Energy Analysis of Power Systems

UIC Nuclear Issues Briefing Paper # 57

March 2006

- ***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 with centrifuge enrichment, only hydro electricity is closely comparable.***
- ***External costs, evaluated as part of life cycle assessment, strongly favour nuclear over coal-fired generation.***

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 is part of Life Cycle Analysis (LCA).

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 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 UF6 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.) *

* Most energy analyses do not quantify the energy content of the fuel. It is similarly ignored here.

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 I will 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 re-surfaced.

The figures in Table 1 are based as far as possible on current assumptions and current data for enrichment, mining and milling, etc. Where current data is unavailable, that from earlier studies is used. For nuclear power, enrichment is clearly the key energy input where the older diffusion technology is used - it comprises more than half the lifetime total. However, with centrifuge technology it is far less significant than plant construction. There is an overall threefold difference in energy ratio between these two nuclear fuel cycle options.

As yet, no figures seem to have been tabulated for a closed fuel cycle with reprocessing, such as is UK policy (and upsetting some Irish observers), although this would probably reduce the energy inputs for nuclear power production somewhat *. 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.

* there would be extra energy inputs, but about a 25% eduction in enrichment input.

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.

Table 1. **Life Cycle Energy Requirements for Nuclear Power Plant**

(after ERDA 76/1, Appendix B, with current data where available)

	GWh (e)	TJ (th) Annual	PJ (th) 40 year	PJ (th) 40 year
Inputs			diffusion	centrifuge
Mining & Milling - 230 t/yr U_3O_8 / 195 tU at Ranger		39	1.56	1.56
Conversion (ConverDyn data)			9.24	9.24
Initial enrichment: diffusion @ 2400 kWh/SWU	480		5.18	
OR: Initial enrichment: Urenco centrifuge @ 63 kWh/SWU	12.6			0.14
Re-load enrichment: diffusion @ 2400 kWh/SWU	276	2981	119	
OR: Re-load enrichment: Urenco centrifuge @ 63 kWh/SWU	7.3	78		3.12
Fuel Fabrication (ERDA 76/1)			5.76	5.76
Construction & Operation (ERDA 76/1)			24.69	24.69

Fuel storage, Waste storage, Transport (ERDA 76/1, Perry 1977, Sweden 2002) allow			1.5	1.5
Decommissioning (Ontario data)			6.0	6.0
Total (diffusion enrichment)			**173**	
OR: Total (centrifuge enrichment)				**52**
Output: 7 TWh/yr	7000	75 670	**3020**	**3020** PJ

Input percentage of lifetime output, thermal	(diffusion)	5.7%
	(centrifuge)	1.7%
Energy ratio (output/input), thermal	(diffusion)	17.5
	(centrifuge)	58

Assumptions:
Fuel Cycle: 1000 MWe, 40 year life, 80% capacity factor, enrichment 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 2004 was 0.234% U. Energy: 165 GJ/t U_3O_8, 195 GJ/tU. (Note that if ore of 0.01% U is envisaged, this would give 924 TJ/yr, 37 PJ total for mining & milling, hence total 89 PJ for the centrifuge option, thus inputs become 2.9% of output and energy ratio becomes 34.)
Figures for Beverley ISL operation 2004-05 are 187 GJ/t U_3O_8, 221 GJ/tU.
Rossing 2004: 306 GJ/t U3O8, 361 GJ/tU, with calculated ore grade 0.0276%U.
Calculations: Electrical inputs 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, Cogema's McClean Lake mine there input 72 TJ and two Cogema mines in Niger in 2000 input 47 TJ. Urenco enrichment at Capenhurst input 62.3 kWh/SWU for whole plant in 2001-02, including infrastructure and capital works.

Comparison with ERDA 76/1: Ranger data (1997-98) x 34 years shows only 20% of the mining & milling energy use but excludes plant construction. The 2000 ConverDyn data is identical to ERDA. The diffusion enrichment data above (on higher tails assay, burn-up, and capacity factor) gives only 66% of the ERDA figure but excludes plant construction. ERDA notes that "the centrifuge process is expected to reduce the direct requirement for electricity by a factor of ten", in fact today it is better than that.

Other figures for construction (but not operation) of 1000 MWe PWR power plant are: 13.6 PJ (Chapman 1975, recalculated), 14.76 PJ (Held et al 1977, if converted direct), 24.1 PJ (Perry et al 1977), 2 PJ for 1200 MWe Forsmark-3.
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 30 PJ or 25 PJ is taken for diffusion and centrifuge enrichment respectively as the energy capital cost of setting up, then at 75 PJ/yr output the initial energy investment is repaid in 5 months or 4 months respectively 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).*

Life cycle analysis for Vattenfall's Environmental Product Declaration for its 3090 MWe Forsmark power plant for 2002 have yielded some energy data which complement those in Table 1 and broadly confirm them, for lower-grade ores, but over 40 year lifetime. Electrical inputs have been multiplied by 3 on the assumption that they might have come from coal-fired plant (though most were hydro).

On basis of PJ (thermal) per 1000 MWe the input figures are:

Mining	5.5
Conversion	4.1
Enrichment	23.1
Fuel fabrication	1.2
Plant operation	1.1
Build & decommission plant	4.1
Waste management	4.3
TOTAL	43.4 PJ

The output of Forsmark is 7.47 TWh/yr per GWe. Over 40 years: 299 TWh or 3226 PJ.

Input is thus 1.35% of output.

