and the uranium has become more and more dispersed within the background substrate, plus the total amount of uranium we can extract can decrease as well. Leuwen (2005) argues that the empirical extraction yield declines much more sharply than the hypothetical one, which could come into play if there is a large increase in nuclear capacity in the coming decades.

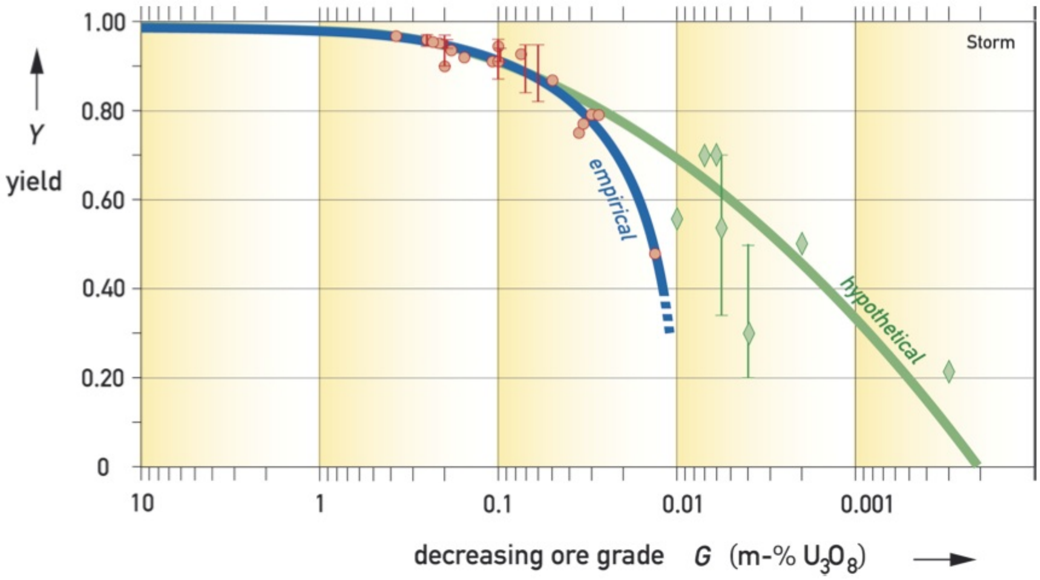

Figure 6 – % of Uranium Extracted from Ore as a Function of Ore Grade (Leeuwen 2005).
Click to Enlarge.

An increasing portion of the world's uranium comes from in-situ leaching (ISL) (Hore-Lacy 2007).

Figure 7 – In Situ Leaching (WISE 2007).
Click to Enlarge.

With ISL oxygenated groundwater is circulated through a porous ore-body to dissolve the Uranium and bring it to the surface. This should help the energy balance, as much less materials are being moved around, although it is unclear how concentrated (what grade) the ore must be.

Seawater

Uranium salts exist in seawater at low concentrations, as is the case for essentially every other element, and hence can be extracted from the massive total supplies in seawater. Some scientists in Japan are considering this, although according to at least one source, extraction of uranium from seawater would cost much more energy than contained in the uranium itself (Leeuwen 2006).

EROI

We have found the information about the EROI of nuclear power to be mostly as disparate, widespread, idiosyncratic, prejudiced and poorly documented as information about the nuclear power industry itself. Much, perhaps most, of the information that is available seems to have been prepared by someone who has made up his or her mind one-way or another (i.e. a large or trivial supplier of net energy) before the analysis is given. As is usually the case, the largest issue is often what the appropriate boundaries of analysis should be. The following diagram, which should be considered conceptually if not necessarily quantitatively appropriate, illustrates the main issues. The diagram indicates from left to right the timeline of a power plant, with the initial negative values ("phase 1") indicating the initial energy costs of plant construction, the large positive value generated over the reactor's lifetime (with a correction for the energy to get/refine the fuel) and phase 3 indicating the energy required for dismantling the plant and sequestering the dangerous by products.

