Energy Return on Investment

(*Updated August 2017*)

- **Life-cycle analysis, focused on energy, is useful for comparing net energy yields from different methods of electricity generation.**
- **Nuclear power shows up very well as a net provider of energy, and only hydro electricity is nearly comparable.**
- **External costs, evaluated as part of life-cycle assessment, strongly favour nuclear over coal-fired generation.**
- **Energy return on (energy) investment is a way of measuring relative inputs and outputs.**

The economics of electricity generation are important. If the financial cost of building and operating the plant cannot profitably be recouped by selling the electricity, it is not economically viable. But as energy itself can be a more fundamental unit of accounting than money, it is also essential to know which generating systems produce the best return on the energy invested in them. This energy return on investment (EROI), the ratio of the energy delivered by a process to the energy used directly and indirectly in that process, is part of life-cycle analysis (LCA). Since any energy costs money to buy or harvest, EROI is not divorced from economics. An EROI of about 7 is considered break-even economically for developed countries. The US average EROI across all generating technologies is about 40. The major published study on EROI, by Weissbach *et al* (2013, since the early editions of this paper) states: “The results show that nuclear, hydro, coal, and natural gas power systems (in this order) are one order of magnitude more effective than photovoltaics and wind power.”

Analysing this energy balance between inputs and outputs, however, is complex because the inputs are diverse, and it is not always clear how far back they should be taken in any analysis. For instance, oil expended to move coal to a power station, or electricity used to enrich uranium for nuclear fuel, are generally included in the calculations. But what about the energy required to build the train or the enrichment plant? And can the electricity consumed during uranium enrichment be compared with the fossil fuel needed for the train? Many analyses convert kilowatt-hours (kWh) to kilojoules (kJ), or vice versa, in which assumptions must be made about the thermal efficiency of the electricity production.

Some inputs are easily quantified, such as the energy required to produce a tonne of uranium oxide concentrate at a particular mine, or to produce a tonne of particular grade of UF_6 at a uranium enrichment plant. Similarly, the energy required to move a tonne of coal by ship or rail can be identified, although this will vary considerably depending on the location of the mine and the power plant. Moving gas long distances by pipeline is surprisingly energy-intensive. (Several studies which include gas take LNG shipment to Japan as the norm.)

Other inputs are less straightforward such as the energy required to build a 1000 MWe power plant of a particular kind, or even to construct and erect a wind turbine. But all such energy inputs, as with cash inputs by way of capital, need to be amortised over the life of the plant and added to the operational inputs. Also the post-operational energy requirements for waste management and decommissioning plants must be included.

As well as energy costs, there are external costs to be considered, those environmental and health consequences of energy production which do not appear in the financial accounts. Recent studies have plausibly quantified them in financial terms, and there is comment on those at the end.

Many energy analysis studies done in the 1970s seem to have assumed that a rapid expansion of nuclear generating capacity would lead to a temporary net energy deficit in an overall system sense. However, this requires dynamic analysis of whole systems, and is not considered here. Studies were also driven by a perception that primary energy sources including uranium would become increasingly difficult and expensive to recover, and would thus require undue amounts of energy to access them. This notion has since resurfaced, despite being demonstrably wrong for any plausible scenarios.

The figures in Table 1 are based as far as possible on current assumptions and data for enrichment, mining and milling, *etc*. For nuclear power, enrichment was clearly the key energy input historically where the older diffusion technology was used – it comprised more than half the lifetime total. However, with centrifuge technology now universally used it is far less significant than plant construction. There was an overall threefold difference in energy ratio between these two (past and present) nuclear fuel cycle options.

As yet, no figures seem to have been tabulated for a closed fuel cycle with reprocessing, although this would probably reduce the energy inputs for nuclear power production somewhat (there would be extra energy inputs, but about a 25% reduction in enrichment input).

It is also important to recognise that precise energy figures for plant construction are not readily available, although several studies use a factor converting monetary inputs to energy.