Details:
Re mining: 42% of U comes from Rossing (0.025%U), 37% from Olympic Dam (0.042%U), 21% from Navoi (ISL).
Enrichment: 20% Eurodif (diffusion), 60% Urenco, 20% Tenex (both centrifuge) - over 90% of energy input is from nuclear.
CO2 emissions: 3.10 g/kWh.

Table 2. **Life Cycle Energy Ratios for Various Technologies**

		Source	R3 Energy Ratio. (output/input)	Input % of lifetime output
Hydro		Uchiyama 1996	50	2.0
		Held et al 1977	43	2.3
	Quebec	Gagnon et al 2002	205	0.5
Nuclear (centrifuge enrichment)		see table 1.	59	1.7
	PWR/BWR	Kivisto 2000	59	1.7
	PWR	Inst. Policy Science 1977*	46	2.2
	BWR	Inst. Policy Science 1977*	43	2.3
	BWR	Uchiyama et al 1991*	47	2.1
Nuclear (diffusion enrichment)		see table 1.	21	4.8
	PWR/ BWR	Held et al 1977	20	5.0
	PWR/BWR	Kivisto 2000	17	5.8

		Uchiyama 1996	24	4.2
	PWR	Oak Ridge Assoc.Univ. 1976*	15.4	6.5
	BWR	Oak Ridge Assoc.Univ. 1976*	16.4	6.1
	BWR	Uchiyama et al 1991*	10.5	9.5
Coal		Kivisto 2000	29	3.5
		Uchiyama 1996	17	5.9
		Uchiyama et al 1991*	16.8	6.0
	unscrubbed	Gagnon et al 2002	7	14
		Kivisto 2000	34	2.9
Natural gas	- piped	Kivisto 2000	26	3.8
Natural gas	- piped 2000 km	Gagnon et al 2002	5	20
	LNG	Uchiyama et al 1991*	5.6	17.9
	LNG (57% capacity factor)	Uchiyama 1996	6	16.7
Solar		Held et al 1997	10.6	9.4
Solar PV	rooftop	Alsema 2003	12-10	8-10
	ground	Alsema 2003	7.5	13
	amorphous silicon	Kivisto 2000	3.7	27
Wind		Resource Research Inst.1983*	12	8.3
		Uchiyama 1996	6	16.7
		Kivisto 2000	34	2.9
		Gagnon et al 2002	80	1.3
		Aust Wind Energy Assn 2004	50	2.0

* 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 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).

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.

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.

Uranium enrichment in USA is by diffusion and some of this capacity is supplied by coal-fired plants. If a national average, allowing for different sources of power, is applied, this input has a value of around 650 kg CO_2/MWh. This gives a greenhouse contribution for nuclear power of about 40kg/MWh overall. In France, however, which has the world's largest diffusion enrichment plant, electricity is supplied by on-site nuclear reactors (which also supply the grid). Because of this, the greenhouse contribution from any nuclear reactor using French-enriched uranium is similar to a reactor using centrifuge-enriched uranium -- less than 1kg/MWh for the enrichment input, and less than 20 kg/MWh overall.

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.

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 web site.

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.

---

see also Melbourne University nuclearinfo web page

Sources:

Chapman P.F. 1975, Energy analysis of nuclear power stations, Energy Policy Dec 1975, pp 285-298.
ERDA 1976, A national plan for energy research, development and demonstration: creating energy choices for the future, Appendix B: Net energy analysis of nuclear power production, ERDA 76/1.
ExternE 1995, Externalities of Energy, vol 1 summary, European Commission EUR 16520 EN.
Held C. et al 1977, Energy analysis of nuclear power plants and their fuel cycle, IAEA proceedings.
IAEA 1994, Net energy analysis of different electricity generation systems, IAEA TecDoc 753.
Kivisto A. 1995, Energy payback period & CO2 emissions in different power generation methods in Finland, , in International Association of Energy Economics conference proceedings 1995 (also Lappeenranta University of Technology series B-94, 1995) plus personal commucincation 2000 with further detail on this.
Perry A.M. et al 1977, Net energy from nuclear power, IAEA proceedings series.
Rashad & Hammad 2000, Nuclear power and the environment, Applied Energy 65, pp 211-229.
Uchiyama Y. 1996, Life cycle analysis of electricity generation and supply systems, IAEA proceedings series.
Vattenfall 1999, Vattenfall's life cycle studies of electricity, also energy data 2000.
Vattenfall 2004, Forsmark EPD for 2002 and SwedPower LCA data 2005.
British Energy 2005, EPD for Torness Nuclear Power Station.
Voss A. 2002, LCA & External Costs in comparative assessment of electricity chains, NEA Proceedings.
Alsema E. 2003, Energy Pay-back Time and CO2 emissions of PV Systems, Elsevier Handbook of PV.
Gagnon L, Berlanger C. & Uchiyama Y. 2002, Life-cycle assessment of electricity generation options, Energy Policy 30,14.
Tokimatsu K et al 2006, Evaluation of Lifecycle CO2 emissions form Japanese electric power sector. Energy Policy 34, 833-852.

Supplement, August 2002
LCA comparisons updated 2005

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 CO2-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 numericallydepleted 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.

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

For further information Search this site or Return to Index

Uranium Information Centre Ltd
A.C.N. 005 503 828

GPO Box 1649, Melbourne 3001, Australia
phone (03) 9629 7744
fax (03) 9629 7207