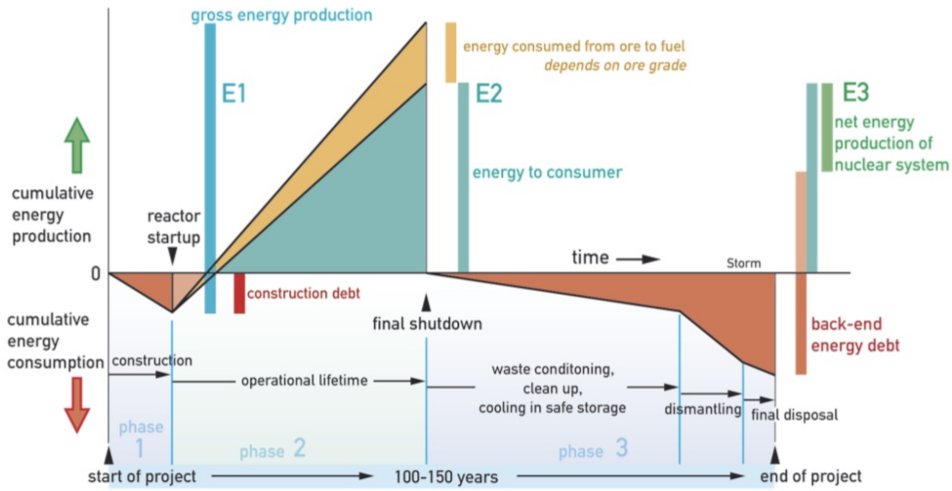

Figure 8 – Lifecycle view of energy costs and production (Leeuwen 2005). The above figure is a general outline of the energy costs and gains lifecycle, but does not accurately reflect the operational lifetime (which is more likely to be around 50 years) or the EROI (which depends on the study looked at).
Click to Enlarge.

The seemingly most reliable information on EROI is quite old and is summarized in chapter 12 of Hall et al. (1986). Newer information tends to fall into the wildly optimistic camp (high EROI, e.g. 10:1 or more, sometimes wildly more) or the extremely pessimistic (low or even negative EROI) camp (Tyner et al. 1998, Tyner 2002, Fleay 2006 and Caldicamp 2006). One recent PhD analysis from Sweden undertook an emergy analysis (a kind of comprehensive energy analysis including all environmental inputs and quality corrections as per Howard Odum) and found an emergy return on emergy invested of 11:1 (with a high quality factor for electricity) but it was not possible to undertake an energy analysis from the data presented (Kindburg, 2007). Nevertheless that final number is similar to many of the older analyses when a quality correction is included.

