Rebuttal of critique of the analysis presented on this website

The critique quoted below is the concluding section of a document written by or for the World Nuclear Association (WNA), interspersed with our rebuttals of their arguments. The name(s) of the author(s) is(are) not given. The original text of the WNA can be found on Internet at the following URL:

http://www.world-nuclear.org/info/inf11print.htm

The reader will note that, apart from a few questions of presentation (not facts), the WNA criticism is baseless.

It is also interesting to look at the energy costs that the WNA paper *leaves out* of consideration. These are (1) the safe disposal of depleted uranium, (2) the safe disposal of mill tailings and (3) returning the mine area to its original state ("green field" conditions) and finally (4) the permanent sequestering of spent fuel elements. The need for the first has become urgent since the use of this poisonous, carcinogenic material in ammunition has become current. The tailings of uranium mining and milling and the chemical agents used are at present simply discharged into the environment with no thought for the consequences. This practice has potentially deadly effects on life forms. Uranium mining brings the radioactive products of uranium mining into the environment. The milling operation use highly corrosive and poisonous chemicals. These mining and milling detriments will slowly be washed into the soil and rivers unless something is done to prevent this. They should therefore be packaged and returned to the mine where they can be sealed off permanently. The (energy) costs of the second and third operations will increase immensely as ores become leaner. The WNA paper also did not make any comment on our treatment of the fourth operation, consisting of interim storage, conditioning and final disposal. This seems to show that they accept this cost as part of the operation of a nuclear power plant, even though our calculations show that it will require (present estimate) some 7% of the energy produced by the plant on the first load, and 2.3% of the energy produced every reload.

Together these four energy costs, for a 1% ore, will use ten percent of the energy produced by the initial load, and more than 3.5% of the energy produced by the reloads. For a 0.02% ore these figures rise to 26% and 62%, respectively, making the use of nuclear energy a rather doubtful undertaking.

We proceed below to show that the criticism of the WNA of our analysis is wrong. Italicized, double-indented text is that of the critique by the WNA. Our rebuttals are in normal type.

Critique of August 2001 paper by Storm van Leeuwen and Smith: "Is Nuclear Power Sustainable?"

> *A "semi-technical" document by Jan Willem Storm van Leeuwen and Philip Smith with this title was prepared for circulation during the meeting in April 2001 of 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. It dismisses arguments that nuclear energy is sustainable, either physically, environmentally or in terms of its energy costs. It purports to offer "evidence" that building, operating and producing fuel for a nuclear plant produces as much carbon dioxide as those produced by a similar sized gas-fired plant.*
>
> *However, the arguments are based on a very narrow view of nuclear energy as well as 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.*

We are grateful to the World Nuclear Association for the stimulus that this critique has given us to dispense with "secondary" references, i.e. references to sources which sometimes could only be found in the earlier study referred to above. This has led to a great improvement in our presentation. Original references are used almost exclusively in the revised documents which, together with this rebuttal, have been placed on the website. All important statements we make are backed up by references that are available in the open literature, or are based on specifically mentioned private sources. We cannot agree that we previously used outdated information. All of the information given by us is, or was at the time of presentation, up to date. By attributing to our present work outdated statements from an older publication which have been replaced by up-to-date facts, the WNA author(s) appear to make an attempt to discredit our analysis. We do not feel that this is fair. Furthermore their statement that "many of the figures used are taken from a study originally done in 1982" is simply not true. Every figure with numerical information was created, and in the case of graphs, calculated and plotted specifically, for this work.

The criticism that our analysis is based on a "narrow" view of nuclear power is strange. Our work is an energy life-cycle analysis, and it would be interesting to know which factors the WNA writer(s) think that we have left out.

For those who have read the articles on our website the statement of the WNA that our work "purports to offer 'evidence' that building, operating and producing fuel for a nuclear plant produces as much carbon dioxide as those (sic) produced by a similar sized gas-fired plant" will come as a surprise. Figures 2a and 2b in the article entitled "Is nuclear power sustainable; would its use reduce CO_2 emission?" (SLS) give quite a different and subtler picture than that suggested by the WNA writer(s). We refer the reader to the either the original or the recently revised version of SLS now on this website to confirm this. It is important to note that while nuclear energy is anything but CO_2 - free, it does produce *less* CO_2 than an equivalent gas-fired plant as long as there are rich ores. Looking at it from a long-term point of view, however, gives a different picture. We prove that if nuclear power continues to be used that when the rich ores are used up and leaner ores are used, nuclear energy will produce more CO_2 than simply burning the gas for energy.

> *Only diffusion enrichment is considered, whereas centrifuge methods now widely used are up to 50 times more energy efficient.*

The WNA statement that centrifuge enrichment is up to 50 times more energy efficient is a gross misstatement and is not based on a life-cycle energy analysis but only on the electrical energy used. That is indeed very small compared to the energy needed for diffusion enrichment. A life-cycle analysis must take everything into account, including the (total) energy costs of the materials used (including the buildings and the special tools needed for the production) and the (safe) disposal of wastes, not just the electricity used to make the centrifuges spin. Our consideration of diffusion enrichment is based on real life. Most of the enrichment done to date has been by diffusion. That was the reason for our choice, and not a predilection for an energy-expensive method. We know of no extensive energy life-cycle analyses for centrifuge enrichment. If a real-life life-cycle analysis for centrifuge enrichment becomes available we would be only too glad to incorporate the results, in the proportion that this technique is used in practice, into future revisions of our analysis.

> *The future use of new reactor designs, including fast reactors, is dismissed out of hand on the grounds that some research programs in Europe have been closed down. However, Russia has been operating a very successful 600 MW commercial fast reactor at Beloyarsk in the Urals for decades and 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.*

We ask the reader to compare the statement of the WNA above with what we actually wrote. Our statement was (see SLS, under the heading "The fast breeder") and is:

"It would be unwise and unscientific if we were to claim that breeders can never be a viable energy source. No one can possibly prove that. But after a half a century of failed attempts, the dreams of a fast-neutron breeder appear to be pipe dreams."

Does this statement "dismiss out of hand" the use of fast reactors?

On grounds of excellent authority (please refer to chapter 2 of Facts and Data) we state that fast-neutron **breeder** reactors are not a present possibility. A **fast-neutron reactor** is not a **breeder reactor** unless it breeds more fuel than it uses fuel in a time short compared to its lifetime. Indeed the fast-neutron reactor at Beloyarsk (Beloyarsk-3) has been in operation for two decades. As of June 2001 it had been operating for 21.2 years but had achieved a total of only 14.2 full-load years (Knox 2001, see the chapter 'References'). This performance record indicates, according to the judgement of the WNA, that it is "a **very successful** 600 MW commercial fast reactor." One wonders how bad the performance of a reactor would have to be in order to be considered **unsuccessful** by the WNA.

