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Energy from Uranium

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In the perspective of rising prices of fossil fuels and climatological concerns, nuclear power gained renewed interest as a solution to the energy problems. This paper discusses some unique aspects of nuclear power, which may be important in the considerations of the options for the future energy supply mix

This paper is based on the study Storm & Smith 2005 [6], comprising a full life cycle assessment (LCA) and analysis of the energy and mass flows of a light-water reactor (LWR) in the once-through mode.

Content

Quantities and units

FPY = Full-Power Year
One full-power year FPY, corresponds with one year continuous operation at 100% power output. This unit avoids discussion about load factors and lifetime of the power plants. In the energy analysis the lifetime energy production and lifetime energy inputs of the system are analysed.

1 Mg = 1 megagram = 10^6 gram = 1 metric tonne.
1 Gg = 1 gigagram = 10^9 gram = 1000 metric tonnes
1 Tg = 1 teragram = 10^{12} gram = 1 million metric tonnes
1 TJ = 1 terajoule = 10^{12} joule, corresponds with 2.78×10^5 kWh

Note

In this document the references are coded by Q-numbers (e.g. Q133). Each reference has a unique number in this coding system, which is consistently used throughout all publications by the author. In the list at the back of the document the references are sorted by Q-number. The resulting sequence is not necessarily the same order in which the references appear in the text.

1. Breeders and Burners

There are two main classes of nuclear reactors: burners and breeders. In a burner reactor no more than about 0.7% of the atoms in the natural uranium leaving the mine can be fissioned. In a breeder reactor more non-fissile uranium-238 atoms are converted into fissile plutonium atoms, than are consumed by fission in the reactor. Theoretically, some 30-60% of the atoms in natural uranium could be fissioned in this way. Breeder reactors operate with fast neutrons and therefore are often called ‘fast breeders’, which doesn’t mean the breeding process goes fast. Not every fast reactor is a breeder.

Burners

All power reactors currently operating are burner reactors, based on fission with thermal (slow) neutrons. The three main classes are:

- light-water reactors (LWR): Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR),
- graphite-moderated reactors gas-cooled reactors, e.g. Magnox and AGR
- heavy-water moderated reactors, e.g. CANDU.

At present 88% of the power reactors of the world are LWRs. The newest currently operating power reactors may achieve an overall uranium utilization of about 0.6%, which means that about 6g of each kg natural uranium, as mined, is actually fissioned. The remaining 994g leave the nuclear energy system as depleted uranium and highly radioactive spent fuel. Advanced reactors, such as the so-called Generation III and IV and Pebble Bed Reactor, all are burner reactors, with a maximum uranium utilization of about 0.7%.

Breeders

Fifty years of intensive research in seven countries (USA, UK, France, Germany, former USSR now Russia, Japan and India), with investments of many of tens of billions of dollars so far have failed to demonstrate that the breeder cycle is technically feasible (see Appendix A). Even if the breeder cycle starts working flawlessly next year, the share of breeder power could become significant only at the end of this century. The high fissionable fraction of natural uranium theoretically achievable by the breeder is the source of the old nuclear dreams from the 1950s: the ‘all nuclear society’ using energy ‘too cheap to meter’. Today these unproven figures still give rise to the technical dreams of untold quantities of cheap, clean nuclear energy for all mankind for the coming centuries.

The coming decades

The MIT 2003[1] study *The Future of Nuclear Power* [Q280], does not expect breeders (in effect the breeder cycle) to come into operation during the next three decades. The MIT study concluded that for the next three decades, and probably beyond, nuclear energy generation has to rely on thermal-neutron reactors, mainly LWRs, in the once-through mode. In the once-through mode no uranium and plutonium is recycled, consequently spent fuel is not reprocessed. The authors of MIT considered the proliferation and safety risks of reprocessing and the use of MOX fuel unjustified. But there are also economic reasons not to recycle.

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[1] http://web.mit.edu/nuclearpower/

2. Energy costs energy

What we call ‘energy’ in everyday life is freely usable energy: electricity, heat and ready-to-use fuels for transport. Conversion of a mineral energy resource (fossil fuels, uranium) into ‘free energy’ requires a number of processes: extraction from the earth’s crust, transport, refining, conversion. Often also processes are needed to reduce adverse effects on the environment by the use of the mineral energy resource

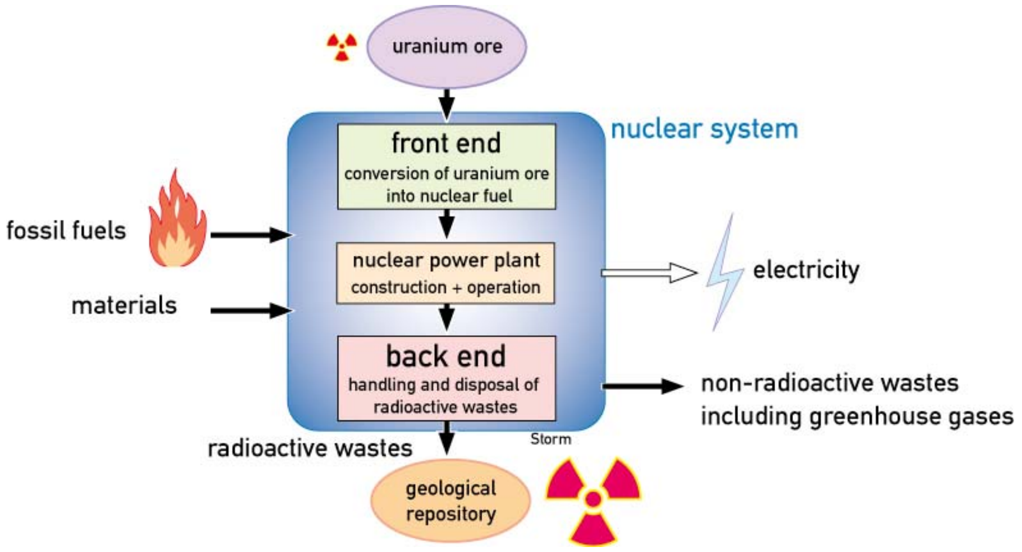
To generate useful energy from uranium a complex system of industrial processes is needed (see Figure 1). The nuclear system is the most complex and extensive of all energy systems. The three main parts of the nuclear system, also called the nuclear process chain, are:

1 The sequence of processes needed to convert an uranium-bearing rock into nuclear fuel.

2 Construction, operating, maintenance and refurbishment of the nuclear power plant. This is the part in which nuclear energy is converted into electricity.