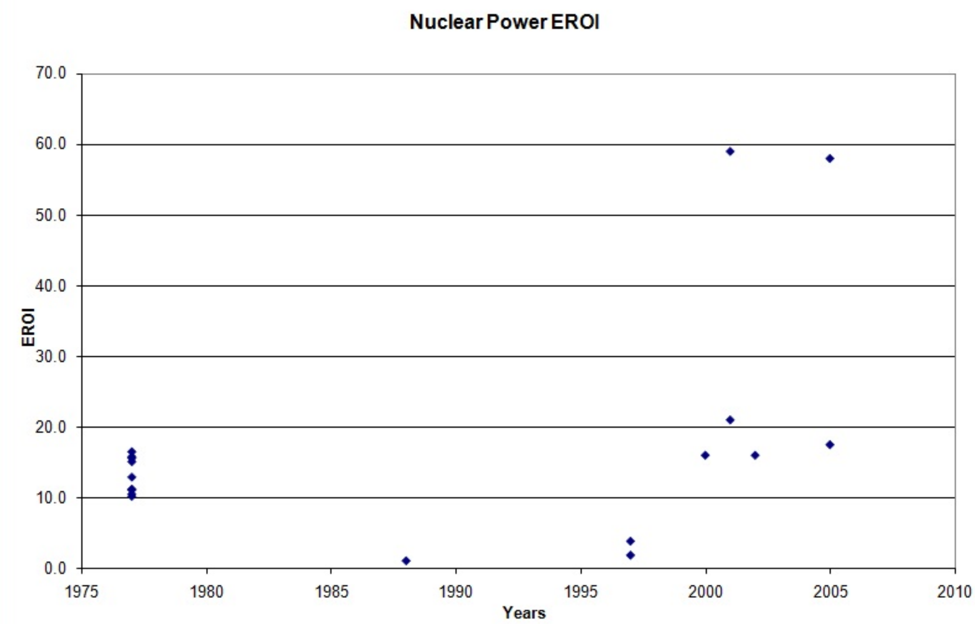

Figure 9. EROI for nuclear power plotted vs. year of analysis. (Source Robert Powers).
Click to Enlarge.

Tyner was the author (or co-author) on the 1988 and 1997 reports which are examples of the lower EROI numbers -- less than 5:1. Tyner's 1997 paper reported an "optimistic value" of 3.84 and a "less-optimistic" value of 1.86 and may be based on "pessimistic" cost estimates. For example capital monetary costs were 2.5 times higher than those reported for Generation III and III+ plants (Bruce Power 2007, see below). Fleay's 2006 on line paper at least gives very detailed numerical analyses of costs and gains and hence probably can be checked explicitly. Different boundaries are used for these "low EROI" studies than most other recent studies that effect the results. For example Tyner takes interest (with a 4-5x larger energy cost magnitude than capital energy costs) into account in EROI (Tyner 1997). The two large EROI values reported here were for nuclear lifecycles which used centrifuge fuel enrichment as opposed to diffusion-based enrichment. Centrifuge enrichment uses much less electricity than other methods (Global Security 2007). We do not know how to interpret these analyses because centrifugal separation is an old technology. Newer rotor materials allow more rapid rotor spin which might influence results. At present much of the enriched uranium used for nuclear power is coming from dismantled nuclear warheads from the US-Russian agreement to decrease nuclear warheads but, apparently, that program will soon come to an end and we will have to contemplate again generating nuclear power from mined uranium. Much of the arguments about the great or small potential of future nuclear power comes from those who argue about the importance of technology vs. those who focus on depletion. As usual, however, technology is in a race with depletion and the winner can be determined only from empirical analysis, of which there seems to be far too little.

Charles Hall inserts:

As an example of the disparity in information "out there" I quote the following from the responses to our earlier posting of the balloon graph on the web:

(From mkwin): ....A recent study I read from Melbourne University quantified the EROEI from the Forsmark Plant in France as 93:1. Source:

http://nuclearinfo.net/Nuclearpower/TheBenefitsOfNuclearPower

How can there be such a discrepancy (with the balloon graph)? This discrepancy on the EROEI figure for nuclear has to be clarified as one of the most urgent energy issue.

(a reply was posted by Chris): There is a large discrepancy because the report you read is intentionally deceptive. Their goal is to hide carbon emissions associated with nuclear power so when they calculate the EROEI they hide the energy needed to enrich the uranium. This is currently the largest energy input. France devotes the entire output of three reactors to enrichment so the EROEI of their program should be around 7 or less..... (Charles Hall stupidly gave the critics ammunition by extrapolating from that number to all reactors in France).

Charles Barton added later:

I f I were researching EROEI, I would identify who in India might be helpful in identifying information that would lead to an understanding of the EROEI of the Indian fuel cycle. If I were looking for information you might start with the Indian Department of Atomic Energy. http://www.dae.gov.in/ I would also suggest contacting the AECL of Canada, to get a picture of the EROEI of the CANDU reactor. http://www.aecl.ca/site3.aspx

I understand your frustration but your assumption that you can get a good picture of the EROEI of the nuclear Industry by a literature review and a **meta-analysis will lead to a distorted and inaccurate picture**. As I told you my interest in establishing a basis of comparison between competing or potentially competing nuclear power systems. **If you only analyze the EROEI of one system, and ignore the existence of other systems in Canada, and India, you will leave yourself open to criticism, and not just to me**.

