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10 April 2007

Critical note on the estimation by Storm van Leeuwen J.W. and Smith P. of the energy uses and corresponding CO_2 emissions from the complete nuclear energy chain

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Extreme evaluations should not be used for drawing conclusions on specific technologies

The estimation of energy uses and corresponding greenhouse gas emissions (GHG) from the nuclear energy chain by Storm van Leeuwen J.W. and Smith P. (last available version: SvLS 2005)[1] is often quoted especially by nuclear opponents who question the characteristic of nuclear energy to be near GHG-free. SvLS guesstimate relatively high to very high energy requirements and hence corresponding CO_2 emissions for the electricity of nuclear origin, the highest to be found in the literature circulating in Internet,[2] especially when low grade uranium ores are considered. The main explanation for SvLS' high figures lies in their extreme assumptions (often rough guesses, as the authors admit themselves) and partially flawed methodology.

However, because of ideological connotations of the opposition to nuclear energy, often the quotation of (SvLS 2005) is not accompanied by citation of and comparison with the tens of other relevant technical studies that have been and are being produced on the subject, with different results although prevalently converging to relatively low GHG emissions. An opponent to nuclear energy likely chooses the reference that best matches his presumptions, without undergoing the process of critically analyzing and comparing its assumptions and results vs. other studies. Symmetrically, a supporter of nuclear energy may wish to refer only to those studies that conclude that nuclear energy is the best performer among electricity options with respect to GHG emissions. Correct approach would be to use transparent life cycle assessment (LCA) studies best fitting specific conditions being addressed,[3] with inclusive boundaries, and compare/quote the obtained results with other likewise transparent and possibly reviewed studies to capture the likely ranges in order to account of uncertainties.

This Note is not such a complete comparative study, which would require substantial resources and time; rather it is aimed at pointing out the major flaws of (SvLS 2005) comparing it with the

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[1] "There are a number of publications by Storm van Leeuwen and Smith (SLS) […] that have received considerable attention because of these authors' critical attitude regarding nuclear power. In particular, their study has been cited in many submissions to the [Australian] Prime Minister's Uranium Mining, Processing and Nuclear Energy Review […]. There have also been counter arguments by the World Nuclear Association […], with a rebuttal by SLS […], and by the University of Melbourne […], with a rebuttal […], a response by the University of Melbourne […]; a second rebuttal […], and a second response […]. The arguments put forward in the most recent exchanges are not new: The literature documents a similar debate between Mortimer […] and opponents […]."
(http://www.pmc.gov.au/umpner/docs/commissioned/ISA_report.pdf)

[2] Frequent contacts with the SvLS website and other linked websites cause their work to be top in Google searches on nuclear energy and its CO_2 or GHG emissions.

[3] E.g., as a matter of fact the energy and GHG intensity of the nuclear chain may differ with technology and country/region of application, mostly depending on the background energy/electricity mix and the process used for enrichment for the current situation. Also uranium ore grade and mining practice may be important factors in view of possible exhaustion of high grade ores.

PSI study (Dones 2003) and one very recent Australian study (ISA 2006) which on the one hand is criticizing, on the other hand selectively using some figures from (SvLS 2005). The study (ISA 2006), applicable to Australian conditions, estimated moderately high emissions of GHG from an hypothetical Australian complete open-cycle nuclear chain, yet lower than in (SvLS 2005) on the average. Hereinafter, evidence will be provided to criticize also (ISA 2006).

For simplifying the use of this Note by a non technical person, each argument is summarized by a title in bold. However, essential technical details are provided in the explanations following.

SvLS (2005) is not the only publicly available evaluation of the entire nuclear chain

SvLS (2005) is just one attempt to the estimation of the energy intensity and associated CO_2 emission from the nuclear energy chain, whose merit is to raise the issue of the assessment of energy expenditures in mining low-grade uranium ores that may need to be exploited in the long-term, pessimistic scenarios. However, assumptions and results in (SvLS 2005) for current nuclear energy are contradicted by assumptions, data and results from the vast majority of other technical reports dealing with the same subject.[4] Some very recent reviews and studies on the topic are (the list may not be complete):

- Vattenfall (2004; 2005):	LCA for Environment Product Declaration (EDP); GHG for operational Swedish Light Water Reactors (LWR) is calculated below 4 g(CO_2-eq)/kWh. Construction and decommissioning of mining, milling, conversion, enrichment and fuel fabrication are not included, with claim that the related error is only 1-2%.
- BE (2005):	LCA for EDP of the Torness two Advanced Gas Cooled Reactors (AGR); 5 g(CO_2)/kWh. If Torness used ore from Olympic Dam (conservatively allocating 25% of all mine energy uses to uranium) for all its fuel, emissions would raise to 6.85 (CO_2)/kWh.
- ISA (2006):	LCA; GHG for hypothetical Australian nuclear chain of about 60 g(CO_2-eq)/kWh for Light Water Reactors (LWR), with a range 10-130 g(CO_2-eq)/kWh considering parameterization. This study is used herein for more detailed comparative purposes.
- SDC (2006):	Survey of 31 sources reporting on LWR energy chain; range of 30 studies: 2-77 g(CO_2)/kWh, thereof only 3 studies give >40 g(CO_2)/kWh; one outlier with 140-230 g(CO_2)/kWh (the anti nuclear WISE, from a 1992 Dutch study).[5]

[4] SvLS (2005, Introduction, #3) quote a few of such studies up to year 2004. However, the authors do not critically address their own evaluation in view of findings from those studies. Instead, they extract worst data from just one presentation (Orita 1995: Preliminary Assessment on Nuclear Fuel cycle and Energy Consumption), which is a highly incomplete survey, was never reviewed, nor it reports the used sources. ISA (2006, #35) discard figures reported in Orita (1995) on mining as "outliers". This presentation material is included in a non finalized document labeled "Working Material" reporting on an IAEA Advisory Group Meeting (IAEA 1996: Working Material (limited distribution) - Assessment of Greenhouse Gas Emissions from the Full Energy Chain for Nuclear Power and Other Energy Sources – Papers presented at an Advisory Group Meeting, IAEA, 26-28 Sept. 1995, Vienna). SvLS qualify the data presented at that meeting as oversimplified and incomplete as if this were representing the whole of studies on the nuclear chain. Incidentally, several studies whose intermediate results were presented at the IAEA had and have been published in reports and journal papers and are acknowledged as reference LCA studies. The writer of this Note participated in the meeting and has issued an LCA study of the current nuclear energy chain for LWR (Dones 2003; previous versions 1994 and 1996) which is contained in the background LCA database ecoinvent (www.ecoinvent.ch) used in all commercial LCA software tools.