A report on the operating history presented at an IAEA meetng by the plant manager (Saraev 1998, see the chapter 'References') does not even mention breeding. It has never bred any fuel, although it has experienced quite a number of accidents. In the U.S.A. or western Europe such a record would probably have led to closing down the reactor. It is true, of course, that with the present low price of uranium, it might not be commercially viable to use the plutonium produced in a fast-neutron reactor to fuel another fast-neutron reactor. But it is crucial for the future viability of nuclear energy (from fission) to prove that a fast-neutron reactor system can breed and prepare for use more fuel than it uses. It is also crucial to the viability of a breeder system (the reactors themselves, plus the reprocessing and fuel fabrication plants) that it must succeed in producing at least one reload within a limited time, certainly within twenty years. This requirement, apart from the question of whether it is possible at all, is made extremely difficult by the intense radioactivity of the fuel to be reprocessed. This is so great that a considerable number of years must pass before the spent fuel can even be reprocessed at all. This may, in itself lead to the impossibility of creating a viable energy system.

The amount of ^{235}U in ores that can be mined and milled profitably (in energy terms) is simply too small to make nuclear energy a long-term solution (this is shown quantitatively in Chapter 2). Although most political leaders and the public were not aware of this, one must realize that in the 1950's the belief in the great promise of nuclear energy was based on the assumption that fast-neutron breeders would provide a practically infinite amount of fissionable fuel by breeding plutonium from ^{238}U. The use of ^{235}U was seen as a temporary stopgap to be used until breeders took over the energy supply. After a half a century of failed attempts at building a breeder system, this assumption has quite disappeared from public utterances of the nuclear-power industry. If breeding is impossible it will mean that nuclear energy can **never** be a viable energy source. That after twenty years of operation the Beloyarsk reactor has bred no new usable fuel apparently (one can never be sure, of course) tolls the bell for long-term energy production by nuclear fission. If this situation changes, in real life and not in theory alone, we would be quite ready and willing to redo our analysis.

> *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.*

In part 2 of Chapter 3 (*The Power Plant*) of Facts and Data there is specific reference to refurbishing (and the energy costs thereof). It is obvious that the overall performance, including useful lifetime, of the plant is thereby improved. Below the reader will see that the performance of existing nuclear power plants is enormously overstated in the WNA article.

> *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 far more efficient than traditional mining methods in terms of both cost and energy use.*

Our exhaustive data on, and analysis of the yield and the energy costs of, traditional mining methods will be treated in detail somewhat further on. They show that our statements in the first version of this website were quite accurate. We regret that we did not include the background information which makes clear that our conclusions are well founded. In the revised Chapter 2, now on the website, we do that.

As far as new technologies are concerned we here only point out that while *in situ* leaching uses much less energy than traditional methods, it has serious disadvantages. Foremost among these are that the yield of uranium from a given ore mass is very low (most of the uranium remains in the ore mass), it is only applicable to porous ores, and above all, the environmental consequences of its use will (would) be disastrous. Immense quantities of sulphuric acid must be pumped into the earth and then pumped out with a low recovery rate, so that in the course of time (we are speaking here of hundreds of years) the sub-soil over large areas will be permanently poisoned. What this would mean for the existence of life in the region is not hard to imagine.

> *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 funded during operation. Moreover, they are minor and of the same order as those of other industrial plant.*

This is untrue. All debts that we refer to from the building and operation of a nuclear-power are explicitly and quantitatively supported by literature of the nuclear industry, with the exceptions of decommissioning, cleaning up of the mining area and waste from the milling plants and the permanent sequestering of depleted uranium. These are ignored by the industry and unless suitable legislation is enacted, and enforced, future generations will inherit massive environmental destruction, with no available energy source to alleviate the consequences. And just to set the record straight, no reference to economic debts is to be found in our work, since these are quite irrelevant in an energy analysis. The fact that other industrial plants, and waste, are not radioactive is overlooked by the WNA writer(s). The debts incurred by a nuclear plant are of a totally different order than for other industrial plants. For the first time in history a technology is being used that permanently damages the environment; not just for a while, but in the time scale of human history, forever.

There is no similarity between the debts incurred by nuclear energy and the debts incurred by any other technology.

> *The brief paper itself (six pages) refers to a 52-page "Facts and Data" supplement, which is little closer to real life than the earlier 29-page version, though it does correct some gross errors. Rather than using audited industry data it uses 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 @ 33GWd/t and reference to 4.2% enrichment and 46 GWd/t. (Electrical figures multiplied by 3 to give basis comparable with main paper.)*

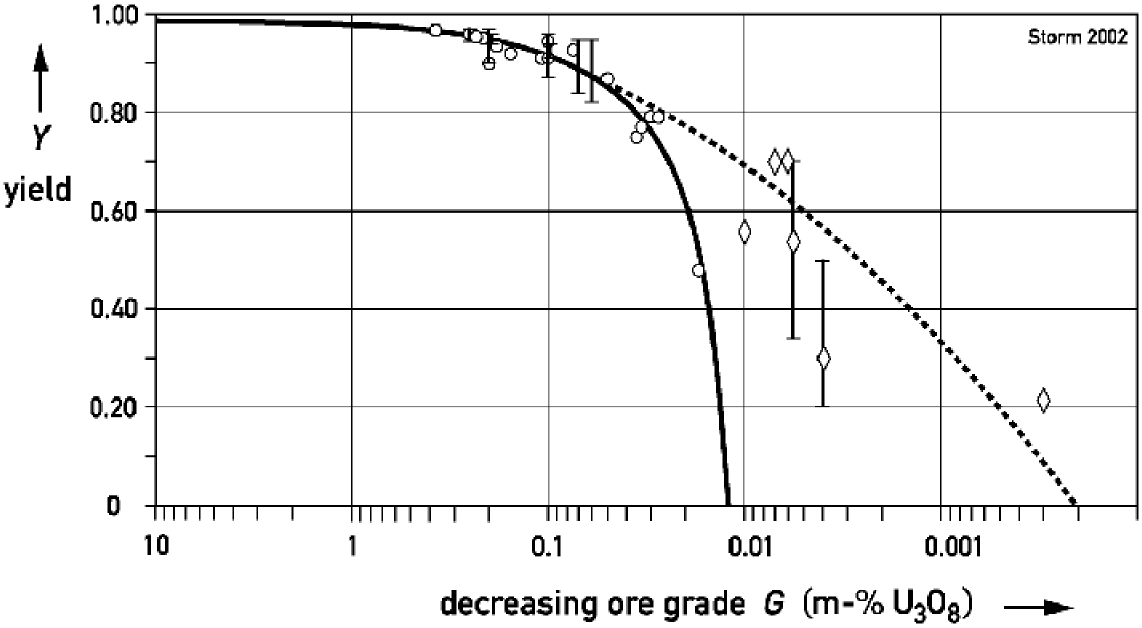

Figure 6 The extraction yield Y, or recovery, of uranium oxide U_3O_8 as a function of ore grade. The circles are empirical values from the literature (see below). The diamonds are taken from hypothetical mining and milling operations. The solid curve changing to dashed at G=~0.05% (Eq. 2.2 in Chapter 2) is fitted to the empirical data, but is seen to be a good fit to the hypothetical points also. The solid curve is fitted to the empirical data down to the leanest ore for which there is data.