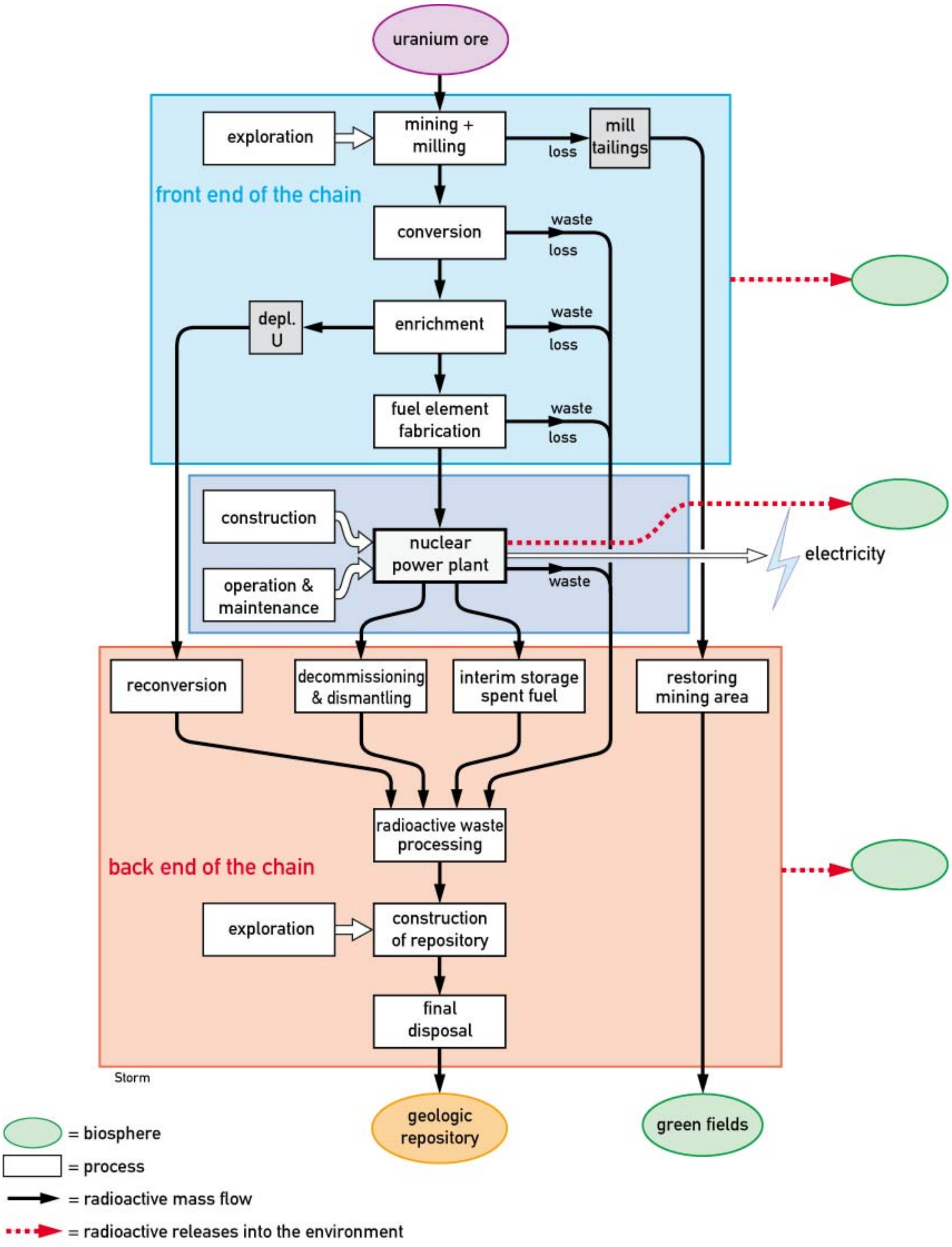
3 Waste management, dismantling of the reactor after its retirement, construction of a geological repository to isolate the radioactive waste from the biosphere, and safe disposal of all nuclear waste, including dismantling waste, in the repository.

Figure 1: The nuclear system: a chain of industrial processes



Each process of the chain, except the operating nuclear reactor itself, is a common industrial process. Each process consumes energy – electricity and fossil fuels –, materials, capital goods and manpower. So each process of the nuclear chain, except the nuclear reactor itself, emits carbon dioxide, among other greenhouse gases and other waste. Consequently, nuclear energy is not carbon-free and not GHG-free (see next section).

Figure 2



Nuclear fuel chain, LWR once-through

The full nuclear process chain of industrial processes, needed to generate useful energy from uranium. The LCA and energy analysis of this study are based on this diagram.