[5] Actually, 62-230 g(CO_2)/kWh are given in the WISE website: http://www10.antenna.nl/wise/index.html?http://www10.antenna.nl/wise/389/3791.html

- Weisser (2007): Survey of recent LCA studies on electricity technologies; range in four studies on or including LWR is 3-24 g(CO_2-eq)/kWh.
- Fthenakis and Kim (2007): LCA of US specific current conditions for photovoltaics and nuclear; range for LWR is 16-55 g(CO_2-eq)/kWh.
- Dones (2003; et al. 2005): LCA of Swiss and European LWR, as well as other energy systems (Dones et al. 2004a, b); range for LWR is 5-12 g(CO_2-eq)/kWh (lowest value is calculated with centrifuge enrichment, including or not a quota from Eurodif diffusion enrichment).

Table 1 reports an overview of the conclusions on CO_2 (or GHG, in CO_2-eq.) emissions from the three sources compared herewith. Table 2 reports the main characteristics of these three references.

Table 1: Comparison of GHG emission per kWh from the three sources (SvLS 2005), (ISA 2006) and (Dones 2003).

Greenhouse gas emission [unit]	SvLS (2005, Chapter 1, #5)	ISA (2006)	Dones (2003) ecoinvent
[g(CO_2)/kWh]	ores > 0.2%: 66 (no decommissioning) 120 (full decommissioning)		
	ores = 0.02%: 160 (no decomm.; soft ores) 200 (no decomm.; hard ores) 235 (full decomm.; soft ores) 285 (full decomm.; hard ores) Faster increasing with further decreasing ore grade		
	Faster increasing with further decreasing ore grade		
[g(CO_2-eq.)/kWh]		60 (range 10 -130) [a]	5-12 [b]

[a] Most of the values calculated in (ISA 2006) for LWR are around 60 g(CO_2)/kWh. Lower end of this range is calculated on the basis of a low-carbon economy, i.e. a “90% renewable/nuclear economy”. As commented in (ISA 2006, #114): “The greenhouse gas intensities for the best-case scenario agree with those obtained for the low-carbon economies Switzerland (Dones et al. 2004a) and Japan (Hondo et al. 2000; Uchiyama 1999).” Upper range values were calculated on the basis of low-grade (0.01%) shale uranium mining, high-carbon economy, and 100% diffusion enrichment.

[b] Using ISA (2006) assumption 70/30 mix centrifuge/diffusion, and electricity supply to diffusion and centrifuge from the Australian electricity mix (2014) as reported in ISA (2006), ecoinvent would calculate approximately 18-21 g(CO_2-eq.)/kWh cumulative from the full energy chain. If the US diffusion enrichment plant Paducah, supplied by fossil electricity, were the exclusive enrichment service supplier for a PWR, ecoinvent would calculate about 52-58 g(CO_2-eq.)/kWh cumulative from the full energy chain.

The original study is by Biesiot W., “Kernenergie: Een Beoordeling van de Risico's van Nieuw te Bouwen en Bestaande Installaties”, Groningen 1992 (in Dutch). It is not available to the author of this Note. However, based on few information in the antinuclear Stichting Laka “Kernenergie geen remedie tegen broeikaseffect”, retrived at http://www.laka.org/info/publicaties/broeikas/1996-broeikas.pdf, the high values are likely originated by consideration of mining low grade uranium ores. However, no evidence is provided in this pamphlet on the origin of the values adopted.

Table 2: Main characteristics of the methodology and modeling used in the three sources (SvLS 2005), (ISA 2006) and (Dones 2003).

SvLS (2005)	ISA (2006)	Dones (2003) ecoinvent
- Partially based on AEI = Method of multiplying total cost with (national) Average Energy Intensity, w/o discrimination of component costs. - When not guesstimated with AEI, energy intensities are taken from old literature - Evaluation focused on energy consumptions and CO_2 emissions. - Preferred choice of upper or near upper range values - Generic open cycle (or once through chain, i.e. w/o reprocessing and recycling of plutonium) for LWR, non country-based - Guessed modeling for decommissioning to green field; upper estimations	- Based on hybrid LCA, i.e. combining Process Analysis (PA) & Input/Output (I/O) methodologies - Denial of AEI - Evaluation focused on energy consumptions and CO_2 emissions. - Energy intensities partly taken from old literature (e.g. disregard of modern centrifuge enrichment) - Choice of average to near upper range values - Specific for hypothetical nuclear energy development in Australia, although basis data may be generic; data on mining/milling are real Australian-specific - Open cycle for LWR and Heavy Water Reactors (HWR) - All phases of the life of all stages of the chain are considered; mill tailings reclamation according to Australian current practice also included.	- Based on full Process Analysis (PA) of the entire nuclear energy chain for Swiss and European conditions; calculation of cumulative results is performed using a PA-based background database (ecoinvent, adopted in virtually every commercial LCA software tool) to describe full life cycle of industries (material & chemical manufacturing, energy conversion, electricity network, transport, waste management) - Energy intensities and environmental burdens (full spectrum) from old and recent literature and industry data - All species of GHG included. - Choice of average to near upper range values if data are from literature; use of average and best estimate for data from Swiss industry - Model designed specifically for nuclear energy chain associated to Swiss LWR, including Swiss interim storage and repositories (open cycle as well as cycle with reprocessing and MOX fuel use); extrapolated to European chains - All phases of the life of all stages of the chain are included; energy uses for mill tailings reclamation may be incomplete. - Enrichment is modeled with two diffusion plants and two centrifuge plants, each with appropriate electricity supply.