So, dear reader, take your pick. I am not technically qualified to judge from all these differing perspectives. Please send any hard analyses you may have. We need a really good review by a committee of qualified people with few axes to grind. I leave you with one thought my mother told me long ago: caveat emptor.

ECONOMICS

There has been a general upward trend in the cost (in inflation-corrected dollars) of constructing a new nuclear power plant in the U.S., although there has not been a new plant completed for decades.

Plant Costs

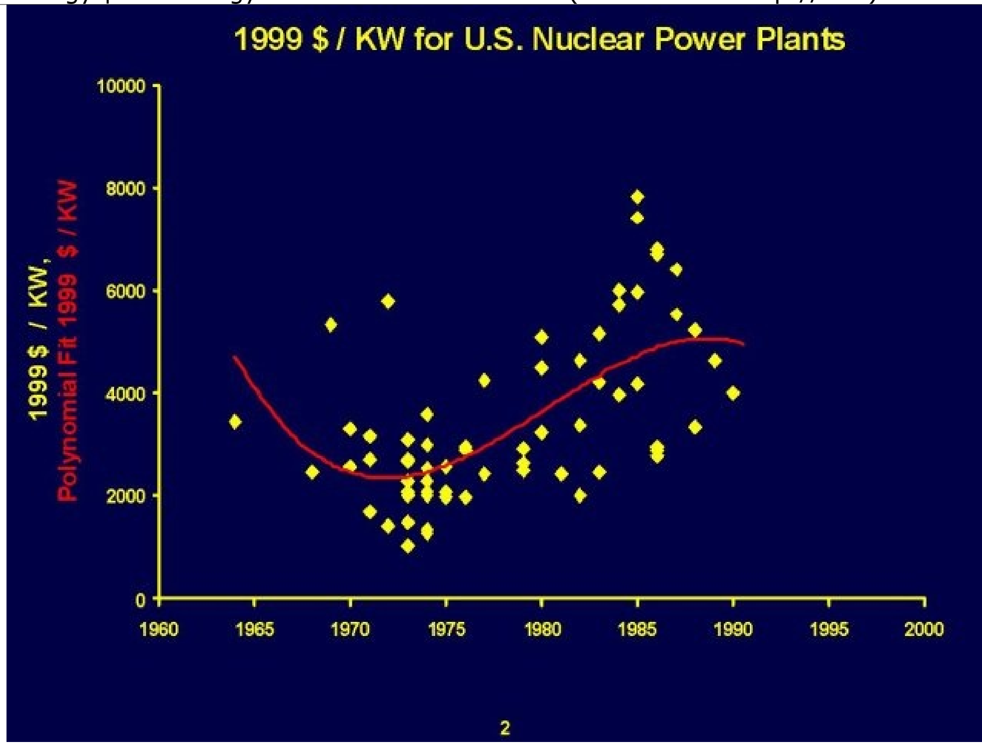

Figure 10 – Historical Capital Costs per KW of Nuclear Capacity Installed Over Time In the US
Click to Enlarge.

Bruce Power (2007) gives cost estimates for new plant construction (no subsidies included) as --- $1,000-1,100/KW for a Westinghouse AP1000 and $1,160-1,250/KW for a GE ESBWR. These costs are significantly lower than historical trends, and no plants with these designs have been completed yet in the US, so it remains to be seen if these cost projections are accurate. In general as the price of oil has increased so has the cost of just about everything.

Another unresolved issue is that of government subsidies. Proops (2001) lays out three main types: subsidies from the military nuclear industry, non-military government subsidies, and artificially low insurance. In the US the initial expenditure on uranium enrichment plants was exclusively from military budgets, so for these commercial plants the capital costs were written off. The figures for direct government subsidies are hard to come by, however billions have been spent by the government directly and through grants on nuclear power R&D (Proops 2001). In addition, the US government has pledged to cover up to $500 million in cost overruns due to regulatory delays for the first 2 new nuclear plants built, and half that for the next 4 (Energy Policy Act of 2005). There are also funds to cover the Nuclear Power 2010 Program, "a joint government/industry cost-shared effort to identify sites for new nuclear power plants, develop and bring to market advanced nuclear plant technologies, evaluate the business case for building new nuclear power plants, and demonstrate untested regulatory processes" (DOE 2007).