We make no comment on this criticism here. The reader will discover, upon reading further, that none of the WNA critique is based on facts, but rather on distortions of our text, or on exaggerated claims (particularly on the performance of nuclear power plants; see below). All of our data are from the industry itself, as can be seen by examining the references chapter. As mentioned above, in the previous website version the source of the data was not always clear. This was a shortcoming, and has now been entirely corrected.

> *Mining & milling (not quoted, simply grade-based formula)*

This is a case in point concerning the first version of website presentation (in Chapter 2 of Facts and Data). The expression for the yield of mining and milling (Eq. 2.2) was indeed simply stated with no references to back it up. This shortcoming has been corrected, and a figure has been added (with 29 references to the original data, given below). The figure is also shown above (in Figure 6), which shows that Eq. 2.2 represents the data well. There some is evidence (see Chapter 2) that the useful (for energy production) reserves are considerably smaller than even given by Eq. 2.2 (cf. the solid line in Figure 6).

Table of values of ore grade and yield, with references

Ore grade in mass-% U_3O_8	Yield of mining and milling	References See chapter "References" for the details of the references.
0.34	0.97	Franklin et al. 1971
0.26	0.958	James & Simonson 1978
0.25	0.962	Ross & Guglielmin 1968
	0.95-0.97	Simonson, Boydell & James 1980
0.24	0.95	James & Simonson 1978
0.22	0.949	James & Simonson 1978

0.208	0.95	Rotty, Perry & Reister 1975
0.20	0.959	Ross & Guglielmin 1968
	0.94-0.96	Simonson, Boydell & James 1980
	0.90-0.97	GJO-100 1980
	0.90	SRI 1975
	0.95	Rombough & Koen 1975
0.18	0.937	James & Simonson 1978
0.156	< 0.92	James & Simonson 1978
0.15	0.954	Ross & Guglielmin 1968
	0.935-0.95	Simonson, Boydell & James 1980
0.14	0.924	James & Simonson 1978
0.125	0.95	Ross & Guglielmin 1968
0.11	0.909	GJO-100 1980
0.10	0.944	Ross & Guglielmin 1968
	0.91-0.94	Simonson, Boydell & James 1980
	0.87-0.96	GJO-100 1980
	0.910	James & Simonson 1978
0.075	0.933	Ross & Guglielmin 1968
0.07	0.84-0.95	GJO-100 1980
0.06	0.82-0.95	GJO-100 1980
0.05	0.87	Simonson, Boydell & James 1980
0.035	0.75	James, Boydell & Simonson 1975
0.033	0.77	Simonson, Boydell & James 1980
0.030	0.79	Huwyler, Rybach & Taube 1975
0.0267	0.786	Kistemaker 1976
0.013	0.472 (see text)	Kistemaker 1976
0.010	0.55	Simonson, Boydell & James 1980
0.007	0.70	Rotty, Perry & Reister 1975
0.006	0.70	Burnham et al. 1974
0.0055	0.34-0.70	Mutschler, Hill & Williams 1976
0.004	0.30	Simonson, Boydell & James 1980
	0.20-0.50	James & Simonson 1978
0.0003	0.21	Huwyler, Rybach & Taube 1975

In the table we have presented all empirical and hypothetical data that we have found. Only those data where the ore grade is specifically stated are used in Figure 6.

The (two-valued) energy constant c (Eq. 2.1) for mining and milling was also not derived in the previous version of Chapter 2. This is now the case, and the values are slightly different than the old ones. The general picture remains the same, i.e. the available uranium ores are not sufficient to provide energy for the long term. That is why the question of whether a breeder reactor can be designed, built, and safely operated so that it actually breeds is so crucial to the future of nuclear energy.

Conversion 1.6 GJ/kgHM

Enrichment (diffusion only, 0.2% tails) 31.3 GJ/SWU = 2900 kWh/SWU

Fuel fabrication 5.9 GJ/kg

Power plant construction 81 PJ, or 95 PJ if all thermal basis (this is from Storm van Leeuwin 1982/1985 paper, see below).

It is quite true that the data on the construction of nuclear power plants is from the 1980's. It could hardly be any more recent since no nuclear plants have been ordered since then, for well-known reasons. Below we present the reliable data which supports the figure mentioned here by the WNA. It is a very conservative figure; some sources give much higher energy costs.

Operation & maintenance 2.8 PJ/yr

Decommissioning 240 PJ

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.*
>
> *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 for which there is no empirical evidence in the case of nuclear power.*

This last remark is hard to understand, but easy to rebut. Extensive studies show, in contradiction to the above statement, that there is a very definite relationship, albeit with considerable error bars, between the (monetary) cost of a nuclear-power plant (or any other construction) and the energy requirements. This is well known in the field, and it is surprising that the WNA writer(s) is(are) not aware of this fact. Originally we did not show the derivation of the energy costs of nuclear-power plant construction in Chapter 3. This was certainly a shortcoming, and has now been corrected. The entire study, to be found in the revised Chapter 3, is summarized below. From the final table (Table 11) one sees that different approaches yield a range of values of the energy cost of construction. We have used the most conservative, to be sure that the energy costs we present are rather low than high.

Construction

This analysis is based on PWR's in the USA because of the availability of data on a large number of nuclear power plants built and operating under the same economic conditions.

Historical overview of construction costs

All PWR power plants connected to the grid in the USA are of 1980-85 vintage or older. After 1978, no new plants have been ordered. The costs of nuclear power plants up to 1986 in the USA are represented in Figure 7 which is taken from Chapter 3, with data from [Roddis & Ward 1971], [Mooz 1981] and numerous reports in Nuclear News, Nucleonics Week and Nuclear Engineering International.