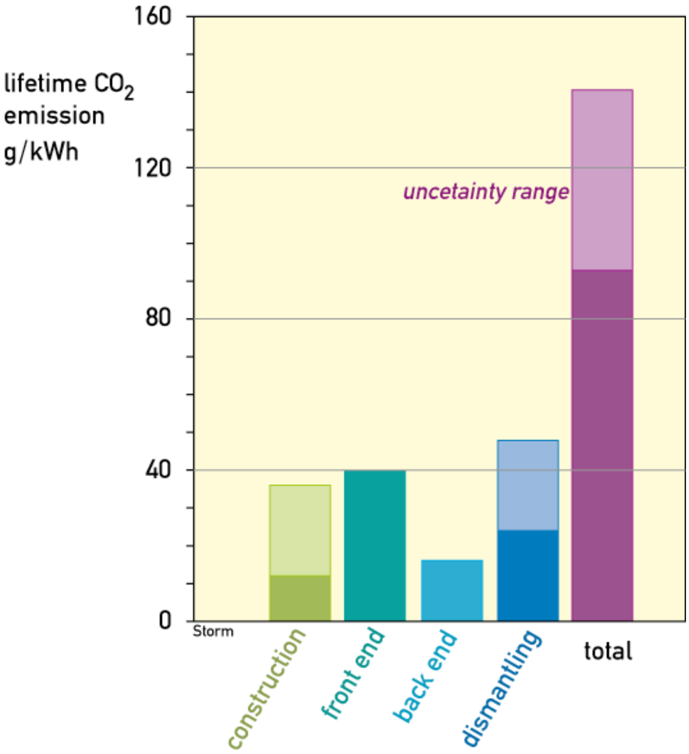
3. Emissions of CO2 and other Green House Gases (GHGs)

CO_2

The specific emission of carbon dioxide (CO_2) by the nuclear system depends on a number of variables. The two main parameters are the operational lifetime of the nuclear power plant and the grade of the uranium ore used to obtain the uranium. The operational lifetime is important because the nuclear system has a large fixed amount energy consumption, with its unavoidable CO_2 emission, for construction and dismantling (see section *Energy debt*). The energy debt is practically independent of lifetime.

The ore grade of the uranium ore determines the amount of fossil fuels needed to extract the uranium from the host rock, and so the CO_2 emission per kg uranium. As the quantity of electricity generated from one kg uranium has a fixed value in a given reactor system, the specific CO_2 emission (gram CO_2 per kWh) increases with decreasing ore grade.

Figure 3:

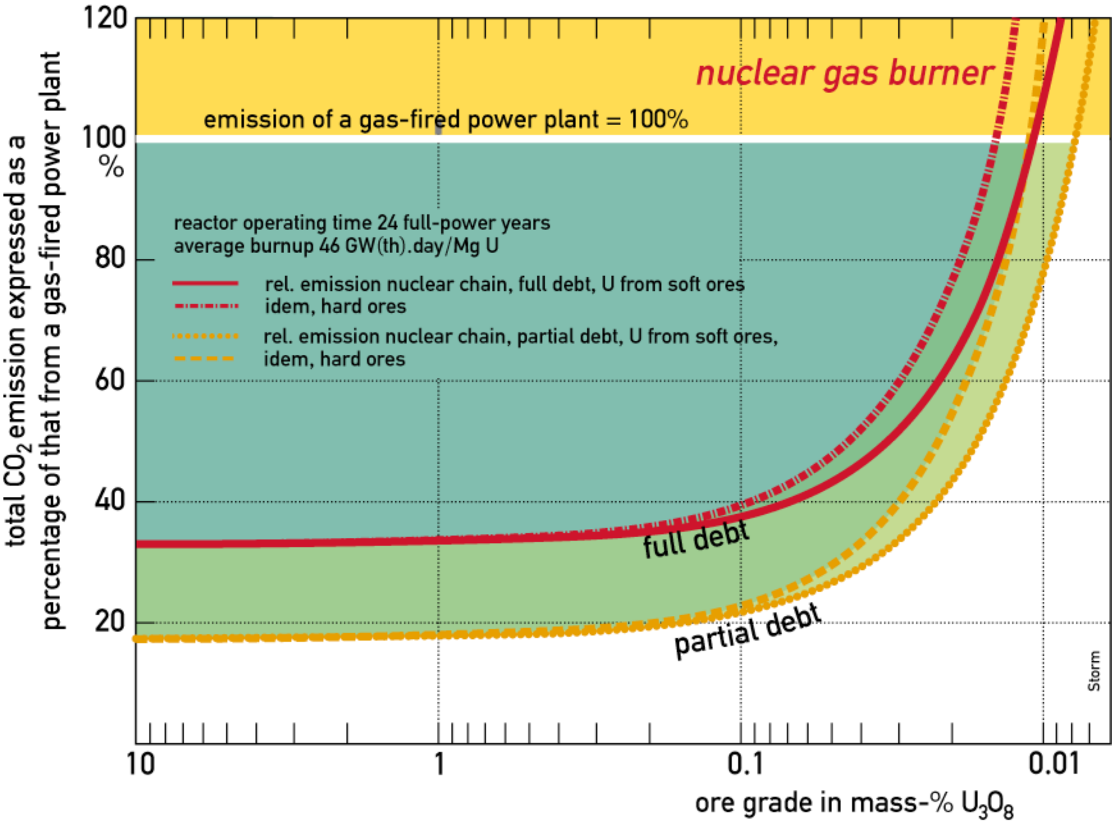


The specific carbon dioxide emission of the nuclear system, averaged on about 31 years operation and using uranium ore with 0.15% U_3O_8. The uncertainty range is explained in section 5, Lifetime costs.

In Figure 3 the specific emission of carbon dioxide is given for the three main parts of the nuclear process chain. The back end of the chain is split up into two components: the variable emission, dependent on the operation of the reactor, and the fixed emission, due to dismantling and the final repository. To construct this diagram, the operational lifetime is assumed to be 24.6 full-power years (about 31 calendar years) and the ore grade has an assumed value of 0.15% U_3O_8, the current world average. The unit full-power year (FPY) is explained on page 2. At present few, if any, nuclear power plants in the world ever achieved a lifetime energy production corresponding with 24.6 FPY.

The second and third bar in Figure 3 depend both on the ore grade. The leaner the ores from which the nuclear system gets its uranium, the higher these two bars get, and so the total CO_2 emission. In Figure 4 the specific CO_2 emission as fraction of the emission of gas-fired power plant, is given as function of the ore grade, at a fixed operational lifetime of 24.6 full-power years.