SvLS (2005) methodology, assumptions and reporting are highly questionable

a) SvLS (2005, Introduction, #3) state that [sic] “The issue is that an honest evaluation of any system used to produce energy (this is the conventional wording – the correct terms is to “convert” energy), energy units should be used, both for the production and for the costs.” This because “the use of a money scale introduces the unpredictable effects of such factors as market prices, cartel price-forming and price regulations” that may alter the comparison in view of the evaluation of environmental (and overall) sustainability. They also state: “We have chosen, as been done in most of the analyses in which environmental values are considered, to use units of energy in this analysis because energy is a conserved quantity, whereas money is an arbitrary, and more importantly, a variable measure.”

The problem is that **SvLS (2005) often convert costs into energetic terms using generic factors, not reported in the text, lacking critical consideration of cost components, and lacking use of technical match to compare with real energy expenditures**.

b) Furthermore, **SvLS (2005) add thermal to electric energy directly to give "total energy", which is certainly not recommended practice**. Correct would be to convert electricity into thermal equivalent (through appropriate efficiency) to finally add only thermal energy figures (or vice-versa, with electric energy) or use primary energy only.[6] Although SvLS (2005) regularly report the ratio thermal to electric energy for own data and data from the literature, accompanying the given total "energy", the way this information is used for the final calculation is not transparent.

c) **SvLS do not provide explicitly conversion factor(s) PJ_e or PJ_{th} to CO_2 mass.**

Quoting from (ISA 2006): "The study [(SvLS 2005)] neither states energy nor greenhouse gas intensities".[7]

SvLS (2005) comparison of CO_2 emission from nuclear with natural gas is not consistent

SvLS (2005) does not include different species of GHG but only CO_2. Nevertheless, CO_2 is certainly the most important GHG species for current energy systems.

Fig. 6 in (SvLS 2005, Chapter 1, #5) compares emission of CO_2 from the nuclear chain with a "gas-burning plant", in relative terms (%). For high ore grades in uranium mines (i.e. the current situation), the (generic, for SvLS do not specify sites) nuclear chain is estimated to emit either 18% or 33% of the CO_2 from the *operation* of the gas plant, depending whether decommissioning of the nuclear facilities with complete reclamation of land to green field is not performed or is performed, respectively. From data in (SvLS 2005) one can deduce that the "gas-burning plant" emits 364 g(CO_2)/kWh. This is most likely a modern gas combined cycle (GCC) plant, with presumably 55% efficiency. Therefore, according to (SvLS 2005) the (current) open nuclear cycle emits approximately 66 g(CO_2)/kWh or 120 g(CO_2)/kWh, respectively without and with full decommissioning throughout the chain.

However, when comparing energy (electricity) systems with one another, similar system boundaries should be chosen for a fair comparison of the different technologies. In this case, **SvLS (2005) omits emissions of different GHG from the supply natural gas chain**.

This would add about 20%[8] to SvLS (2005) 364 g(CO_2)/kWh, giving approximately 440 g(CO_2-eq)/kWh. Nuclear would then emit 15% or 27% of the gas chain, under SvLS' assumptions.

Besides, for comparisons of future systems, future conditions should be assumed for all systems.

SvLS (2005) use references that are likely to be outdated

The upstream chain is described using overwhelmingly references that date back to the 1970s.

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[6] Primary energy should be differentiated in terms of energy of fossil, nuclear and renewable origin (as in the ecoinvent database).

[7] ISA (2006) assumes an average carbon content of 90 g CO_2-eq/MJ to recalculate figures from SvLS (2005) for own comparisons.

[8] Based on ecoinvent result for average European conditions (Dones et al., 2004a,b; Dones et al. 2005). The contribution from upstream may substantially change depending on methane leak rates and/or amount of LNG in the natural gas supply mix.

SvLS (2005) is not accounting for mine industry practices

SvLS (2005) point out at the (dramatically) growing energy expenditures for the extraction of uranium from very low-grade ores, which might lead nuclear energy to match the CO_2 emission of a gas plant for ores around 0.01% or below (SvLS 2005, Chapter 1, #5). However, SvLS (2005) pay **no consideration of co-production of minerals** as common practice for economically viable mining and milling (processing) of the ore especially in case of low grades. If co-production or by-production occurs, the energy expenditures shall be allocated to the different products according to the specific needs, accurately analyzing (to the extent possible) the complete process flow.

For example, as reported in (ISA 2006), in the Olympic Dam mine, where uranium is extracted as a byproduct of copper, "most energy requirements would have been attributable to the recovered copper" under consideration of energy allocation to different products by process flow analysis. ISA (2006) reports the results of Olympic Dam's own calculations based on such energy allocation, obtaining 0.012 GJ of energy to uranium "for every tonne of ore that we process in its entirety (from mining through to final product)". This would correspond to 0.012/0.7/0.85/0.82 = 0.024 GJ/kgU for U-grade of 0.07% (proved ore reserves), or 0.041 GJ/kgU for 0.04% U-grade (total resources).[9] Application of the formula in (SvLS 2005, Chapter 2, #5) would give for 0.07% grade the energy intensity of 4.4 GJ/kgU and 10.6 GJ/kgU, respectively for soft and hard ores, while with 0.04% the energy intensity would be 8.2 GJ/kgU and 19.5 GJ/kgU, respectively for soft and hard ores: i.e., SvLS formula would calculate two to three orders of magnitude higher values than this specific case.