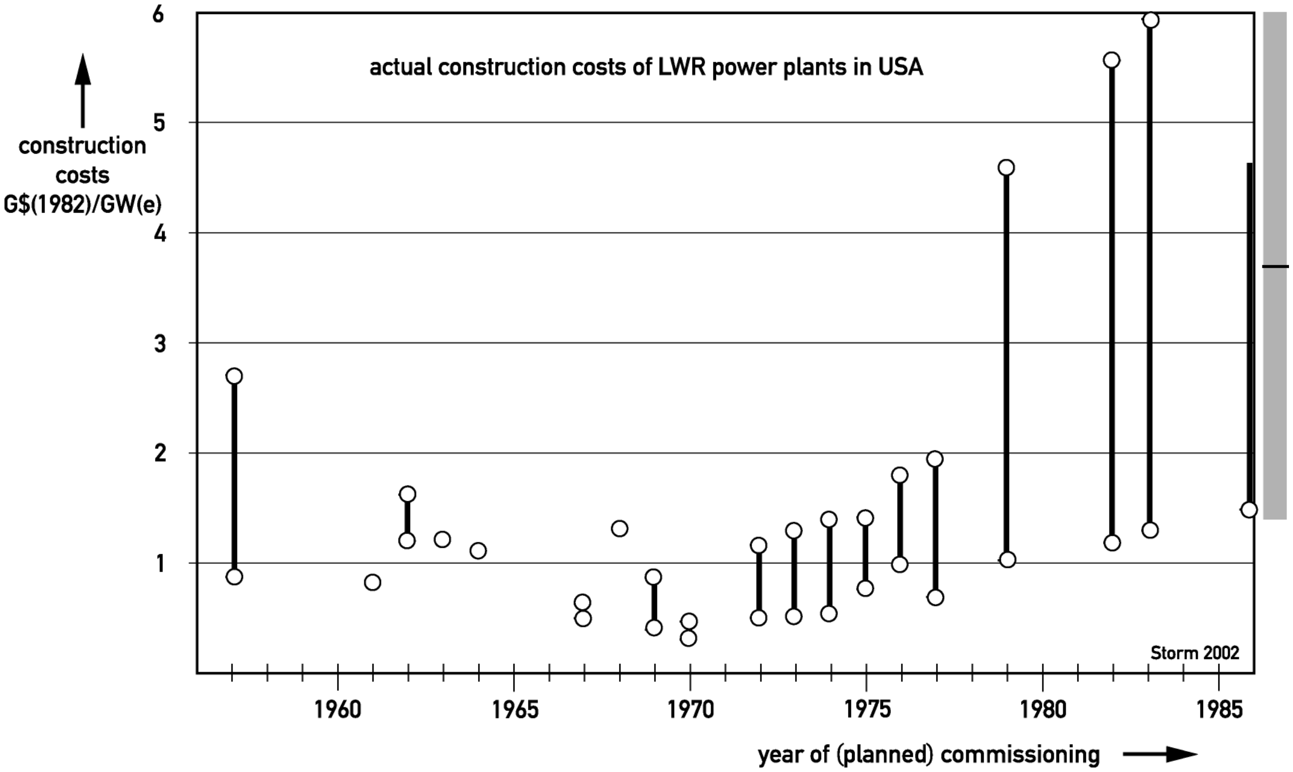

Figure 7. Historical construction costs of LWR power plants in the USA. During the 1980's a number of plants in the high range of costs were cancelled before completion, so the average of construction costs of actually commissioned plants was lower than the average cost of plants under construction. This is indicated in the figure. Specifically, in 1986, the cancelling of plants caused a lowering of the upper limit of costs. Construction costs of ~ 4G$(1982)/GW(e) may remain a ceiling above which the construction of a nuclear power plant is cancelled.

The actual construction costs as function of the year of (planned) commissioning show a striking pattern. After construction of the first commercial nuclear power plants, the unit costs fell to a low in 1970. Probably this wass (partly) caused by economy of scale. During the first decade, the mean power rating increased by a factor of more than ten: from a few tens of megawatts (electric) to many hundreds of megawatts.

After 1970 the (reported) costs rose more and more steeply. The scatter of the published costs per unit increased as well. In 1983 the highest reported unit cost was nearly 6 G$/GWe and the lowest about 1.3 G$/GWe. In 1986 the lowest value was about 1.5 G$/GWe and highest about 4.7 G$/GWe (all values in $(1982)). The decrease in the high end of the range was not caused by cheaper construction, but by cancelling further construction on plants with higher costs. A ceiling value may be about 4 G$/GWe. Probably, the escalation of construction costs is part of the reason that no new nuclear power plants have been ordered in the USA since 1978. The cancellation of the construction of power plants before completion, when the costs rise into the high end of the range, does not change the real average construction costs or real energy requirements.

Usually, after introduction of a new technology the unit costs decrease with time, as more experience is built up and more units are produced (learning curve: learning by doing). After 1970 the learning curve effect is completely absent in the nuclear industry, quite the reverse happened. See also references quoted in [Tyner, Constanza & Fowler 1988]. We have no explanation for the large and increasing differences between lowest and highest reported costs. One must bear in mind that it is difficult to get a picture of the real costs of nuclear power during the first decades after the introduction of the program "Atoms for Peace". Invisible government subsidies paid for much of the construction costs and essentially all of the technological development.

In this study a range of 1.4-6 G$(1982)/GWe, is taken as starting point of calculations. For purposes of energy analysis, the full cost range is a realistic basis; we have somewhat arbitrarily chosen the average of the highest and the lowest values, 3.7 G$(1982)/GWe as the base of our calculations.

Energy requirements

The energy requirements for construction are not measurable directly, because of the sheer complexity and scale of the activities. Indirect methods to estimate the construction energy are used throughout in the studies carried out in the past, a number of which are summarized in Table 9 in Chapter 3. We limit ourselves here to a description of the methods used to estimate the energy costs.

Methodology

The construction of a nuclear power plant is an extensive and very complex activity. During the 1970's and 1980's the methodology of energy analysis was developed, maturing to a useful tool to calculate the energy requirements of goods or economic activity with reasonable accuracy, see for example [Constanza & Herendeen, 1984], [Bullard, Penner & Pilati, 1978], [IFIAS, 1974], [IFIAS, 1975], [Reister, 1977], [Roberts, 1975], [Roberts PC, 1982], [Chapman, 1975].

The energy requirements for a process or economic activity can be determined by either of two general methods: process analysis or input/output (I/O) analysis (Approach 1, below). In Chapter 3 the reason we reject process analysis to determine energy costs is explained. For reasons which will be explained below (Approach 2, below) we also use an approximation to I/O analysis. In addition a variant based on the weight of materials is applied (Approach 3, below). These three widely divergent approaches deliver quite similar values for the construction energy.