Peterson *et al* (2005) have presented materials figures for four reactor types:

- Generation II PWR of 1000 MWe: 75 m^3 concrete and 36 t steel per MWe.
- ABWR of 1380 MWe: 191,000 m^3 concrete, 63,440 t metal – 138 m^3

concrete and 46 t metal/MWe.

- EPR of 1600 MWe: 204,500 m^3 concrete, 70,900 t metal – 128 m^3 concrete and 44.3 t metal/MWe.
- ESBWR of 1500 MWe: 104,000 m^3 conc, 50,100 t metal – 69 m^3 concrete and 33 t metal/MWe.

The AP1000 is similar to the ESBWR per MWe but no actual data is given.

Using gross energy requirement figures of 50 GJ/t for steel or 60 GJ/t for metal overall, 1.5 GJ/t or 3 GJ/m^3 for pure concrete, this data converts to:

- Generation II PWR needs: 225 GJ concrete + 2160 GJ metal/MWe = 2.3 PJ/GWe.
- ABWR needs: 414 GJ concrete + 2760 GJ metal/MWe = 3.2 PJ/GWe.
- EPR needs: 384 GJ concrete + 2658 GJ metal/MWe = 3.0 PJ/GWe.
- ESBWR needs: 207 GJ concrete + 1980 GJ metal/MWe = 2.2 PJ/GWe.

In common with other studies the inputs are all in primary energy terms, joules, and any electrical inputs are presumed to be generated at 33% thermal efficiency.

The figures now in Table 1 for plant construction and operation, and also for decommissioning, are from Weissbach *et al* (2013) adjusted for 1 GWe. They are slightly higher than the above estimates, but much lower than earlier published US figures (ERDA 76-1). Our fuel input figures are 60% higher than Weissbach. Hence our EROI is 70, compared with 105 in that study.

The only data available for storage and disposal of radioactive wastes, notably spent fuel, suggests that this is a minor contribution to the energy picture. This is borne out by personal observation in several countries – spent fuel sitting quietly in pool storage or underground is not consuming much energy. Decommissioning energy requirements may be considered with wastes, or (as

Vattenfall) with plant construction.

In Vattenfall's 2014 Environmental Product Declaration statements, the Forsmark nuclear power plant had life-cycle energy inputs of 3.8% of output, for Ringhals inputs were 4.2% of output), hence EROI of 56 and 50 respectively. These figures compare with inputs of 6.3% of output for Vattenfall's wind farms, split fairly evenly onshore and offshore, hence EROI of 16 on either basis.

Table 1: **Life-cycle energy requirements for a 1000 MWe nuclear power plant**

Inputs (100% load basis)	GWh (e)	TJ (th) Annual		PJ (th) 40 year	PJ (th) 60 year
Mining & milling – 230 t/yr U_3O_8/195 tU, at Ranger		63		2.51	3.8
Conversion (Schneider 2010)				1.74	2.6
Initial enrichment: Urenco centrifuge	10.0			0.11	0.11
Reload enrichment: Urenco centrifuge	5.8	62		2.48	3.72
Fuel fabrication (Schneider 2010)				1.0	1.5
Construction of plant (Weissbach 2013)				3.0	3.0
Operation of plant (Weissbach 2013)				3.43	5.15
Fuel storage, waste storage, transport (ERDA 76-1, Perry 1977, Sweden 2002)				1.5	2.25
Decommissioning (Weissbach 2013)				0.9	0.9
Total				**18.4**	**23.0**

Output: 7.5 TWh/yr (86% capacity factor)	7500 GWh	27,000 TJ(e)		**1080** PJ(e)	**1620** PJ(e)
Input percentage of lifetime output				**1.70%**	1.42%
Energy return on investment (output/input)				**59**	**70**

Assumptions

Fuel cycle: 1000 MWe, 40 year life, 86% capacity factor, centrifuge enrichment @ 50 kWh/SWU with 0.25% tails (2.5 SWU/kg for initial 80 t fuel load @ 2.3% U-235, 4.8 SWU/kg for 3.5% fresh fuel @ 24 t/yr), 45 000 MWd/t burn-up, 33% thermal efficiency.