ISA (2006) uses data from U-production in the Ranger and Beverly mine/mills, with 0.15% ore grade (in U_3O_8). The energy intensity is approximately 0.45 GJ/kgU [own recalculation converting electricity in thermal units assuming 35% efficiency]. The direct application of the formula in (SvLS 2005 Chapter 2, #5) would give instead 2.0 GJ/kgU and 4.7 GJ/kgU, respectively for soft and hard ores (primary thermal equivalent values would be calculate higher).

Another example of flaws: SvLS (2005) estimate of Olympic Dam for uranium mining & milling energy uses is 70,209 TJ/a against 1,230 TJ/a predicted by the University of Melbourne vs. 5,477 TJ/a actually measured at the mine.[10] In one of the several rebuttals SvLS work has received from nuclear organizations (see Footnote 1), it is stated that "Our conclusion is that the equations from Storm and Smith that predict the energy cost of Uranium mining are unreliable for modern mines."[11]

On the other issue related to future uranium mining, although it is certainly true that in general the energy investment increases with decreasing ore grades (see discussion and graph in (ISA 2006, #94)), nevertheless SvLS (2005) apparently overestimate the total energy consumptions for uranium extraction (see also related point below). Evidently, this particular issue would deserve an appropriate study using data from the real world, starting from (ISA 2006) and direct information from mines.

Nevertheless, the important aspect of energy expenditures for low grade ores (as well as for unconventional uranium resources that may be required in case of long-term energy scenario analyses with large nuclear expansion) cannot be addressed in this Note, for this would require an assessment not conducted so far at PSI.

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[9] Data on U-grades from http://www.uic.com.au/emine.htm. This source also reports that recovery of U has been lifted up from 71% to 82%. However, for the figures calculated within the text for illustrative purposes, the yields have been taken from (SvLS 2005, Chapter 2, #6).

[10] Information from http://www.pmc.gov.au/umpner/docs/commissioned/ISA_report.pdf #67.

[11] http://www.nuclearinfo.net/Nuclearpower/SeviorSvLSRebutall

SvLS (2005) systematically overestimates energy expenditures, thus the associated GHG

Table 3 reports an overview of the energy intensities for the individual stages of the current nuclear energy chain, from the three sources compared herewith (i.e., extreme assumptions and findings by SvLS (2005) on mining of very low uranium ore grades are not included). However, for saving time and for the sake of simplicity of discussion, the recalculation of SvLS (2005) figures performed by ISA (2006) to give total thermal energy consumptions is used herewith (ISA corrected the flaw of the definition of "total" energy as used throughout (SvLS 2005)). Table 4 provides discussion on comparison by stage.

Although it is acknowledged that PA may underestimate the total emissions (as commented in (ISA 2006)), the use of ecoinvent should minimize such effect, for a detail account of several key manufacturing industries is given.[12] On the contrary, the hybrid I/O LCA method introduces overestimations, for a certain degree of double counting occur. The use of AEI for evaluating dismantling/reclamation costs (see Table 2) and the systematic use of upper range estimate from the literature explain the extremely high results claimed by SvLS (2005).

The comparison performed in ISA (2006) between their own values and SvLS' ones showed "that the main differences arise for the following fuel cycle stages: mine clean-up construction, operation, decommissioning, spent fuel storage, [Intermediate and Low Level Waste] ILW/LLW disposal, and [High Level Waste] HLW disposal" (ISA 2006, #64). Considering the case of 0.15% ore grade, the above stages, for which highest doubts arise, would make 82% of the total energy expenditures summed up by SvLS for the nuclear chain – same conclusion for CO_2 emissions if a constant factor CO_2 emission / MJ would be assumed as made by (ISA 2006, #63).

However, in spite of the several basic critics to the simplified methodology of SvLS (2005), ISA (2006) yet uses some of SvLS' figures. Therefore, ISA cannot be taken as a work totally independent from (SvLS 2005).

*A more in-depth comparison of LCA studies would be worth performing. However, it can be anticipated, on the basis of this comparison and the previously mentioned results for energy uses and GHG emissions from the nuclear chain performed by different Institutes and individuals independently, that **SvLS results are definitively outliers**.*

[12] See Table 2; see ecoinvent reports retrievable at www.ecoinvent.ch.

Table 3: Comparison of total energy uses for current nuclear system as from (SvLS 2005), (ISA 2006), (Dones 2003).

Stage of the Nuclear Energy Chain	Unit	SvLS (2005): factors as recalculated by ISA (2006, #65)	ISA (2006)	Dones (2003) ecoinvent: cumulative waste heat[13]
Mining & Milling	MJ_{th}/kgU_{nat} in U_3O_8	2.7E+3 [14]	2.0E+3 [15]	1.3E+3[16]
Conversion	MJ_{th}/kgU_{nat} in UF_6	1.9E+3	1.9E+3	1.0E+3
Enrichment	MJ_{th}/SWU	1.31E+4 [17]	1.1E+4 [18]	8.8E+3 [19] 2.8E+4 [20] 5.4E+2 [21] 1.7E+4 [22]
Fuel Fabrication	MJ_{th}/kgU_{enr} in fuel	6.1E+3 [23]	6.1E+3 [24]	7.0E+2
Power plant	MJ_{th}/kWh			2.7E-2 [25]
Construction + Dismantling	MJ_{th}/GW	1.1E+11 + 1.1E+10	1.5E+10 + 1.5E+9	7.6E+9
Operation	MJ_{th}/kWh	2.7E-1	1.2E-1	2.5E-3 [26] (1.6E-2)

[13] It is a measure of the total energy consumption, for it has been inventoried considering the gross calorific value of fossil energy carriers (and biomass), as well as the thermal energy equivalent of electricity uses. The cumulative waste heat of the full chain matches the cumulative energy demand, but use of the latter indicator for single stages is not straightforward for it contains the (nuclear) energy potential of the fuel.