Estimating the energy embodied in capital goods and services besides the direct energy requirements of the process itself requires the use of I/O analysis. This is well suited to large aggregated activities, such as the construction of a nuclear power plant. Chapman [Chapman, 1975] made the following comment on the use of this approach:

> "In principle this is an unsatisfactory procedure since the inputs to nuclear systems are likely to be uncharacteristic products of the sectors documented in the input-output tables. However there are grounds for believing that provided a product has a large vector of inputs, i.e. requires inputs from many other sectors of the economy, then the average energy intensity derived from the input-output table is fairly reliable."

The I/O analysis can be simplified by using the ratio of the total energy used by a country to the gross national product in a particular year in order to calculate the net energy requirement of a (complex) activity, in this case the construction of a nuclear power plant, from the monetary cost in the same year. The energy/gnp ratio must be corrected for the deviation of the energy costs of the 'new construction' sector from the overall ratio. This simplification gives a fairly reliable value of the energy embodied in that activity, including energy costs of labor, services, subsidies, etc. [Tyner, Constanza & Fowler, 1988]. This is affirmed by other studies, e.g. [Rombough & Koen, 1978], [Roberts PC, 1982], [Bullard, Penner & Pilati, 1978], [Constanza & Herendeen, 1984]. As Constanza & Herendeen who calculated the energy costs in this way, put it:

> "Embodied energy (calculated the way we suggest) is a good, non-trivial static correlate of the economic value of the relatively large aggregates of goods and services that make up the entries in the I/O tables."

Certainly, the construction of a nuclear power plant is a large aggregate of goods and services. Nuclear technology is "high-tech", on top of an extensive industrial and economic infrastructure of other "high-tech" production processes.

The studies of [Rombough & Koen, 1975] and [Bullard, Penner & Pilati, 1978] showed that the energy costs calculated via a detailed I/O analysis of the sector "new construction of utilities" is approximately 1.16 times the value found via the simplified method: costs x total energy/gnp (Method A in Table 11, Chapter 3). Both studies concluded that an accurate estimation of the construction energy construction of a power plant can be found by multiplying the construction costs of a plant in a given year with the energy/cost ratio (in MJ/$) of this sector.

Roberts [Roberts PC, 1982] found a strong, non-linear, correlation between costs of a product in dollars per mass unit and the energy embodied in that good, in energy units per mass unit. From his graphical presentation of this correlation, based on UK and US I/O tables of 1967, the energy requirements for construction of a nuclear power plant can also be deduced.

The energy cost of constructing a nuclear power plant in the year 2000

The overall energy/gnp ratio is given in primary energy units per dollar gross national product. In published energy statistics, e.g. [BP, 2001], electrical energy in the main is converted to primary energy by multiplying it by a factor f: $J_{\mathbf{prim}} = J_{\mathbf{th}} + f \cdot J_{\mathbf{e}}$. The factor f is usually taken to be 3.

The construction energy requirements are here defined as the sum of electric and thermal energy ($J_{\mathbf{con}} = J_{\mathbf{th}} + J_{\mathbf{e}}$), with given thermal/electric ratio R ($R = J_{\mathbf{th}}/J_{\mathbf{e}}$). Therefore: $\underline{J_{\mathbf{con}}} = (1 + R)/(f + R) \cdot J_{\text{prim}}$

Since no recent I/O tables are available, the energy requirements for construction in the year 2000 have to be approximated, using available data. The following three approaches, based on [Bullard, Penner & Pilati, 1978] and [Roberts PC, 1982], appear to be the most reliable. In Chapter 3 the detailed calculations are presented. Below we summarize these.

Approach 1

The energy cost of a nuclear power plant is calculated by multiplying the monetary cost by the energy/$ ratio of the sector 'new construction'. The latter was found by input/output analysis to be 83.8 MJ/$ in 1967 [Bullard, Penner & Pilati, 1978]. The energy cost in 1982 is then obtained by deflating the (monetary) construction costs in 1982 dollars to 1967 dollars by multiplying by the Consumers Price Index ratio between these years (0.346).

The advantage of this approach is the availability of the correct energy/cost ratio for construction. However, it assumes that the construction energy requirements remained unchanged during the period 1967 to 2000. This is probably not the case, as the overall energy efficiency of economic activity improves with time. Moreover, the average thermal/electric energy ratio R in 2000 is lower than in 1967. On the other hand, construction of nuclear power plants historically has shown a strong trend to become more complex, at least partly due to greatly increased concern for safety, demanding more materials, energy and manpower, all manifested in sharply rising costs. This trend may offset an improved energy efficiency in the construction sector.

Considering these arguments, this method should result in a fairly reliable value of the energy requirements for construction. We take, as discussed above, the base cost of 3.7 G $(1982), for a 1 GWe nuclear power station in 1982. This comes to 1.28 G$ in 1967 dollars using the Consumers Price Index ratio mentioned above to deflate the costs. Using the value of 83.8 MJ/$(1967), the construction energy requirements then are $J_{\mathbf{con}} = J_{\mathbf{th}} + J_{\mathbf{e}} = 1.28\text{ G\$} \cdot 83.8\text{ MJ/\$} = 107\text{ PJ}$, with R = 4.8.

The full uncertainty range is 40 – 174 PJ, as is shown in Table 13 of Chapter 2.

Approach 2

Here, instead of using the input/output value of 1967, we extrapolate from 1982 to the year 2000. There have been no I/O analyses published for the construction sector for this year, however. We therefore use the overall energy/gnp value but correct it with the factor 1.16 to get a good approximation to the construction sector [Bullard, Penner & Pilati, 1978]. Since no new nuclear power plants have been ordered we use the values for the 1980s by inflating the costs in \$(1982) to \$(2000) and use the energy/gnp ratio of 2000.

In this way the improved energy efficiency of the economy in 2000 is accounted for. A trouble, however, is whether the multiplier in the year 2000 and the ratio R are the same in 2000 as in 1967. This problem was discussed under approach 1.

From the statistics in [Europe Energy Scenario's 1996], [Europe Energy Outlook 1999], [Europe Energy 1999] [Q9], [BP 2001] [Q91] and [WNA-ueg 2001] [Q93], the value of the general energy/gnp ratio in the year 2000 can be deduced: energy/gnp = 10.64 MJ/\$(2000), valid for the whole OECD: EU, USA and Japan. Applying the multiplier 1.16 to account for the new utilities construction sector, the energy/\$ ratio in 2000 for the sector new utilities construction we have: 12.34 MJ/\$(2000). After correcting this figure through application of the Consumers Price Index factor of 1.78 mentioned above to the 1982 cost of 3.7 G\$ for a 1 GWe power station as we find the construction energy as 3.7 G\$ • 1.78 • 12.34 MJ/\$ = 81 PJ.