Mining: Ranger ore in 2008 was 0.26% U head grade. Energy: 273 GJ/t U_3O_8, 322 GJ/tU, including significant development work. (Note that if ore of 0.01% U is envisaged, this would give 1638 TJ/yr, 70 PJ total for mining & milling, hence total 108 PJ for the centrifuge option, thus inputs become 3.3% of output and energy ratio becomes 30.) All Ranger inputs are thermal (it generates own electricity). The Schneider 2010 figure for mining & milling is similar to Rössing.

Figures for Beverley ISL operation 2004-05: 187 GJ/t U_3O_8, 221 GJ/tU.

Rössing 2012 & 2013: 650 GJ/t U_3O_8, 770 GJ/tU, with ore head grade 0.020%U.

Calculations: Electrical inputs including those in Schneider *et al* 2010 are converted to thermal @ 33% efficiency (x 10 800, kWh to kJ)

Other figures for front end: Cameco mines in Saskatchewan input 41 TJ per 230t U_3O_8 over 1992-2001 including some capital works. On the same basis, Areva's McClean Lake mine there had input 72 TJ, and two Areva mines in

Niger in 2000 input was 47 TJ per 230 t product.
Urenco enrichment at Capenhurst input 62.3 kWh/SWU for whole plant in 2001-02, including infrastructure and capital works. In 2006 Urenco confirmed 50 kWh/SWU as indicative whole plant figure including infrastructure, so this figure is used above. Weissbach has 9.65 PJ for all fuel-related input with centrifuge enrichment for 1340 MWe over 60 years.

Other figures for construction (but not operation) of 1000 MWe PWR power plant: 13.6 PJ (Chapman 1975, recalculated), 14.76 PJ (Held *et al* 1977, if converted direct), 24.1 PJ (Perry *et al* 1977), 4 PJ (of which 35% electrical – Weissbach 2013 for 1340 MWe), 2 PJ for 1200 MWe Forsmark-3. Using data from Peterson *et al* 2005 as in text above, 2.3 PJ for Gen II PWR, 3.2 PJ for ABWR for materials only, estimated to be 95% of energy input to construction.

for 30 yr conversion: 1.67 PJ (Chapman 1975), 9 PJ (Perry *et al* 1977, table IV).
for 30 yr fuel fabrication: 0.42 PJ (Chapman 1975), 5 PJ (Perry *et al* 1977, table IV).
for waste facilities in Sweden: 0.19 PJ
for decommissioning: Bruce A 5.2 PJ, Bruce B 4.3 PJ, Darlington 4.5 PJ, Pickering A 5.7 PJ, Pickering B 6.2 PJ.

Energy payback time. If 3.1 PJ is taken as the energy capital cost of setting up (with centrifuge enrichment), then at 27 PJ/yr output the initial energy investment is repaid in about six weeks at full power. Voss (2002) has 3 months. Construction time for nuclear plants is 4-5 years.

Key: GWh (gigawatt hour); PJ (petajoule = 10^{15} J); TJ (terajoule = 10^{12} J); TWh (terawatt hour); SWU (separative work unit)

Table 2: **Life-cycle energy ratios for various technologies**

		Source	R3 energy ratio – EROI (output/input)
Hydro		Uchiyama 1996	50
		Held *et al* 1977	43
	NZ run of river	Weissbach 2013	50
	Quebec	Gagnon *et al* 2002	205
Nuclear (centrifuge enrichment)		See Table 1	81
	PWR/BWR	Kivisto 2000	59
	PWR	Weissbach 2013	75
	PWR	Inst. Policy Science 1977*	46
	BWR	Inst. Policy Science 1977*	43
	BWR	Uchiyama et al 1991*	47
Coal		Kivisto 2000	29
	black, underground	Weissbach 2013	29
	brown,open pit, US	Weissbach 2013	31
		Uchiyama 1996	17
		Uchiyama *et al* 1991*	16.8
	unscrubbed	Gagnon et al 2002	7
		Kivisto 2000	34
Natural gas	- piped	Kivisto 2000	26
	- CCGT	Weissbach 2013	28
	- piped 2000 km	Gagnon *et al* 2002	5
	LNG	Uchiyama *et al* 1991*	5.6