[14] Approximate. Recalculated from (ISA 2006) using 0.15% U_3O_8 grade to compare with ISA (2006) and 1.07 kgU/t of ore. Value likely assumed by SvLS (2005) for *"soft ores"*. ERDA-76-1 data have been used by SvLS (2005, Chapter 2, #5) for soft ores. However, ERDA-76-1 used likely Ranger's ore grade, which is now reported to be 0.234% (grade information retrieved from http://www.uic.com.au/nip57.htm). This grade would require a (calculated) energy use of approximately 1.7E3 MJ_{th}/kgU_{nat} in U_3O_8. For *"hard ores"*, SvLS (2005, Chapter 2, #5) estimate energy consumption per unit mass of ore 2.4 times higher than for soft ores.

[15] Approximate. Recalculated from (ISA 2006) with 0.15% U_3O_8 grade (Ranger & Beverly mines) and 1.07 kgU/t of ore.

[16] Ore grade not specified. One Canadian mine assumed for underground mines; US average for open pit mines.

[17] 30% diffusion (2630 kWh/SWU) & 70% centrifuge (290 kWh/SWU).

[18] 30% diffusion (2630 kWh/SWU) & 70% centrifuge (290 kWh/SWU).

[19] Calculated using (ISA 2006; SvLS 2005) shares 30% diffusion & 70% centrifuge, for direct comparison.

[20] 100% diffusion Eurodif (2400 kWh/SWU). Eurodif plant is powered by on-site PWRs.

[21] 100% centrifuge Urenco (40 kWh/SWU). Urenco plants are assumed in ecoinvent to be powered by average electricity UCTE, medium voltage.

[22] 60% diffusion Eurodif (2400 kWh/SWU) & 40% centrifuge Urenco (40 kWh/SWU) as assumed for PWR Gösgen (Switzerland). However, when MOX are used (making 8% of total lifetime fuel energy in PWR CH in ecoinvent), the corresponding energy for missing enrichment has been subtracted for the calculation of total energy consumption per kWh.

[23] ISA (2006) reports 1.68E+0 GWh_{th}/tU^{235}. Here it is assumed that the unit mass corresponds to the mass of enriched uranium in fuel, not to U^{235} only.

[24] ISA (2006) reports 1.69E+0 GWh_{th}/tU^{235}. Here it is assumed that the unit mass corresponds to the mass of enriched uranium in fuel, not to U^{235} only.

[25] The modeled PWR rejects 7.65 MJ_{th}/kWh waste heat in operation, obviously not included in the table.

[26] The assessment of NPP operation in (Dones 2003) is based on direct information from a Swiss nuclear utility and includes diesel consumption, lubricants and chemicals, cement and steel for conditioning of LLW, as well as transports. It does not take into account hardware replacement and (explicitly) electricity from the grid during refueling/maintenance. Nonetheless, the annual electric energy consumption from the grid is reported in Dones (2003 #167) being 34 TJ_e/a (i.e. nearly 1E7 kWh/a) for the PWR Gösgen, 1992. This amount was included in the NPP self-consumption of electricity. This electricity could be explicitly modeled in ecoinvent, most appropriately with the "electricity, medium voltage, production CH, at grid", overwhelmingly made of hydro and nuclear, being close to the actual Swiss Summer mix, when Switzerland is net exporter of hydropower and when refueling of NPPs usually occurs. Adding this contribution, the total obtained is shown within parenthesis, which is within the low range of values from the literature reported in (ISA 2006, #47).

Table 3 (contd.): *Comparison of total energy uses for current nuclear system as from (SvLS 2005), (ISA 2006), (Dones 2003).*

Stage of the Nuclear Energy Chain	Unit	SvLS (2005): factors as recalculated by ISA (2006, #65)	ISA (2006)	Dones (2003) ecoinvent: cumulative waste heat[27]
Reprocessing	MJ_{th}/kg_{HM}	-	-	6.9E+3
Storage	$MJ_{th}/t_{waste\ (HLW)}$	1.3E+7 [28]	3.1E+6 [29]	9.2E+5 [30]
Repository ILW	MJ_{th}/m^3_{waste} [31]	4.3E+6 [32]	6.4E+5	2.2E+4
Repository HLW	MJ_{th}/m^3_{waste} [33]	5.0E+6 [34]	1.7E+6	2.6E+5
Depleted Uranium	MJ_{th}/tU_{dep}	1.9E+6	1.9E+6	-
Mine/mill cleanup	$MJ_{th}/t_{tailings}$	5.5E+3	-	-[35]

[27] It is a measure of the total energy consumption, for it has been inventoried considering the gross calorific value of fossil energy carriers (and biomass), as well as the thermal energy equivalent of electricity uses. The cumulative waste heat of the full chain matches the cumulative energy demand, but use of the latter indicator for single stages is not straightforward for it contains the (nuclear) energy potential of the fuel.

[28] Recalculatd using density of HM (10.9 t/m^3).

[29] Recalculatd using density of HM (10.9 t/m^3).

[30] Recalculated from (Dones 2003) using the cumulative MJ requirements for the Interim Storage (5700 m^3 HLW + 28,300 m^3 LLW+ILW inventoried; all volumes include canisters) attributed only to the mass of spent fuel (approximately 2586 t_{HM} Heavy Metal), to make it comparable with the other two references.

[31] Including canisters.

[32] Assuming for the waste the density of concrete 2.3 t/m^3.

[33] Including canisters.

[34] Assuming density HLW in spent fuels within canisters, i.e. approximately 400 kgHM/m^3 after data from the industry (Dones 2003).

[35] Mine restoration was not modeled for lack of data. For mill dismantling, 25% of the energy used for construction has been accounted for, and is included in the figure above for mining & milling.