The longest standing, and perhaps most important, direct subsidy for nuclear power in the US is the Price-Anderson Nuclear Industries Indemnity Act. This act artificially maintains low insurance costs with "no-fault" insurance for operators. The first ten-billion dollars of damage from a major disaster would be covered by the nuclear industry (not solely the operator), and above that the government up the tab. Thus the nuclear industry in the USA has had to bear only a small proportion of the risk, the rest is assumed by the state or imposed as an uncovered risk on the public (Proops 2001). If commercial plants had to cover the full risks, such as the human, environmental and property damages from a major accident or terrorist attack, nuclear power would be extremely uneconomic (Proops 2001). In unsubsidized markets there are many natural-gas plants being built but not a single new nuclear plant, suggesting unsubsidized returns are not competitive with similar sized fossil-fuel plants (Proops 2001)

ENVIRONMENTAL IMPACTS

As in any large heavy industry there are substantial environmental impacts of operating the nuclear fuel cycle. Although the accidental release of radiation has received the largest attention, (even there have been no such deaths in the U.S. from more than 50 years of nuclear power), there are far more actual fatalities from the routine mining and processing of the material that will eventually enter a plant. The same perhaps could be said about environmental impact although no such overview exists to our knowledge. We next look at the impacts at each stage:

Mining

Open pit uranium mining has similar environmental impacts to other forms of open-pit mining, such as ecosystem removal or physical disruption, dust. leachates entering into water supplies and so on. In all uranium mining (except, perhaps, in situ leaching tailings are a major issue. While the leachates themselves are relatively low in radioactivity, the sheer amount of tailings (usually 100-1000x the amount of uranium extracted) make them a major issue (Anawa 2007). Radiation-emitting particles can leech into groundwater, or dried tailings from soft ores can be carried by wind and deposited on plants. The most serious (human) issue is lung cancer from inhaling uranium decay products (Anawa 2007).

Plant Operation

Accidents causing small to large releases of radiation can occur impacting either the local environment (in the case of a small loss of primary coolant) or much larger geographic areas (as was the case with the plume of radioactive fallout from Chernobyl). Large accidents also have the possibility of making huge areas of land uninhabitable, as was also the case for the area surrounding Chernobyl were over 300 thousand people were moved and resettled. There is production of radioactive waste from routine plant operation. These include: Low-level waste (such as tools used in the reactor, containment suits, used piping, etc) which are often dealt with on site, typically by burying for several years until it is not significantly radioactive anymore (Fentiman 2007). High-level waste includes materials such as spent fuel, and is much more radioactive and difficult to deal with. It must be stored on site for several years to cool down before the possibility of moving it to a geological repository is considered.

Waste Storage

Waste from nuclear reactors can contain lethal doses of radiation for thousands of years. The best known way to deal with waste is to store it in a geological repository, deep underground. Currently Yucca Mountain, Nevada is the only site being developed or investigated as a repository in the US, and is scheduled to begin accepting waste in 2017. More repositories will be needed especially if the use of nuclear power is expanded in the US. Even then, over tens of thousands of years waste could possibly leak into the water table. Again the issue is controversial even after extremely expensive and extensive analyses by the U.S. Department of Energy.

SOCIAL IMPACTS

People around the plant

While no one living near a nuclear power plant in the US has been killed accidents are an ever present fear and risk for those living near current power plants. Plants are also targets for terrorist attacks. New designs greatly reduce the probability of serious events associated with plants, but not necessarily the perception of high risk around plants.

Nuclear proliferation

Main fear in the US is that spent fuel will be stolen for use in a 'dirty bomb.'

Yucca Mountain

The area surrounding Yucca Mountain has traditionally been holy lands of the Western Shoshone, Southern Paiute, and Owens Valley Paiute and Shoshone peoples who arenaturally not enthusiastic about the construction or operation of the facility.