	LNG (57% capacity factor)	Uchiyama 1996	6
Solar		Held *et al* 1997	10.6
Solar thermal parabolic		Weissbach 2013	9.6
Solar PV	rooftop	Alsema 2003	12-10
	polycrystalline Si	Weissbach 2013	3.8
	amorphous Si	Weissbach 2013	2.1
	ground	Alsema 2003	7.5
	amorphous silicon	Kivisto 2000	3.7
Wind		Resource Research Inst.1983*	12
		Uchiyama 1996	6
	Enercon E-66	Weissbach 2013	16
		Kivisto 2000	34
		Gagnon *et al* 2002	80
		Aust Wind Energy Assn 2004	50
		Nalukowe *et al* 2006	20.24
		Vestas 2006	35.3

* In IAEA 1994, TecDoc 753.

These figures show that energy ratios are clearly sensitive not only to the amount of energy used, but also to capacity factors, particularly where there are significant energy inputs to plant. Just as with cash inputs to plant construction, the higher the input cost in consruction the more output is needed to amortise it. With technologies such as wind, this is inevitably spread over a longer period due to lower capacity factors.

The LNG figures quoted are for natural gas compressed cryogenically and shipped to Japan and used largely for peak loads. The solar and wind figures relate to intermittent inputs of primary energy, with inevitably low capacity utilisation and relatively high energy costs in the plant (for silicon manufacture in the case of solar cells, or steel & concrete for wind turbines).

Schneider *et al* (2013) have a detailed assessment of energy use in mining and conclude (without fuel cycle data) that the energy use in uranium production represents less than 1% of the energy produced in the once-through nuclear fuel cycle, and that even with the most pessimistic scenarios to 2100 the energy input from mining will remain less than 3% of output.

Unlike some others in use, the R3 energy ratio converts between electrical and thermal energy, including a thermal efficiency factor. Nevertheless the reciprocal percentage seems more meaningful.

Uchiyama (1996) points out that hydro, nuclear and fossil fuel plants have high energy ratios because of their higher energy density as well as capacity factors. Wind and solar, however, are under 10 because of their lower energy density.

Vattenfall (1999) mentions that the production of pure silicon for solar photovoltaics (PV) requires large energy inputs and accounts for most resource consumption in solar cell manufacture.

Voss (2002) shows hydro, wind and nuclear with inputs less than 7% of lifetime outputs, then gas and coal between 17 and 30%.

Alsema (2003) shows inputs of 8 to 13% of output for solar PV, along with 50-60 g/kWh for CO_2 emission.

The Nalukowe *et al* 2006 study on wind looks at 3 MWe Vestas turbine on land in Denmark over 20 years with 30% capacity factor, and the 2006 Vestas LCA study is on basis of same criteria.

It is noteworthy that for all present energy options EROI includes the full fuel cycle, but imputes no energy value to what may be intrinsic in the fuel. In contrast, at this stage energy return figures for nuclear fusion relate only to the energy input to the fusion process relative to what the device yields. The objective is for this yield to become significantly positive.

Life-cycle analysis: external costs and greenhouse gases

A principal concern of life-cycle analysis for energy systems today is their likely contribution to global warming. This is a major external cost.

If all energy inputs are assumed to be from coal-fired plants, at about one tonne of carbon dioxide per MWh, it is possible to derive a greenhouse contribution from the energy ratio. With major inputs, this is worth investigating further.