Table 4: Comments on the comparative table for energy uses (Table 3).

Mining & Milling	Same order of magnitude for operation of mining & milling of soft ores with moderate ore grades; highest value in SvLS; Dones lowest for assumes Canadian mine for underground and US average for open pit mines. Consideration of hard ores by SvLS. For ores >0.2% practically no differences between cumulative results for CO_2 from the chains using either soft or hard ores are estimated by SvLS. Importance of soft/hard ores increases with decreasing ore grades according to SvLS (2005, Chapter 1, #5).
Conversion	Same order of magnitude in the three references, highest in SvLS.
Enrichment	Highest for SvLS for same technology mix share. Incongruent use of the technology mix and old energy intensities in ISA, for enrichment share is steadily growing and use of centrifuge only may likely occur within a few years from now. Strong overestimation of centrifuge energy uses by SvLS & ISA, based on definitively outdated figures. Furthermore, Dones takes into account realistic differences in the energy supply to diffusion and centrifuge, hence appropriate GHG intensities.
Fuel Fabrication	Highest for SvLS & ISA, Dones four times lower.
Power plant	
Construction + Dismantling	SvLS 16 times higher and ISA two times higher than Dones. Higher lifetime and capacity factor in Dones, matching real Swiss data (40 years lifetime). SvLS uses same masses as in Dones but overestimates energy requirements for material manufacturing (and associated GHG). SvLS largely overestimates dismantling, using extreme assumptions.
Operation	Dones uses real data from Swiss operators. Dones gets lower energy uses by two orders of magnitude compared to SvLS & ISA due to modeling assumptions on electricity uses during refueling (subtracted from production). When corrected with real data from plant (in report), energy input is still one order of magnitude lower than SvLS & ISA. However, Swiss electricity supply during refueling is basically hydro & nuclear, therefore GHG-free, for which results in Dones for GHG from nuclear would not change.
Reprocessing	Not included in SvLS & ISA.
Storage	Dones uses data from design of Swiss interim storage plant, attributing all burdens to LWR wastes; three times lower than ISA but 14 times lower than SvLS for they use extreme assumptions. However, (spent fuel) storage is differently defined and conditions differently modeled in SvLS and ISA.
Repository ILW	Dones uses data from design of Swiss repository. SvLS is two orders of magnitude higher than Dones, determined by overestimations.[36] ISA, based on previous I/O studies (tendential overestimating method) is one order of magnitude higher than Dones, based on PA (tendential underestimating method)
Repository HLW	Dones uses data from design of Swiss repository. SvLS is one order of magnitude higher than Dones, determined by overestimations.[37] ISA, based on previous I/O studies (tendential overestimating method) is 1.6 times higher than Dones, based on PA (tendential underestimating method)
Depleted Uranium	ISA imports SvLS figures for energy expenditures for storage of DU as waste, without explanation. SvLS arbitrarily assume same total energy of conversion (from a US source of 1976) for “deconversion”. Dones explicitly does not consider DU fate, for it may be seen as co-product of enrichment, therefore process energy may be allocated to it (DU is used – though for the moment only part of the stock – in MOX fuel, airplane ballast and hardening material for military application; it has potentially very high energy content for its use in breeder reactors).

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[36] Some assumptions are completely arbitrary like: energy intensity for “producing, filling, handling and transport” of some radwaste canisters taken the same as the (over-)estimated energy intensity for NPP construction (SvLS 2005, Chapter 4, #3).

Radwaste from centrifuge enrichment is assumed substantially higher than for diffusion (factor of nearly four), without any physical/technical explanation, resulting in a value about four times higher than declared by Urenco in its environmental report (Dones 2003).

In SvLS (2005, Chapter 4, #8) the volume of radwaste from NPP decommissioning is guesstimated at 93,900 m^3 (all included; conversion factor volume to mass is not given). Official estimations by Swiss operators made before 1985 and used in input to the total inventory of radwaste for designing (1985) the Swiss final repositories, gave for the 1000 MW-size PWR and BWR 7,000 m^3 and 14,000 m^3, respectively (canisters included). These data were reported and used in (Dones 2003). Actually, recent re-estimations have given volumes of below 5,000 m^3 for the same PWR and below 10,000 m^3 for the same BWR (direct information, unpublished). Therefore, SvLS likely overestimate the volumes of waste from NPP decommissioning by one order of magnitude.

[37] However, SvLS assume granite rock vs. Swiss clay formation as host for the waste; the total masses of rock to dig out per unit mass of HM may differ with the design of the repository (depth, length of tunnels, density and hardness of rocks to dig through, etc.). Nevertheless, SvLS miscalculate the energy expenditures because their estimation is based on the projected costs of a repository by using energy conversion factors identical to what used for energy expenditures in NPP construction (SvLS 2005, Chapter 4, #7). ISA (2006) comments on this regard: “monetary values not stated [in (SvLS 2005)]” and criticizes herewith explicitly the AEI method used by SvLS (ISA 2005, #53). Furthermore, an independent verification or re-estimation of the geological repository addressed by SvLS cannot be made, for the characteristics of the assumed repository are not given in the reference (SvLS 2005).

Table 4 (contd.): Comments on the comparative table for energy uses (Table 3).

Mine/mill cleanup	Energy uses partially included in Dones (25% of expenditures for mill construction assumed for mill dismantling). SvLS claim that reclamation has never been done which is not true, although SvLS may be imagining an ideal restoration. SvLS arbitrarily assume that the energy for restoration of mill tailings is four times the energy of mining. However, SvLS state that "this procedure is a model to estimate the energy expenditure, not a real process" (SvLS 2005, Chapter 4, #4). ISA argues that part of SvLS' assumed restoration "process is based on their own hypothetical model and that in reality mine tailings are not treated in this manner" (ISA 2006, #53).[38]

Example: SvLS (2005) greatly overestimate energy expenditures for construction & decommissioning of nuclear power plant

SvLS (2005) estimate huge energy consumptions for construction and decommissioning of one 1000 MW nuclear power plant (NPP): 80 PJ for construction only and 240 PJ total with complete decommissioning. These values are contradicted by all technical references available.