The construction energy requirements then are: $J_{\mathbf{con}} = J_{\mathbf{th}} + J_{\mathbf{e}}$ = 81 PJ, with R = 4.8.

The full uncertainty range is 31 – 132 PJ.

Any real escalations in costs (excluding inflation) and requirements of energy, materials and manpower to construct a PWR power plant of the 2000 vintage (not yet existent), compared to 1978 vintage (in 1978 the last new US nuclear power plant was ordered), are neglected in approach 2 as in approach 1.

Approach 3

In this approach the energy costs are approximated on the basis of the total weight of the construction [Roberts PC 1982]. Unfortunately, all energy values in his paper are given in primary energy units and no distinction is made between electric and thermal energy. Extrapolation of Roberts' method to the year 2000 is not possible, so the specific costs have to be deflated to the 1967 level.

From his graphical presentation we derived the following correlation for the year 1967 by curve fitting:

$\log E = -0.283 + 0.79 \log C$, with

E = energy per unit mass [$J_{\mathbf{prim}}$(GJ) / mass(Mg)] and
C = cost per unit mass (in \$(1967)/Mg)

This can de solved for the primary energy, $J_{\mathbf{prim}}$, needed for the construction of a 1 GWe nuclear power plant. We find then for the total of electrical and thermal construction costs:

$$J_{\mathbf{con}} = J_{\mathbf{th}} + J_{\mathbf{e}} = (1 + R)/(f + R) \bullet J_{\mathbf{prim}} = (1+R)/(f+R) \bullet M \bullet 10^{[-0.283 + 0.79 \log C]}.$$

A recent figure, M = 516 Gg (1 Gg = 1000 metric tonnes), is used for the construction mass of a 1 GWe nuclear power plant. This (rounded) value is found from a graphical presentation given by [Lako 1995], see Table 10. [Uchiyama 2002] reports a much higher mass: 1291 Gg.

Using the mass of 516 Gg and assuming a cost of the power plant of 3.7 G\$(1982) = 1.28 G\$(1967), the specific cost C = 2480 \$/Mg. Entering these values into the formula with f = 3 and R = 5 we find:

$J_{\mathbf{th}} + J_{\mathbf{e}}$ = 97 PJ, with an uncertainty range 45-142 PJ.

These figures are quite close to those found in approach 1 and 2. The fact that three quite different ways of calculating the energy cost of the construction of a nuclear power plant indicates, in our view, that the underlying principles are reliable.

Construction materials	Reinforced steel	Stainless steel and other steels	concrete and cement	copper &copper alloys	aluminum	total (approximate)
mass (Mg)	40000	25000	450000	1200	200	516400

Table 12 Construction materials of a 1 GWe nuclear power plant by mass
Data of Leibstadt PWR and Japanese PWR power plants

Source: [Lako 1995] and Y. Uchiyama, quoted by Lako.

Monetary cost in G$(1982)	Energy cost in PJ according to:		
	Approach 1	Approach 2	Approach 3
1.4	40	31	45
3.7	107	81	97
6	174	132	142

Table 13 Construction energy requirements (in petajoules, PJ)

Given the large scatter in construction costs of a LWR power plant (1.4-6.0) G$(1982)/GWe), a detailed I/O analysis would not be very meaningful. In our view the approximations above are as reliable as can be expected. It is highly unlikely that construction costs should have declined in recent years.

In this study we choose the lowest value, $J_{\mathbf{con}}$ = 81 PJ, not because this is the most plausible value, but because we want to be sure that we do not exaggerate the energy requirements.

> *The most contentious figures come from an earlier paper "Nuclear Uncertainties" by Storm van Leeuwen (Energy Policy 13,3, June 1985), itself based on an earlier 1982 study. This is examined briefly below.*
>
> *Presuppositions:* ***A PWR "optimistically" has an operating life of 12 full-load years (cf typical 40 years @ 90% = 36 full-load years).***