Rashad & Hammad conclude that the life-cycle CO_2 emission coefficient for nuclear power, on the basis of centrifuge enrichment, is 2.7% of that for coal-fired generation. This is consistent with other figures based on fossil fuel inputs. Norgate *et al* (2013) estimate nuclear life-cycle GHG emissions as about 34 g/kWh CO2e for 0.15% U_3O_8 ore grade, and increasing to about 60 g/kWh for 0.01% ore.

The ExternE study (1995) attempted to provide an expert assessment of life-cycle external costs for Europe including greenhouse gases, other pollution and accident potential. The European Commission launched the project in 1991 in collaboration with the US Dept of Energy (which subsequently dropped out), and it was the first research project of its kind "to put plausible financial figures against damage resulting from different forms of electricity production for the entire EU." A further report, focusing on coal and nuclear, was released in 2001.

The external costs are defined as those actually incurred in relation to health and the environment and quantifiable but not built into the cost of the electricity to the consumer and therefore which are borne by society at large. They include particularly the effects of air pollution on human health, crop yields and buildings, as well as occupational disease and accidents. In ExternE they exclude effects on ecosystems and the impact of global warming, which could not adequately be quantified and evaluated economically.

The methodology measures emissions, their dispersion and ultimate impact. With nuclear energy the (low) risk of accidents is factored in along with high estimates of radiological impacts from mine tailings and carbon-14 emissions from reprocessing (waste management and decommissioning being already within the cost to the consumer).

The report shows that in clear cash terms nuclear energy incurs about one tenth of the costs of coal. In particular, the external costs for coal-fired power were a very high proportion (50-70%) of the internal costs, while the external costs for nuclear energy were a very small proportion of internal costs, even after factoring in hypothetical nuclear catastrophes. This is because all waste costs in the nuclear fuel cycle are internalised, which reduces the competitiveness of nuclear power when only internal costs are considered. The external costs of nuclear energy averages 0.4 euro cents/kWh, much the same as hydro, coal is over 4.0 cents (4.1-7.3 cent averages in different countries), gas ranges 1.3-2.3 cents and only wind shows up better than nuclear, at 0.1-0.2 cents/kWh average.

The EU cost of electricity generation without these external costs averages about 4 cents/kWh. If these external costs were in fact included, the EU price of electricity from coal would double and that from gas would increase 30%. These particular estimates are without attempting to include possible impacts of fossil fuels on global warming. See also ExternE website.

Figures published in 2006 for Japan show 13 g/kWh, with prospects of this halving in future.

Adding further confirmation to figures already published from Scandinavia, Japan's Central Research Institute of the Electric Power Industry has published life-cycle carbon dioxide emission figures for various generation technologies. Vattenfall (1999) has published a popular account of life-cycle studies based on the previous few years experience and its certified environmental product declarations (EPDs) for Forsmark and Ringhals nuclear power stations in Sweden, and Kivisto in 2000 reports a similar exercise for Finland. They show the following CO_2 emissions:

g/kWh CO_2	Japan	Sweden	Finland
coal	975	980	894
gas thermal	608	1170 (peak-load, reserve)	-
gas combined cycle	519	450	472
solar photovoltaic	53	50	95
wind	29	5.5	14
nuclear	22	6	10 - 26
hydro	11	3	-

The Japanese gas figures include shipping LNG from overseas, and the nuclear figure is for boiling water reactors, with enrichment 70% in USA, 30% France & Japan, and one-third of the fuel to be MOX. The Finnish nuclear figures are for centrifuge and diffusion enrichment respectively, the Swedish one is for 80% centrifuge.

As noted earlier, Vattenfall's most recent EPD shows life-cycle carbon dioxide emissions for Forsmark of 3.10 g/kWh. The figure for British Energy's Torness nuclear power plant in 2002 was 5.05 g/kWh.

For a further and unrelated critique see Melbourne University-based discussion and more specifically, the rebuttal of SLS.