Figure 4



The specific CO_2 emission of the nuclear system as fraction of the emission of gas-fired power plant, as function of the ore grade. The operational lifetime is assumed to be 24.6 full-power years. The green areas represent the domains in which the nuclear system produces less carbon dioxide per kWh than a gas-fired power plant. Full debt means dismantling and dismantling waste disposal is included, in the partial debt these activities have been deleted. The diagram shows that the uncertainty range posed by the uncertainties in the height of the energy debt, has a relatively small effect on the value of the 100% CO_2 ore grade.

The specific CO_2 emission of nuclear power rapidly rises with decreasing uranium ore grade and exceeds that of a combined cycle gas-fired power plant at grades of about 0.01% (100 grams uranium per tonne rock). At that point the nuclear system in effect becomes a complex and expensive *gas burner*.

Nuclear electricity generated from ores with a grade of 0.15% U, the world average at this moment, has a specific carbon dioxide emission of nearly 90-140 grams CO_2 per kilowatt-hour, depending on accounting the energy debt or not.

Table 1

	g CO_2/kWh **24 FPY**	**G CO2 / kWh** **24 FPY**
Construction	11 – 26	8.5 – 25.4
Front end	40.3	40.3
Back end	16.6	16.3
Dismantling	24 – 48	17 – 34
Total	**93 - 141**	**82 – 116**

Lifetime specific CO_2 emission of the nuclear system, approximation, ignoring process losses and first core. Averaged on the gross electricity production. Average ore grade G = 0.15% U. Emission of greenhouse gases other than CO_2 are ignored

The production of nuclear fuel from uranium ore and conditioning and disposal of the operational wastes contribute about 57 gram CO_2 per kilowatt-hour, using ores with grades of 0.15% uranium. This contribution to the specific CO_2 emission does not depend on the operational lifetime.

Construction and dismantling of the nuclear power plant stand for a large energy debt as well as a CO_2 debt. Redemption of this debt contributes 15 – 84 grams CO_2 per kilowatt-hour, under the most favourable assumed conditions. For comparison: a gas-fired combined-cycle power plant has an emission of about 380 gram CO_2 per kWh.

The calculated values of the specific CO_2 emission of nuclear power show a large uncertainty range. This range is partial due to physical variations of the observed systems, but mainly due to large uncertainties in the processes itself, particularly those of the back end of the nuclear process chain. Any statement of only one fixed value of the specific CO_2 emission of nuclear power is misleading and not scientifically founded.

Emissions of other GHGs

In 2001 the US enrichment plants alone emitted 405.5 Mg of freon 114 (CFC-114), according to EIA-DOE 2005 [Q316]. The US fleet of nuclear reactors produced 769 billion kWh in 2001. Freon-114 has a Global Warming Potential (GWP) of 9300-9800, meaning that one mass unit of freon-114 has the global warming potential of 9300-9800 mass units of carbon dioxide. Assuming that all enrichment work was done for US customers only, the freon emission means a specific GHG emission of 5 grams CO_2 equivalents per kilowatt-hour, from enrichment alone.

In all processes from uranium ore to nuclear fuel very large amounts of fluorine, chlorine and compounds of these elements are used, often in combination with organic solvents. Fluoro-compounds are essential in these processes, because enrichment of uranium requires uranium hexafluoride (UF_6), the only gaseous compound of uranium.

As with all chemical plants, significant amounts of those compounds will be lost to the environment, due to unavoidable process losses. No chemical plant is leak proof. From a chemical point of view, it is conceivable that in several processes potent GHG's arise or are used. Notably chloro- and fluorohydrocarbons (CFCs) have GWPs many thousands times stronger than carbon dioxide.

Fluorine use

In the processes of uranium ore milling through fuel element fabrication fluorine and/or its compounds and organic solvents are involved. Yellow cake from the uranium mill, containing $Na_2U_2O_7$ and/or $(NH_4)_2U_2O_7$, is converted into UF_6, using fluorine and/or its compounds, for instance HF and elemental fluorine (F_2). Stoichiometric ratio F:U = 0.48 in UF_6, meaning that for each gram uranium, 0.48 gram fluorine is needed. In practice the ratio will be higher than the stoichiometric ratio, because of unavoidable losses and secondary reactions.

The reference reactor in our study consumes 20.3 Mg fresh enriched uranium during each reload period (in practice about one year). To prepare 20.3 Mg enriched uranium 162 Mg natural uranium has to be mined. For conversion of 162 Mg natural uranium into UF_6, a stoichiometric minimum of 77.6 Mg fluorine is needed. The UF_6 has to be extremely pure.

After enrichment the total amount of UF_6, comprising one fraction of depleted and one of enriched in U-235, should be reconverted into a stable compound, e.g. UO_2. In practice only the enriched fraction, containing 20.3 Mg uranium, is converted into UO_2 as nuclear fuel. In this case 9.72 Mg fluorine is set free. In which form is it disposed of? Depleted uranium is stored generally as UF_6 in special vessels, often on storage facilities in the open air. UF_6 is very reactive. Of course this way of storage cannot be a permanent one, in view of deteriorating and leaking vessels and increasing chances for accidents or terrorist actions.

World wide some 68000 Mg natural uranium is fluorinated each year, consuming a stoichiometric minimum of 32600 Mg fluorine.

Chlorine use for fuel fabrication

Nuclear fuel, uranium oxide UO_2 enriched in uranium-235, is clad in tubes of Zircalloy, an alloy of extremely pure zirconium and a few percents of another metal, e.g. tin or nickel. Technical-grade zirconium always contains hafnium, which has adverse effects in the core of a nuclear reactor and therefore has to be removed.

Zirconium is purified by chlorination the metal and distillation of the resulting chlorides, to remove all traces of hafnium. The stoichiometric mass ratio chlorine : zirconium = 1.56 grams of Cl per gram of Zr, to make $ZrCl_4$. To produce the 20-40 Mg Zircalloy needed for each reload of 20.3 Mg enriched UO_2 a stoichiometric minimum of about 31-62 Mg chlorine (in any chemical form) is needed. In practice the amount of chlorine may be much larger. To obtain an extremely pure product, large waste streams are unavoidable.