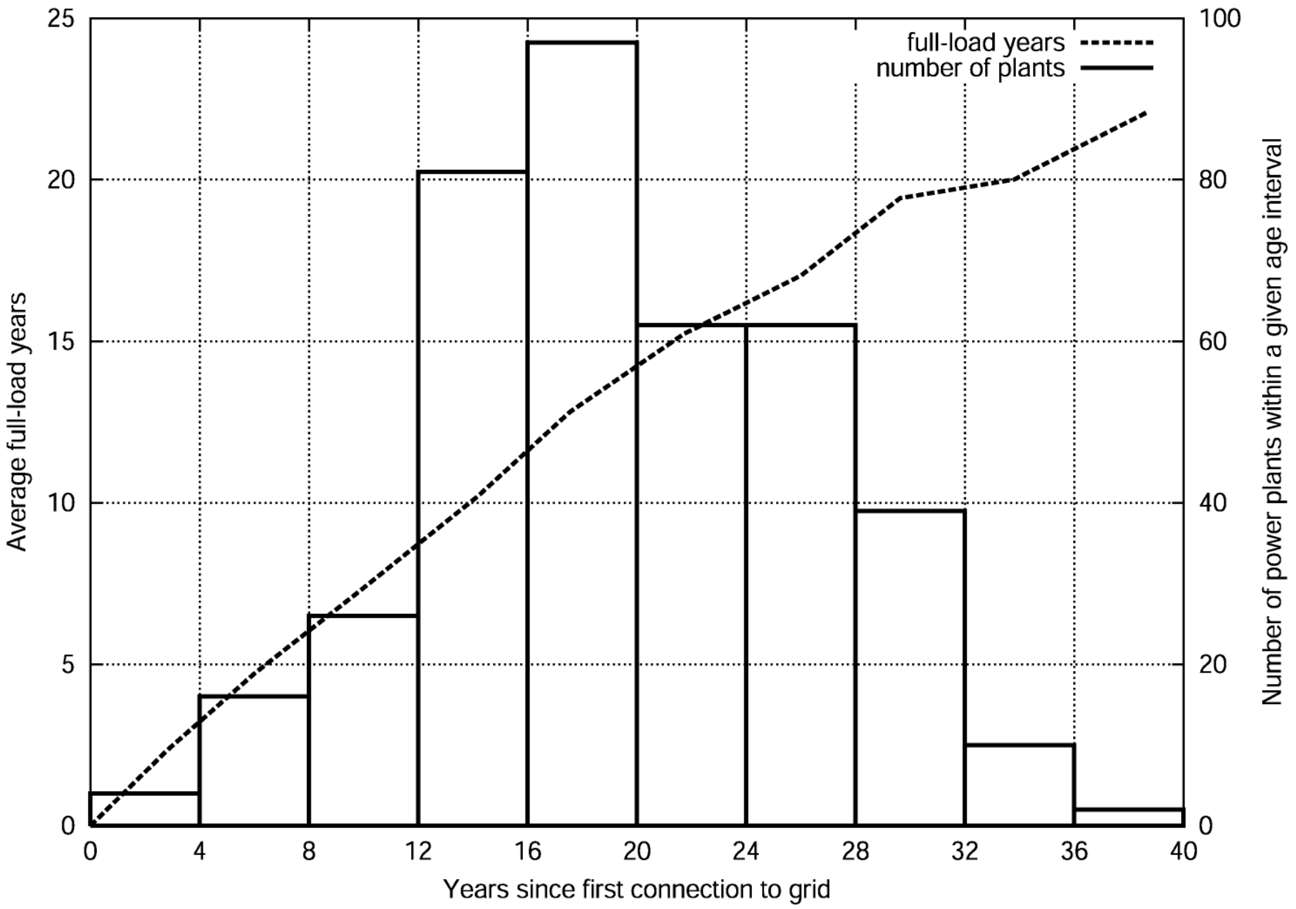

Figure 8 The average full-load years achieved by 399 slow-neutron power reactors, averaged over ten four-year periods. The result is in piercing contrast with the WNA claim that 36 full-load years in typical. The left-hand ordinate and the dashed curve refer to full-load years. The right-hand ordinate scale and the staff diagram give the number of power plants found in each of the ten age intervals.

This "contentious figure", supposedly quoted by the WNA writer(s), does not exist in our study. Our statement in Chapter 1 of Facts and Data is quite different, and to make this clear we cite here exactly what was said in Chapter 1, pp. 4&5:

"The present study differs from many other studies in that the energy expenditure and net energy production of the full nuclear process chain are calculated as a function of the operating time (T_{100})[1], measured in full-power years. Usually a fixed operating time is assumed, mostly an optimistic high estimate of 30 to 40 years with high load factors of 0.7 - 0.8. These high values are not substantiated by the statistics of the present nuclear power plants in the world. Only a few reactors have reached an operational age of 30 years and the average load factor of all operating reactors, including the newest ones, is about 0.7. An effective operational lifetime of 24 full-power years (30 calender years with an average load factor of 0.8) is the highest that can be expected."

In the present, revised, version, the text is slightly different, but in neither text is there any reference to 12 full-load years. Our estimate of 24 full-power years as the maximum to be expected is actually quite optimistic, as is shown in Figure 8, which is based on the compilation given in the November 2001 number of Nuclear Engineering International, where the life-time performance of 399 slow-neutron power plants is given (in the chapter References see: Knox 2001). The average full-load years of all these reactors are plotted as a function of the time since each plant was first connected to the grid. The averages were taken over ten four-year periods. The average of the longest-lived plants reaches barely above 22 full-load years, a far cry from the 36 full-load years cited as "typical" in the WNA website document (see above). Let the reader judge who it is who is misrepresenting facts (facts from the nuclear industry itself).

We take care to rather overestimate the performance of nuclear power plants to be sure that we do not present an overly negative picture of nuclear energy, but the WNA estimate of 40 years life with 90% load factor is pure fantasy. Note also that the real situation is even worse, reactors which have suffered serious accidents have been "forgotten" in the statistics presented by the industry (Knox 2001).

We see little point in arguing about the total lifetime. Only 12 reactors out of 399 have reached a lifetime greater than 32 years, but this says actually very little. It was only about forty years ago that nuclear-power plants began to be built in large numbers, so it hardly surprising that no operating reactor has even reached an age of 40 years. Considering the claim of the industry it is surprising, though, that the average full-load lifetime of the group of the oldest operating reactors does not even reach 23.

We stated (see above) that the average load factor of all nuclear reactors was 70%. The average (lifetime) load factor of the 399 reactors in the compilation quoted is, in fact, 70.5%. Again one sees that our statements are based on hard facts, not wishful thinking, and one should not forget that the really bad cases were not included in the compilation.

> Mining & milling: *apparently speculative energy-grade curves are presented, and there is preoccupation with very low grade ores which are far from typical. Also it assumes 2815 tonnes of natural uranium is required for the 12 full-load years, which is about one third too high on current performance (105 TWh needs circa 2270 t @500 TJ/t).*

This critique has been partly treated above, with excuses offered for not having presented the data in the previous version of the website, showing that our curve (Eq. 2.2) is based on hard facts illustrated in Figure 6. The figure of 12 full-load years, as mentioned above, was apparently pulled out of a hat by the WNA author(s). Considering the quite imaginary statement in the WNA critique on "typical current performance" we will not go into this marginal question.

> Construction of power plant: *There is a very simplistic view of the relationship between capital cost and energy cost (input) without any consideration of whether*

---

[1] Note that, to conform with the standard notation, we now use the symbol T_{100} to denote the number of full-power years, instead of L_{100}, which we used earlier.

> *nuclear plant costs have a different (and over 1960s-1980s, changing) relationship with material and energy inputs compared with other industrial plants.*
>
> *The assumption that increasing capital costs in the USA from the early 1970s are correlated with increased energy inputs is simply without foundation and wrong. The only data are for dollar costs.*

The incorrectness of this critique has been adequately demonstrated above. The references given above make it clear that, besides dollar costs, there is indeed a great deal of information available.

> Reprocessing: *Here the energy figures (again, purely dollar basis) are largely speculative, and in any case irrelevant for most nuclear capacity today. Certainly no reprocessing would occur at the higher figures suggested of $10 million per tonne (1982 $).*

Here again, as in the case of an imaginary statement "quoted" above in the WNA text concerning the maximum full-load life to be expected of a nuclear power plant, a reference is made to something that doesn't even exist in our text. We do not mention reprocessing, not because it doesn't exist, but because at present it is of marginal importance.

> Decommissioning: *Again, only speculative dollar costs are considered with no attempt to estimate energy 'costs' - only an unsupported assumption that the same $-energy relationship applies as for construction! A further very high figure is given for decommissioning the reprocessing plant. In this paper the main energy inputs (for Europe) are shown as construction, reprocessing and decommissioning.*

This criticism has no basis. The $-energy relationship used to calculate the construction cost was obviously not used here at all. It hardly could be, since a complete dismantling and sequestering of all radioactive parts of a nuclear power plant has never been paid for (or done). The energy which will be needed was based on an estimation of the ratio between the energy costs of construction and the costs of decommissioning. Naturally these are estimates, and will have to remain so until more data becomes available. To repeat, we did not, and in the revised documents now on the website do not, mention building, operating, or decomissioning reprocessing facilities.