Information from this source shows that using data from Storm van Leeuwen & Smith one gets annual energy costs for three major uranium mines of 5 PJ for Ranger, 60 PJ for Olympic Dam (both in Australia) and 69 PJ for Rössing in Namibia. These mines report their energy use as 0.8 PJ, 5 PJ and 1 PJ respectively, with that at Olympic Dam including copper production (only about 20% of value of output is uranium). Rössing mines very low-grade ores, but its energy cost is overestimated sixty-fold or more by Storm van Leeuwen & Smith and the figure they predict is more than that for the whole country (c 50 PJ).

Nuclearinfo.net concludes: "Our work shows that this (Storm van Leeuwen & Smith) work is not reliable and in fact leads to outrageously high predictions for the energy cost of Uranium mining for modern mines and mills."

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Sylvia Fedoruk Canadian Centre for Nuclear Innovation, Study shows that Saskatchewan uranium mining emits few greenhouse gases (8 September 2016)

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LCA comparisons updated 2005 & 2006

Critique of 2001 paper by Storm van Leeuwen and Smith: *Is Nuclear Power Sustainable?* and its May 2002 successor: Can Nuclear Power Provide Energy for the Future; would it solve the CO_2-emission problem?
with reference to a 2005 version entitled *Nuclear Power, the Energy balance*

A "semi-technical" document by Jan Willem Storm van Leeuwen and Philip Smith with the title *Is Nuclear Power Sustainable?* was prepared for circulation during the meeting in April 2001of the United Nations Commission on Sustainable Development, and also during the continuation in Bonn in July 2001 of the Climate Conference. An updated version appeared in mid August 2001, then a "thoroughly-revised" version in May 2002, together with a "rebuttal" of this critique. However, at no point do the authors engage or refer to the substantive WNA paper to which this is an appendix! - and which counters their position. This was partly rectified in the 2005 version.

The 2001 Storm van Leeuwen & Smith (SLS) paper dismisses arguments that nuclear energy is sustainable, either physically, environmentally or in terms of its energy costs, and this is repeated in the numerically-depleted May 2002 version. They purport to offer "evidence" that building, operating and producing fuel for a nuclear plant produces as much carbon dioxide as a similar sized gas-fired plant. The foregoing WNA paper, quoting all the reputable studies we are aware of, shows that this is demonstrably wrong - there is a 20 to 50-fold difference in favour of nuclear.

The SLS arguments regarding sustainability are based on a "Limits to Growth" perception of mineral resources and a misunderstanding of the notion of ore reserves. The fallacies of the "Limits to Growth" argument have been well canvassed since the 1970s, and their falsity best illustrated by declining mineral prices (in real terms). In respect to uranium, they are addressed in the WNA paper *Supply of Uranium* in this series. The SLS papers depend on outdated and invalid assumptions, largely because many of the figures used are taken from a study originally done in 1982. Much has changed since then and much more work has been done on quantifying the issue.

- Only diffusion enrichment is considered, whereas centrifuge methods now widely used are up to 50 times more energy efficient (less than 50 instead of 2400 kWh/SWU operationally). There is no reason to suggest that the energy capital of centrifuge plants would be greater. About two-thirds of current enrichment is by centrifuge.
- The future use of new reactor designs, including fast reactors, is dismissed on the grounds that some research programs in Europe have been closed down. However, Russia has been operating a 600 MW commercial fast reactor at Beloyarsk in the Urals for decades and on the basis of its operating success is now building a new larger version on the same site. The main reason there are not more fast reactors is that they are uneconomic in an era of low uranium prices. SLS completely misrepresents the reason for fast reactors being sidelined: the abundance of cheap uranium fuel. Should uranium ever look like becoming scarce, there is over 200 reactor-years of operating experience, including some in breeder reactor mode, on which to base a new generation of fast breeder reactors.
- Over the shorter term, no allowance is made for plant life extension of nuclear reactors, although this is now commonplace and extends operating life significantly, typically to 60 years.
- In uranium mining, energy costs are now very well quantified, and no consideration is given to relatively new technologies such as in-situ leaching which is more efficient than traditional mining methods in terms of both cost and energy use.