Worldwide some 7600 Mg enriched uranium is converted into nuclear fuel each year, requiring some 7600-15200 Mg Zircalloy. Production of that amount of Zircalloy requires a stoichiometric minimum of 11700-23400 Mg chlorine.

Lack of data

We found no data in the literature on the emissions of fluorine- and chlorine-related chemical compounds by the nuclear industry. As we pointed out above, one can be sure there are such emissions. The Vattenfall EPD 2005 [Q152] noticed the absence of data on emission of greenhouse gases by processes needed to convert uranium ore into nuclear fuel.

The nuclear industry should commit itself to publish a thorough and independent analysis of the emissions of greenhouse gases in all processes of the nuclear chain, before claiming that nuclear energy produces less greenhouse gases than other energy systems or even that nuclear is carbon-free or GHG-free.

4. Timescale

The nuclear energy system distinguishes itself from all other energy systems by its extremely long-term commitments (100-150 years) and the irreversibility of the sequence once the reactor starts up. The time sequence of a nuclear project has three main parts:

1. construction of the nuclear power plant
2. operation
3. back end, the aftermath.

Construction

Historical data indicate that a mean construction time of about ten years may expected, even in case of reactors of a mature and proven design. If new types of reactors are to be introduced, the development time of the new designs should be added to the time needed to establish a projected nuclear electricity generating capacity.

Operational life

The longest operating nuclear reactors, only a very small number, reached a life of about 40 years. Some sources are talking about future lifetimes of 60 years. It is not certain if even 40 years might be taken as an average life of all power reactors. Nuclear reactors cannot be operated during an indefinite number of years, due to deterioration of materials and accumulation of radioactive substances in the system, such as corrosion products and fission products from leaking fuel pins. Moreover the construction materials of the nuclear island become more radioactive (by activation) and less reliable, the longer the reactor operates. Life extension generally is achieved by far-reaching refurbishments. The costs of such life extensions may approach the original construction costs.

The aftermath

After closedown, at the end of the operational life of a nuclear power plant, the nuclear project is not finished. To avoid rendering vast areas inhabitable for many centuries by inadvertent dispersion of radioactive materials, several large-scale and troublesome operations have to be done.

Among these operations are: storing and packing the spent fuel, clean-up of the reactor, safeguarding the reactor during cooling down, dismantling, packaging the waste for final disposal, construction of a safe geological repository and final disposal of all radioactive waste in that repository. Winding up a nuclear project after closedown of the reactor may take 30-100 years. Lack of experience with the back-end operations introduces large uncertainties in the aftermath of a nuclear energy generating project.

Sustainability

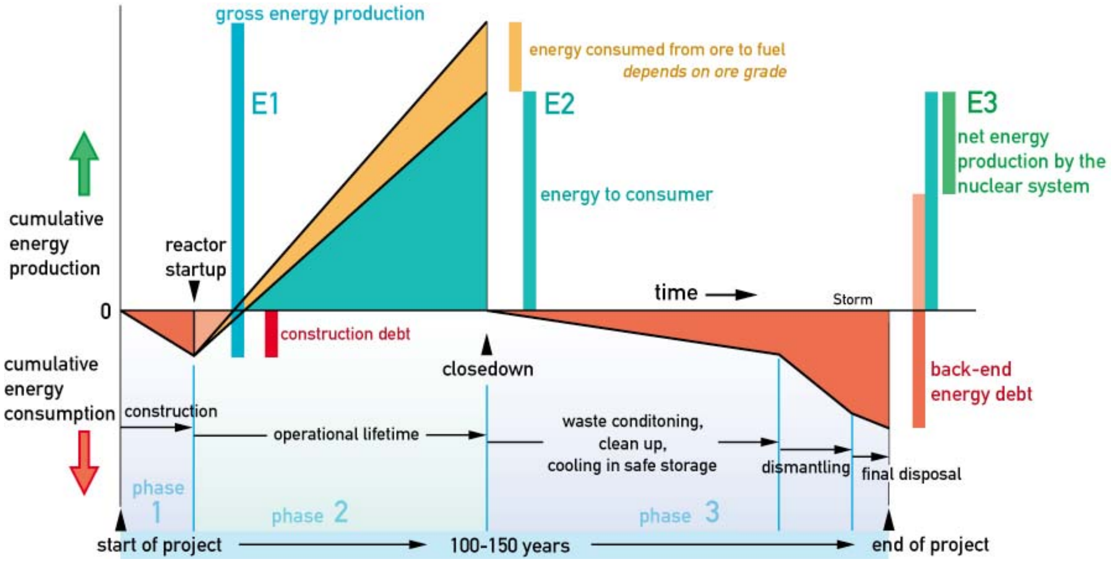
The sustainability principle implies that all future activities arising from the operation of a nuclear power plant started up today are accounted for in the balance of the current operations, and are not left to future generations. In our view the philosophy of '*après nous le déluge*' is not consistent with any sustainability concept. The World Nuclear Association should endorse this viewpoint, where WNA advertises nuclear energy emphatically as sustainable.

4. Lifetime costs

The energy debt

Huge and unavoidable efforts in terms of manpower, materials and energy are required for safely winding up a nuclear project. These facts result in a unique property of the nuclear energy system: the creation of a large energy debt with an extremely long term, during its operational life.

Figure 5



This diagram is a dynamic energy balance of a nuclear power plant and shows the sequence in time of a nuclear project. There are three main parts:

- *Phase 1: construction of the nuclear power plant*
- *Phase 2: productive lifetime: energy generation until closedown of the reactor*
- *Phase 3: cleanup of the reactor, safeguarding the reactor during cooling period, dismantling the reactor and other radioactive parts of the power plant, packing wastes, construction of a safe geological repository and disposing of the wastes in that repository.*

The diagram is not to scale and the height of a curve, not the area beneath a curve, indicates the cumulative energy production or debt. Important quantities are:

- *E1= gross energy production: the electricity put into the grid. This is the quantity listed in the energy statistics (for example Energy Review from BP).*
- *E2= E1 minus the operational energy costs, these are ore grade-dependent.*
- *E3= net energy production of the nuclear system, freely usable and not needed to maintain the production system itself.*

Since no commercial power plant project in the world ever reached its completion, no empirical data based on experience exist. Hence large uncertainties dominate the estimates of the energy costs of the final part of any nuclear project. We estimated the energy requirements of Phase 3 starting from the quantities of materials involved. We concluded that the decommissioning and dismantling activities could consume significantly more energy than the construction of the nuclear power plant. Recent cost estimates of the decommissioning of nuclear facilities in the UK indicate that our estimates may be correct or even on the prudent side.