CONCLUSION

There are great potential gains and great potential costs with nuclear power. Existing reactors seems to work well and mostly safely although waste disposal problems remain. If the uranium resource limitation people are correct then we cannot go much further without a new technology, perhaps based on thorium. Various issues related to terrorism are more important than they used to be. Earlier "new technologies" such as Breeders (Clinch River, Super Phoenix) have been abandoned as too expensive. Plumbing issues have plagued the Candu style reactors, although they appear intrinsically cheaper and safer and do not require energy-intensive enrichment. Fusion is still many decades away. So there is no free lunch with nuclear. Nevertheless it is possible that nuclear fission should be considered as a transition fuel on our way to solar or something else simply because the cycle emits far less CO_2 than does any fossil fuel. In our opinion we need a very high level series of analyses to review all of these issues. Even if this is done it seems extremely likely that very strong opinions, both positive and negative, shall remain. There may be no resolution to the nuclear question that will be politically viable.

REFERENCES

Anawa http://www.anawa.org.au/mining/tailings.html

Bruce Power (Canadian) "New build Project Environmental Assessment" - Round One Open House BrucePower (2006). Retrieved on April 23, 2007.

Caldicott, H. 2006. Nuclear Power Is Not The Answer To Global Warming Or
Anything Else. Melbourne Press, Australia

Cleveland, Cutler J. (Topic Editor). 2007. "Nuclear fuel cycle." In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment). [First published October 8, 2006; Last revised January 28, 2007; Retrieved June 12, 2007].

DOE http://www.ne.doe.gov/np2010/neNP2010a.html

EIA http://www.eia.doe.gov/cneaf/nuclear/page/nuc_reactors/reactsum.html

Fentimann http://www.ag.ohio-state.edu/~rer/rerhtml/rer_10.html

Brian J Fleay. 2006. Nuclear power: energy inputs and life cycle net energy yields.

(Version 3, 23 October 2006. http://blog.greenparty.ca/files/Nuclear_In_Out_3.pdf)

Global Security http://www.globalsecurity.org/wmd/intro/u-centrifuge.htm

Hall, C.A.S., C.J. Cleveland and R. Kaufmann. 1986. Energy and Resource Quality: The ecology of the economic process. Wiley Interscience, NY. 577 pp. (Second Edition. University Press of Colorado).

Hore-Lacy, Ian (Lead Author); U.S. Nuclear Regulatory Commission (Content source);

Lindburg, A. 2007. Emergy evaluation of a Swedish Nuclear Power Plant. Uppsula University Neutron Physics Laboratory Report ISNN 1401 – 6269.

Mills, David. (2006) Comparison of solar, nuclear and wind options for large scale implementation. Presidential Address Australian/New Zealand Solar energy society 2006.

Storm van Leeuwen, Jan Willem and Phillip Smith (2004), "Can Nuclear Power Provide Energy for the Future; Would it

Solve the CO2 Problem?", www.stormsmith.nl.

Proops, J.L. et al (1996). The Lifetime Pollution Implications of Various Types of Electricity Generation – An Input-Output Analysis. Energy Policy 24(3) pp 229-237

Proops J., 2001 "The (non-) economics of the nuclear fuel cycle: an historical and discourse analysis, Ecological Economics,39: 13-19.

Tyner, Gene. 2002. Net Energy from Nuclear Power. Minnesotans for sustainability (web site).

Tyner, Gene, R. Costanza and R. G. Fowler. 1988. The Net-energy yield of nuclear power. Energy Vol. 13, No. 1, pp. 73-81,

WISE Uranium Project http://www.wise-uranium.org

Additional theoildrum.com articles related to net energy analysis and EROI:

An EROEI Review
North American Natural Gas Production and EROI Decline
The Energy Return on Time
Peak Oil - Why Smart Folks Disagree - Part II
Ten Fundamental Truths about Net Energy
The North American Red Queen - Our Natural Gas Treadmill
Energy From Wind - A Discussion of the EROI Research
A Net Energy Parable - Why is EROI Important?