One important point of agreement with Storm van Leeuwen and Smith, however, is that all relevant energy inputs throughout the fuel cycle need to be considered in any comparison with fossil fuels or other sources of electricity. Their assertion that large energy debts are incurred in operating the nuclear fuel cycle, on the other hand, is demonstrably false, as is the assumption that nuclear plants incur excessive economic debts. Any debts incurred are normally funded during operation. Moreover, they are minor and of the same order as those of other industrial plant. The energy debts are trivial in relation to the net output from any nuclear plant.

The brief 2002 paper itself (now 8 pages and devoid of data except for its preoccupation with low ore grades) refers to a "Facts and Data" supplement. The 2001, 52-page version was a little closer to real life than the earlier 29-page version, though it did correct some gross errors. The 2002 version was said to be "thoroughly revised" and chapters of the 2005 web version are fourth and sixth revision.

Rather than using audited industry data the 2001 version used figures which are questionable and need to be examined in more detail. They all refer to the base case of a 1000 MWe (3125 MWth) PWR reactor with 3.3% enriched fuel @ 33 GWd/t burn-up and make reference to 4.2% enrichment and 46 GWd/t "advanced practice". Some of these figures are changed in the 2005 version. (Electrical figures multiplied by 3 to give basis comparable with main paper.)

> Mining & milling: 275 GJ/tU for soft ores and 654 GJ/tU in hard ores, giving respectively 54 TJ/yr and 127 TJ/yr (@ 195 tU/yr)
> Conversion 1.6 GJ/kgHM (1.5 GJ/kgU in 2002 & 2005)
> Enrichment (diffusion only, 0.2% tails) 31.3 GJ/SWU = 2900 kWh/SWU (same in 2002). The 2005 revision has 3.1 GJ/SWU for centrifuge and quotes old figures for diffusion.
> Fuel fabrication 3.8 GJ/kgU in 2005 (6.0 GJ/kg in 2002, using ERDA 76/1 data)
> Power plant construction 81 PJ, or 95 PJ if all thermal basis (this is from Storm van Leeuwin 1982/1985 paper, see below). In 2002 & 2005 a number of figures are given based on mass and costs. Those for $1400/kW plant cost range 31-45 PJ, which are credible but untested.
> Operation & maintenance 2.8 PJ/yr (2.85 PJ/yr in 2002, 3.2 PJ/yr in 2005)
> Decommissioning 240 PJ (same in 2002 & 2005)

> Spent fuel storage, conditioning & disposal: 11.2 GJ/kg, 5.6 GJ/kg, 12.2 GJ/kg respectively, hence say 30 GJ/kg overall, so 2.4 PJ for initial fuel load plus 0.6 PJ/yr. 2002 figures are 11.1, 2.65 & 12.26 respectively, total 26 GJ/kg overall)
> Other radwastes: 56 GJ/m 3

While some figures are based on real data, others depend on a notional relationship between capital costs and energy inputs which in the case of nuclear power need to be qualified for sometimes lengthy construction delays. It is quite obvious that if the capital cost blows out due to delays, the energy cost of a plant does not increase accordingly. It should be possible to get actual energy data for recent nuclear plants constructed in Japan, South Korea and Europe but neither we nor SLS have them. The life-cycle assessment for Vattenfall's Forsmark-3 nuclear plant showed that 4.1 PJ was required for construction and decommissioning, on basis of 40 year plant life.

The most contentious SLS figures came from an earlier paper "Nuclear Uncertainties" by Storm van Leeuwin (Energy Policy 13,3, June 1985), itself based on an earlier 1982 study. This contained some interesting presuppositions which the "rebuttal" strenuously disowns, eg a PWR "optimistically" has an operating life of 12 full-load years (cf typical 40 years @ 90% = 36 full-load years). But reference to this happily seems to have been jettisoned.