Energy is a conserved quantity. A large and complex activity, such as dismantling a nuclear power plant after decades of operation, requiring an input of *x* energy units today, will require at least the same amount 50-100 years later. Energy debts cannot be written off as ‘uncollectable’. Due to deterioration of facilities and materials, unwanted dispersion of radioactive materials the required energy input more likely will rise with the years, though the radioactivity of the waste declines slowly by decay of short-lived radionuclides. During the long cooling period the radioactive part of the power plant has to be maintained and safeguarded. Most probably, energy will become more expensive in the future. So the burden for the economy as a whole to finish the job will become heavier, not lighter.

Uncertainties

The net energy production of the nuclear process chain depends on a large number of variables. We presented our results as function of a few of the most important parameters, such as the operational lifetime of the reactor and the grade of the uranium ore. In this way we showed that large uncertainties exist about the net energy production of a nuclear power plant. These uncertainties are due partly to stochastic variances, partly to methodological uncertainties of the analysis, but for a large part to the fact that no nuclear project ever has been completed, from ore to geologic repository.

Internalising ‘external’ costs, energy pay-back time

To make the nuclear system comparable with other energy system, especially renewable systems, we ‘capitalised’ the energy debt of the future at the start of the operational lifetime. In this way delayed external costs, to be paid in the future, are internalized in the present-day operations.

In Figure 6 we compressed the time-axis of Figure 5, to eliminate the time delay of the back end of the nuclear process chain. Doing so we are able to define and calculate:

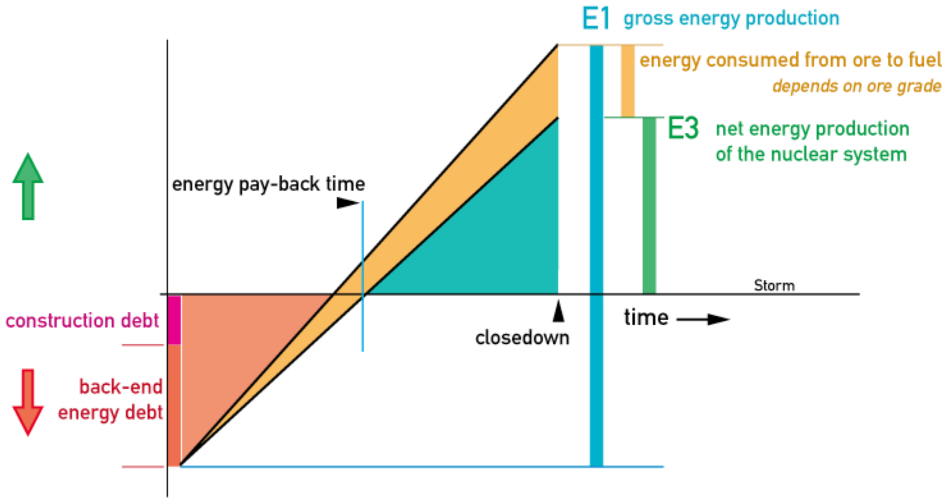
- the energy payback time of the nuclear system
- the energy available for free use (E3 in the diagrams of Figures 5 and 6).

E3 is the quantity of energy available to maintain economic system and to improve the standard of living.

At closedown of the reactor all costs of the full life cycle, in energy units or in monetary units, are accounted for. Of course this bookkeeping trick does not solve the real problem of winding up a nuclear project in a safe and sustainable way. In any case it may avoid a count-you-rich practice.

For comparison of different energy systems the lifetime energy production of a system is a more useful parameter than its operational lifetime is. In this way fluctuating sources such as wind and PV can be compared with other systems.

Figure 6



The energy debt of the activities after closedown are 'capitalised' at the start of operation of the reactor .This diagram shows the definition of the energy pay-back time of the nuclear system. The operational energy inputs (yellow area) depend heavily on the ore grade and increases rapidly when grades get below 0.1% U. The energy pay-back time of the nuclear system is 5-11 full-power years using the currently mined uranium ores (about 0.15% U), or about 6-14 calendar years

Table 2

System	Operational lifetime (yrs)	Energy pay-back time (yrs)
Nuclear (LWR)	30 – 40	6-14 (with ore grade = 0.15%)
PV (UK) PV (South Europe)	30 – 40 30 – 40	4 2
Wind	20	<1
Fossil	30 – 40	<1

The energy pay-back time of an energy system, if calculated in a complete LCA and energy analysis, is a measure of the lifetime investments of that system, in which external costs are internalized. Investments of energy and materials always will correspond with economic investments, the more the scarcer energy and raw materials become.

A system with low construction costs may appear to be producing cheap energy, at the start of the project. If the prices of the raw resource rise faster than inflation, the energy cost rises. If the back end of the process chain of the system requires significant investments, the average lifetime energy costs (per energy unit) may become much higher than anticipated at the start of the project.

Nuclear power is an extreme example of energy systems with hidden and delayed costs. Moreover the uranium price almost certainly will rise significantly during the next decades. Renewables, such as PV and wind, are examples of energy systems with high investment costs, but the energy source has a constant quality and remains free. The back end costs are a small fraction of the construction costs, because all materials are fully recyclable and do not need robotic handling and heavy packing to isolate them from the biosphere. In the long run renewables will be cheaper than energy systems based on mineral resources.