> *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. However, the authors have totally ignored these. The energy costs of nuclear power plant construction can readily be estimated, as can those for waste management and decommissioning, and recent Scandinavian work has quantified these with a higher degree of precision than has previously been attempted. 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.*

We regret that we did not specify the literature (from the industry itself) from which we derived the costs of mining and milling. We obviously did not ignore them, however, as can be seen by examining the revised version of Chapter 2 now on the website. The conclusions are unchanged, namely that, according to the industry itself, the energy costs of mining and milling alone make the use of ores leaner than 0.01% uranium content useless for energy production. Far from being a small part of the total as claimed by the WNA, these energy costs become at the level of 0.01% ores, the determining factor in energy production.

> *The following indicates how widely the 2001 Storm van Leeuwen & Smith paper 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 8.8 PJ for building and decommissioning calculated from 0.27% of lifetime output in the Vattenfall LCA study. Kivisto gives comparable figures for the Finnish study: 650 MWh/MW capacity, hence energy payback in a month's operation.*

We are at a loss to explain why the "results" of the Vattenfall study are even mentioned by the WNA author(s). It is in no way a life-cycle energy analysis, but rather an environmental impact study. The source of the energy values used is not given. One of us communicated our surprise to Vattenfall and received the following answer (see Bodlund 2001 in the references):

> Dear Dr Storm.
> ....
> Our study is not an energy analysis it is an environmental analysis.
> We have, of course, the background on the electricity and fuel side but I am not sure that we will take the trouble to publish that. In my view the environmental impact is the important part and not the number of kWhs.
> I can give you this though:
> Further to section 3.3.6 in the EPD for Forsmark:
> Electricity 1.08E-2 kWh/kWh is PRE-NPP.
> Electricity usage internal NPP is 3.73E-2 kWh/kWh, for a total of 4.81%
>
> Birgit Bodlund, Senior Advisor, Environmental Affairs
> Vattenfall Generation, SE-162 87 Stockholm, Sweden
> Office Address: Jämtlandsgatan 99, Råcksta
> Tel +46 8 739 52 98 Mobil +46 70 539 52 98
> birgit.bodlund@vattenfall.com

Confronted with this answer we consider it futile to react to the figures of the Vattenfall study quoted in the WNA document (and in the one unimportant example mentioned in the email above). They are not derived but apparently taken from another source. In our view it is not too difficult to understand the difference between an environmental impact study and a life-cycle energy analysis.

> Power plant operation: *given as 2.8 PJ/yr, which compares with 0.23 PJ/yr calculated from the 0.28% of lifetime output in the Vattenfall LCA study.*

See the remark on the preceding point.

> Power plant decommissioning*: suggested as being more than twice that for construction, but see above re Vattenfall LCA study where it is aggregated with construction.*

idem.

> Spent fuel management*: 2.4 PJ initial + 0.6 PJlyr compares with less than 0.1 PJlyr in Vattenfall LCA study.*

idem.

> *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, less than 10% of the world's uranium comes from such. In contrast, a modest 0.36 PJ/yr is calculated from the Vattenfall LCA study for mining and milling, and 0.04 PJ/yr would be the contribution on the basis of more limited Ranger mine data (excluding mine and mill construction etc). The increasing production from solution (in situ leaching) mining (including some low grade ores) would be lower again, probably by an order of magnitude.*

For the reason explained above we do not consider the "results" of the Vatttenfall study worth commenting on. We do feel called upon to respond to the remark that "less then 10% of the world's uranium comes from such." The reason that we go into detail concerning the amount of, and the energy costs of retrieving, the uranium from lean ores which are not at present exploited, is that our study, as should be clear from the title and is well detailed in the introduction, is a reaction to the claim of the industry that nuclear industry has a long-range future. In order to do this we demonstrate that when the presently available rich ores are exhausted, the uranium from the leaner ores would cost more energy to mine and mill than it would deliver when used in nuclear power plants. That they are not now needed has nothing to do with a vision of the future.

Conclusion

> *The 2001 Storm van Leeuwen & Smith paper and its 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 LCA study, which is arguably very conservative, gives a bottom line of 8.7% of lifetime energy output being required for all inputs, and only a tiny fraction of this being in the nature of energy debts.*

See the remark above concerning the inapplicability of the Vattenfall study to the issue here under consideration.

> *Finally, it should be pointed out that, even on the basis of their erroneous 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 twenty-fold difference (between nuclear and coal) as significant.*

This statement demonstrates well the difference between our point of departure and that of the WNA. We "are not forced to conclude" anything. We simply present the facts, which prove the inapplicability of nuclear energy to **long-term** energy production as well as show that the oft-repeated claim that nuclear energy causes the emission of **no CO_2** is quite untrue. We have only treated a comparison between a gas-burning plant and a nuclear power plant. Figure 2a shows that a simple factor between the CO_2 emission (such as stated above by the WNA author(s)) caused by a nuclear plant and that caused by a fossil-fuel burning plant does no justice to the facts. It is a much subtler question. As long as there are rich ores available, the application of nuclear energy will cause the emission of not much more CO_2 than that which we categorize under debts, i.e. approximately 16.5 Tg of CO_2 during the plant's (full-load) lifetime (on the ground of practice, about 23 years). For rich, but hard rock ores the amount is not much more. A gas-burning plant will emit approximately 76 Tg CO_2 in this time. This is a significant difference (a factor of 4.6) but a far cry from the exaggerated claim (a factor of 20) of the WNA.

But certainly no sane person would base plans for a long-term, i.e., fifty to a hundred years, energy future on the limited reserves of rich ores. When the available ore grade drops to around 0.02% it becomes questionable as to whether any more energy will be delivered by a nuclear power system than would be obtained by directly burning the fossil fuels needed for maintaining the nuclear fuel cycle. At this level, somewhat dependent on the type of ore, the CO_2 emission produced by the use of nuclear energy (for the same amount of useful electricity) becomes equal or more than that produced by burning the fossil fuel directly. At a level of 0.01% ore grade the nuclear option not only produces no useful energy, but causes the emission of immensely more CO_2 than a fossil-fuel burning plant.

> *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 paper in this series.*

Quite contrary to this baseless assertion, and especially as a consequence of the present revision, our conclusions are strengthened that nuclear energy not only is not sustainable but can at best provide, before exhausting useable ores, only a very small portion of the energy that is predicted to be consumed in the coming fifty years. The energy life-cycle analysis of nuclear-energy production shows not only that the vast amount of uranium in the sea and the earths crust, but also the enormous amounts of uranium in lean ores (such as oil shales), can not be considered a source of energy because the energy necessary to mine and mill these sources, when added to the energy costs of the building, operating, and dismantling a nuclear plant, plus the energy cost of safely sequestering the spent fuel and repairing the vast environmental damage, is more than the energy in the form of electricity produced during the lifetime of a nuclear power plant.