Some of the figures quoted above from the 2001 paper are based on real data, but some are apparently far from having any empirical basis, particularly those depending on speculative and unsupported figures from the earlier paper. The energy costs of uranium mining and milling are well known and published, and form a small part of the overall total. Even if they were ten times higher they would still be insignificant overall. However, the authors first totally ignored these but in 2002 have published data mostly from 1970s but finally arriving the figures quoted above which are reasonable and in line with ours. The energy costs of nuclear power plant construction can readily be estimated, as can those for waste management and decommissioning, and recent Scandinavian work (Vattenfall 1999, 2001 & 2004, *Vattenfall's life cycle studies of electricity* and also Finnish data) has quantified these with a higher degree of precision than has previously been attempted. The Vattenfall EPD studies giving rise to the LCA data are audited. These confirm that the capital, decommissioning and waste management costs are not unduly high nor even close to the well-quantified energy costs of enrichment.

The following indicates how widely the 2001 and subsequent SLS figures diverge from recently-published data (treating it all on thermal basis): Power plant construction: suggested as 95 PJ. This is four times higher than the nearest published figure from the 1970s, and more significantly it compares with 4.1 PJ for building and decommissioning in the Vattenfall 2002 life-cycle study. Kivisto gives comparable figures for the Finnish study: 650 MWh/MW capacity, hence energy payback in a month's operation, and 7.0 PJ overall for a 1000 MWe plant.

> Power plant operation: given as 2.8 PJ/yr, which compares with 1.1 PJ over 40 years in the Vattenfall 2002 life cycle study.
> Power plant decommissioning: suggested as being more than twice that for construction, but see above re Vattenfall life cycle study where it is aggregated with construction.
> Uranium enrichment: 3.1 GJ/SWU for centrifuge compares with actual 0.673 GJ/SWU at URENCO Capenhurst in 2001-02, including some capital works.
> Spent fuel management: 2.4 PJ initial + 0.6 PJ/yr compares with 4.3 PJ total in Vattenfall 2002 life cycle study.
> Mining: It is difficult to discern a sensible figure from the paper, though it is clear that ores of less than 0.1% U are seen as energy-intensive with traditional mining methods. However, little of the world's uranium comes from such. In contrast, a modest 5.5 PJ over 40 years or 0.1375 PJ/yr is shown from the Vattenfall 2002 life cycle study for mining and milling, using low-grade ores, and 0.039 PJ/yr would be the contribution on the basis of more limited Ranger mine data (excluding mine and mill construction etc) for higher-grade ores. If the Ranger operation were producing from 0.01% ore this would give 0.9 PJ/yr. In 2004 ERA reported 199 GJ/tU for Ranger, a figure about one third of SLS for hard ores. The increasing production from solution (in situ leaching) mining (including some low grade ores) would be lower again.

Conclusion

The 2001 and 2002 Storm van Leeuwen & Smith papers and Background Information represent an interesting attempt to grapple with a complex subject but depend on many essentially speculative figures to put the case that nuclear energy incurs substantial energy debts and gives rise to minimal net energy outputs considered on a lifetime basis. Recent life-cycle assessment (LCA) studies such as Vattenfall's show figures around ten times lower for key capital and waste-related energy demands. The Vattenfall life cycle study gives a bottom line of 1.35% of lifetime energy output being required for all inputs, and only a tiny fraction of this being in the nature of energy debts.

Finally, it should be pointed out that, even on the basis of their assumptions and using their inaccurate figures, Storm van Leeuwen & Smith still are forced to conclude that nuclear power plants produce less CO_2 than fossil-fuelled plants, although in their view "the difference is not large". Others might see a 20 to 50-fold difference (between nuclear and gas or coal) as significant. The audited Vattenfall figure for CO_2 emission on lifecycle basis is 3.10 g/kWh, less than one percent of the best fossil fuel figure. This could approximately double if nuclear power inputs to enrichment were replaced by fossil fuel ones, but it is still very low.

It is clear, then that the concerns related to energy costs at the heart of the Storm van Leeuwen & Smith paper can be dismissed. The authors' other point, that nuclear energy is not sustainable, is addressed in the Sustainable Energy and Supply of Uranium papers in this series.

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