6. Uranium Resources

Security of the energy supply from nuclear power is complex problem in which several variable are involved. Uranium is the sole source of nuclear power. Unlike a common misconception, *uranium resources are not the same as energy resources*.

To get a clear picture of the nuclear energy supply problem, in which the uranium ore grade has a crucial role, two parameters should be sharply discerned:

- the amounts of uranium present in the earth's crust and its distribution over different geological reservoirs, as function of the ore grade,
- the energy needed to recover the uranium from the different rocks in the earth's crust.

World known recoverable uranium resources

The abundance of uranium in the earth's crust is about the same as of tin or zinc. Uranium occurs in many kinds of chemical compounds, minerals, in different types of rocks in the earth's crust. A uranium ore is an uranium-containing deposit in the earth's crust from which the uranium can be extracted economically. Obviously the amount of known 'ores' depends on market prices. The currently known uranium resources are listed in Table 3.

Table 3: World known recoverable resources of uranium

	2003 *		2005 **		2006 **	
country	Resources		Resources		Resources	
	Gg U	%	Gg U	%	Gg U	%
Australia	863	28	989	28	1074	30
Kazakhstan	472	15	622	18	622	17
Canada	437	14	439	12	439	12
South Africa	298	10	298	8	298	8
Namibia	235	8	213	6	213	6
Brazil	197	6	143	4	143	4
Russian Federation	131	4	158	4	158	4
USA	104	3	102	3	102	3
Uzbekistan	103	3	93	3	93	3
Rest of world ***	267	9	480	14	480	13
Total world	3107	100	3537	100	3622	100

Reasonable Assured Resources (RAR) plus Estimated Additional Resources (EAR) - category 1, to 80 US$/kgU plus inferred resources. 1 Gg = 1 gigagram = 1000 metric tonnes. Sources:

* *WNA-75 2003 and WNA-48 2003*
** *WNA-75 2005 [Q85] and WNA-48 2005 [Q210],*
figures of 2006 from update February 2006.
*** *Not given by WNA, figure deduced by author from the rest of the table*

Table 4: Uranium resources 2005, RAR + EAR category 1 to US$80/kg U.

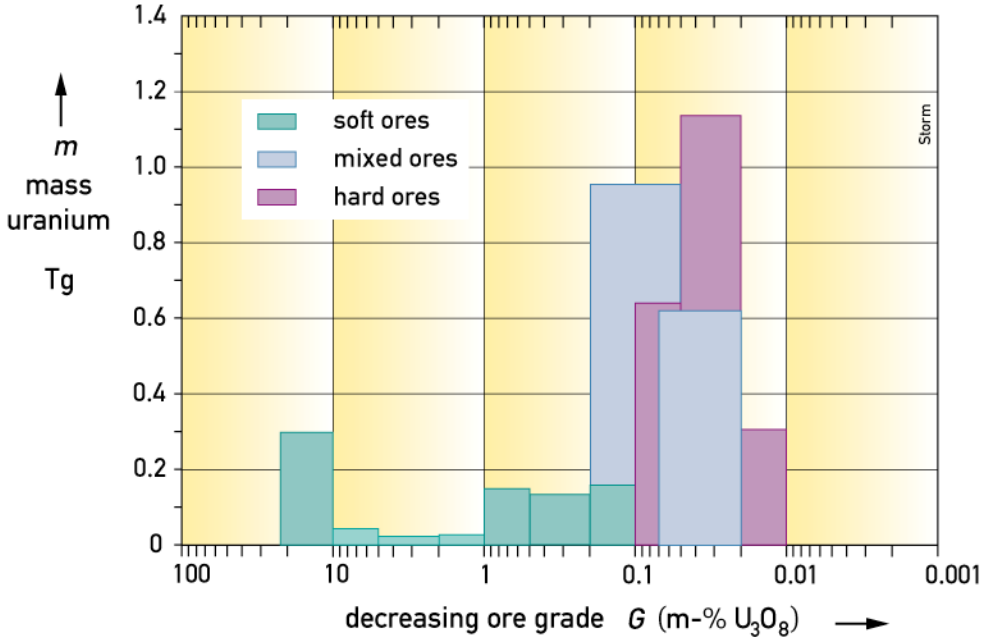
Mine / Region	Grade (G) %U_3O_8	Mean G %U_3O_8	Uranium / soft ores Tg	Uranium / hard ores Tg	Reference
Olympic Dam	0.06			0.0602	Q211, Q86
Olympic Dam	0.05			0.5478	Q211, Q86
Olympic Dam	0.04			0.4817	Q211, Q86
Olympic Dam	0.03			0.4427	Q211, Q86
Jabiluka	0.48-0.57	0.523	0.1984		Q213, Q86
Ranger	0.19-0.27	0.235	0.0487		Q211, Q86
Koongarra	0.8		0.0123		Q213, Q86
Kintyre	0.2-0.4	0.283	0.0297		Q213, Q86
Lake Way	0.096		0.031		Q213, Q86
Ben Lomond	0.25			0.0040	Q213, Q86
Maureen	0.123			0.0025	Q213, Q86
Valhalla	0.144			0.0352	Q213, Q86
Honeymoon ISL	0.15		0.0068		Q213, Q86
Beverley ISL	0.18		0.0210		Q213, Q86
Prominent Hill	0.01			0.0076	Q213, Q86
rest of Australia	0.12-0.15	0.14	0.0804		
total Australia **			0.4004	1.5817	
Elliot Lake	0.087			0.0290	Q53
Key Lake	0.53		0.0003		Q212, Q86
rest of Canada	> 1		0.3902 *		Q212, Q86
total Canada			0.3905	0.0290	
USA ***	0.05-0.4	0.14	0.1020		Q210, Q86
Brazil ***	0.05-0.4	0.14	0.1430		Q210, Q86
South Africa	0.02			0.2980	Q210, Q53
Namibia	0.035			0.2130	Q210, Q53
Kazakhstan ISL	0.02-0.07	0.0374	0.6220		Q210, Q86
Russian Federation ***	0.05-0.4	0.14	0.1580		Q210, Q86
Uzbekistan *** ISL	0.05-0.4	0.14	0.0930		Q210, Q86
rest of the world ****	0.05-0.4	0.14	0.4800 *		
world total			2.3888	2.1217	
world total soft + hard	4.5106				

Sources: [Q53], [85], [Q86], [Q87], Q210], [Q211], [Q212] and [Q213].