The construction energy expenditures in SvLS are derived from total costs and total masses, assuming three different reference plant total costs and three methods based on various estimations of energy factors per unit cost/unit mass. The value SvLS chose is in the medium range of what they estimated. However, when considering the breakdown of materials, also reported in (SvLS 2005) for a total mass of 516 kt,[39] and applying the cumulative energy demand calculated by ecoinvent to each material, a value of merely 3.3 PJ_{th} would be calculated for the total plant, i.e. *roughly 25 times less than SvLS.*[40] Even if one were taking into consideration the theoretical underestimation of the PA method used in ecoinvent, due to truncations in process boundaries, or say a factor of two as maximum difference reported by (ISA 2006) between PA and I/O studies (see below), the difference would always signal the large overestimation by SvLS (2005). Furthermore, SvLS (2005) do not report the value they calculate for CO_2 from construction (and decommissioning).[41]

Vattenfall estimates 8 PJ total, from actual measurements of energy inputs.[42] Dones (2003) also calculates values between 7.6 PJ_{th} and 9 PJ_{th} of cumulative primary energy for LWR construction & decommissioning. In a recent study, Dones (2006, unpublished) estimated the energy requirements for EPR 1600 MW construction and decommissioning, using sufficiently detailed material data and ecoinvent as background LCA database, calculating about 11 PJ_{th} of cumulative primary energy. This value is consistent with the detailed analysis in (Hoffmeyer et al. 1996), where the cumulative energy demand for construction and decommissioning of a 1400 MW LWR

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[38] ISA (2006, #98) also comment: "We do not apply Storm van Leeuwen and Smith's figures [for storage, disposal, and for returning the mine site to "green fields" condition] solely because we regard them as outliers in a statistical sense. Instead, we assume current industry practices, so that the energy requirements for the treatment of mine tailings are included in the energy figures for Australian mining." The same reference (ISA 2006, #64) reports that using SvLS assumptions for lean ore (0.01% ore grade), mine/mill restoration would consume 42% of the estimated total energy expenditures throughout the nuclear energy chain (amounting to 1.63 kWh_{th}/kWh_e, or more than 0.5 kWh_e/kWh_e, i.e. making it a very bad energy converter!), releasing also 41% of the corresponding cumulative CO_2. In case of 0.15% ore grades, mine/mill restoration à la SvLS would use up 5% of the total energy expenditures of 0.66 kWh_{th}/kWh_e (ISA 2006, #63) (approximately 0.22 kWh_e/kWh_e). Such important (guesstimated) effects call for a more accurate technical analysis of the subject.

[39] Incidentally, these masses roughly correspond to what has been inventoried in the first version (1994) of the study (Dones 2003), reported by (Lako 1995), which is the source SvLS mention. The NPP masses in (Dones 2003) equal the masses in the first edition of his study in 1994.

[40] For a correct comparison one should convert the "total energy" in SvLS into primary energy, possibly separating contributions from fossil and nuclear.

[41] Applying CO_2 cumulative factors from ecoinvent to the same materials & masses as in SvLS, 230 Gg(CO_2-eq) total from construction is calculated. Actually, from ecoinvent v1.3 output (http://www.ecoinvent.ch), 324 Gg(CO_2-eq) cumulative are calculated for the NPP infrastructure (construction & decommissioning).

[42] As reported in http://www.nuclearinfo.net/Nuclearpower/WebHomeEnergyLifecycleOfNuclear_Power .

has been also estimated at 11 PJ_{th}.[43] From the above it can be concluded that independent PA LCA studies converge.

However, studies using I/O LCA method (which likely overestimates the total energy needs), summarized by (ISA 2006, #47), show for LWR construction a factor of maximum two higher than PA (which somewhat underestimates the figures), but always well below the much higher factor remarked above for SvLS (2005) compared to PA studies.

About decommissioning, the value SvLS end up with is astonishingly high: twice the energy requirement they assume for construction. SvLS have derived the value from an own guess based on some findings in a few references (though including respectful ones) that "dismantling costs can reach 100-220% of the construction costs", also taking into account an extremely long time assumed between shut down and starting actual dismantling. Nevertheless, the authors still emphasize these own estimates as "not excessive" (SvLS 2005, Chapter 3, #13, but also elsewhere). However, SvLS do not specify for which reactors and what are the costs for construction used in the original references (to mention only the largest missing elements among several others). SvLS simply take a factor of two of their own construction costs, and a factor of two for energy expenditures, to "characterize" dismantling, without the least cost breakdown analysis. NPP construction costs had increased over the last decades, due not to substantial energy or material expenditures increase, rather to other reasons like strong delays in construction, increasingly demanding safety requirements, and so on. However, here it is strongly objected that mere extrapolation from costs to energy without control leads to serious methodological flaws. Furthermore, SvLS ignore other, more frequently found estimations of dismantling costs on the order of a few hundreds M$, which means fractions of the construction costs (order of G$). ISA (2006) reports from other (German) literature a cost ratio decommissioning to construction of a large NPP as 10%-25%. The above figures are consistent with what (IAEA 2005) reports for decommissioning costs.[44] Higher cost ratios are usually found for small or research reactors.

About energy uses for NPP decommissioning, along with the proportion taken in El-Bassioni et al. (1980), Dones (2003) assumes 75% of the electricity as well as 75% of the total diesel requirements (including transports) used up during construction. For material uses during decommissioning, the waste canisters are also accounted for in (Dones 2003).

Appendix: A remark on the study ISA (2006), on uranium enrichment

As remarked in (Dones 2003; Dones et al. 2005), the assumptions on enrichment are a key factor for the estimation of cumulative GHG from the nuclear energy chain. In particular, the share of diffusion enrichment by the US plant Paducah, supplied by fossil electricity, practically controls the final result.[45]

a. **Assumed share 70/30 of centrifuge/diffusion technologies is unrealistic.**

   ISA (2006) uses a mix 70/30 of centrifuge/diffusion technologies (approximately the current commercial worldwide share) for enrichment supplies to hypothetical Australian nuclear power plants that would not start before 2016. Diffusion is a very high energy consuming process which is being substituted by centrifuge (factor of 50 to 60 difference).

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[43] Incidentally, Hoffmeyer et al. (1996) calculate for the rest of the nuclear chain (once-through, including repository) 27.4 PJ_{th}. Considering the total energy converted in the reactor over its lifetime (4300 PJ_{th}), Hoffmeyer et al. (1996) calculate a ratio PJ_{th}-in/PJ_{th}-out of 0.9% which is very close to what obtained by Dones (2003) (minimum of about 1.1% in case of centrifuge enrichment only; the maximum is approximately 5%, obtained in case of use of diffusion enrichment only).

[44] "Estimates of the full decommissioning of a 1000 MW(e) NPP range from about 150 million euros to nearly 750 million euros." (IAEA 2005)

[45] For example, in (Hondo 2005) 22-24 g(CO_2)/kWh are given for nuclear energy NPP in Japan. This value is somewhat higher than other estimations performed in Japan mostly because of a higher share from USEC assumed for diffusion services.

In the USA, “USEC is in the process of demonstrating its next-generation American Centrifuge uranium enrichment technology. USEC will operate a Demonstration Facility in Piketon, Ohio, for the purposes of demonstrating and evaluating the Company’s enhancements to U.S. centrifuge technology and centrifuge performance in a cascade configuration. A Lead Cascade of machines is expected to be installed and operating in the Demonstration Facility by mid-2007. The American Centrifuge Plant is planned to have an annual production level of 3.8 million SWU.”[46] In 2010-2011 the US centrifuge plant will produce 1 MSWU.[47] The very old USEC plant will be eventually shut down. Also the Eurodif plant George Besse in Tricastin (France) will be shut down in 2012 and substituted by a centrifuge plant.[48] Therefore, it is highly unlikely that the given share 70/30 centrifuge/diffusion will remain in ten years from now and even less likely in the following decades. Even if the USEC diffusion plant were operating longer, it would likely serve the internal US market.

b. **Electricity mix adopted to model supply to diffusion leads to an upper value for CO_2.**

The currently only operated USEC Paducah diffusion plant (USA) produces about 5 MSWU/a[49] and Eurodif about 8 MSWU/a (capacity is 10.8 MSWU/a). While Paducah is supplied by fossil power plants, Eurodif is directly supplied by on-site nuclear power plants. Therefore the GHG intensity in the two cases is totally different. This has not been reflected in the ISA (2006) study, while (Dones 2003) does. On the other hand, ISA (2006) ignores other potent GHG like CFC-114 emissions from Paducah, which would add 3-6 g(CO_2-eq.)/kWh (depending on the estimation of CFC-114 leak at Paducah) if all enrichment services were from it. Eurodif emits virtually no such GHGs because it is water cooled (Dones 2003). Emission of HFC from Urenco centrifuge plants is of very minor importance, on the order of 0.005 g(CO_2-eq.)/kWh (Dones 2003). However, compared to CO_2 emission rates (corresponding to about 44-47 g(CO_2-eq.)/kWh from the enrichment step if all enrichment services to a PWR were from Paducah, using different enrichment and burn-up levels as modeled in Dones (2003)),[50] these can be considered of minor importance or even negligible for centrifuge.

c. **Electricity intensity adopted for enrichment is outdated.**

ISA (2006) apparently uses the factor 290 kWh/SWU for centrifuge, same as in (SvLS 2005). This electricity intensity had been taken from very old references and does not correspond to modern technology. Recent literature and reports on/from Urenco give values in the range 35-62 kWh/SWU,[51] and the trend is towards further decreasing it.

The above points imply an overestimation of about 14 g(CO_2)/kWh referring to the average value of 60 g(CO_2)/kWh calculated in (ISA 2006) for the chain associated with a LWR.

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[46] http://www.usec.com/v2001_02/HTML/Aboutusec_enrichment.asp

[47] http://www.portslab.com/v2001_02/Content/News/NewsFiles/FY2002-Earnings.pdf

[48] http://www.francenuc.org/en_sites/rhone_tri_e5.htm ;
http://www.debatpublic-gbesse2.org/docs/pdf/plaquette.pdf

[49] http://media.corporate-ir.net/media_files/NYS/USU/reports/Form10K0902.pdf

[50] In case only Paducah were the only enrichment service provider to a PWR, ecoinvent would calculate approximately 52-58 g(CO_2-eq.)/kWh cumulative for the complete associated energy chain (the range is including the uncertainty on CFC-114). Using ISA (2006) assumption 70/30 mix centrifuge/diffusion, and electricity supply to diffusion and centrifuge from the Australian electricity mix (2014) as reported in ISA (2006), ecoinvent would calculate approximately 18-21 g(CO_2-eq.)/kWh cumulative from the chain (range considering CFC-emission spanning from zero from Eurodif-equivalent plant to max from USEC-equivalent plant.

[51] As from http://www.uic.com.au/nip57.htm and http://www.world-nuclear.org/info/inf11.html “Urenco enrichment at Capenhurst input [is] 62.3 kWh/SWU for whole plant in 2001-02, including infrastructure and capital works.” In its website, Urenco Gronau (Germany) reports in graphs its electricity & natural gas specific consumption (operational) in 2003 as approximately 35 kWh/SWU and 0.35 m^3/SWU (13 MJ/SWU), respectively. The differences are probably due to the operation of less efficient older centrifuges.

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