*	*Mixed ores: hard and soft.*
**	*Including Inferred and Indicated resources*
***	*Assumed average sandstones*
****	*Figure not given by references. Calculated by author from data from Q85. Ore type and ore grade speculative: assumed to be average sandstones.*
ISL	*= Uranium extracted by in-situ leaching (ISL), [Q314].*
RAR	*= reasonably assured resources*
EAR	*= estimated additional resources*

Arranging the world known recoverable uranium resources according to the grade of the uranium ores, see Table 4, gives Figure 7. The peak at the highest ore grades represent the rich Canadian ores. The diagram demonstrates that the uranium resources are larger, the lower the ore grade, a common geologic phenomenon with metal ores. The distinction between hard and soft ores is based on mining and milling energy requirements of the rock.

Figure 7



The world known recoverable uranium resources as function of decreasing ore grade. The total in the diagram amounts to 4.5 Tg, more than the official figure of 3.6 Tg. This diagram is based on Table 4 (= Table 10 in Chapter 2 of Storm & Smith 2005 [Q6]). Please note that the horizontal axis has a logarithmic scale and the vertical axis a linear scale. The quantity of uranium is represented by the height, not the area of a bar. The width of a bar represents the range of ore grades.

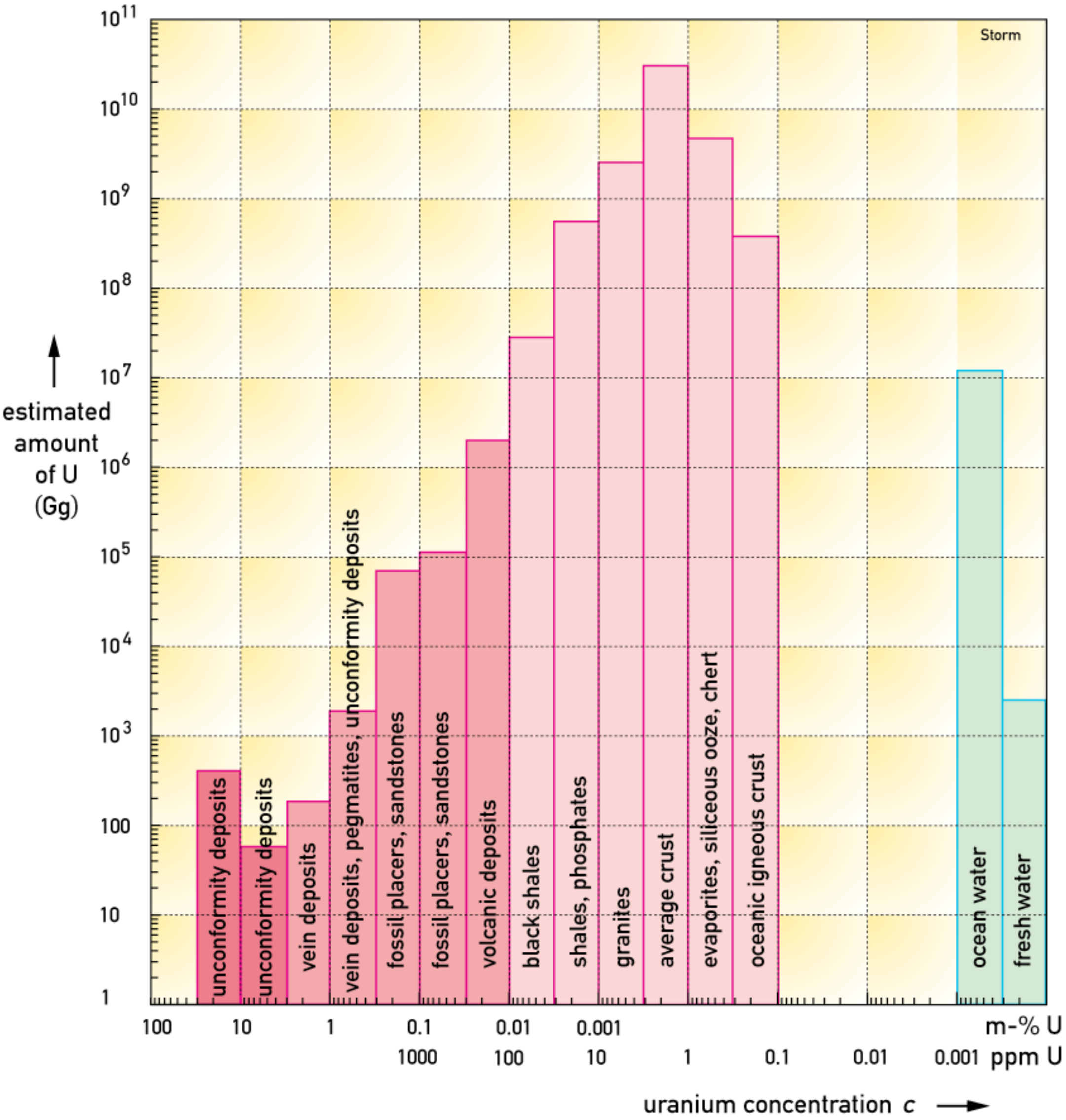
In 2005 the world nuclear fleet consumed about 68000 Mg of natural uranium. Of this amount about 40000 Mg has been actually mined. The remaining 30000 Mg comprised depleted uranium and HEU (highly enriched uranium) from military inventories. Within a few years reserves of HEU will be depleted and from then on all needed uranium has to be mined. When the very rich ores in Canada will get depleted within a decade, the uranium has to be recovered from leaner ores. Likely the uranium prices will rise sharply in the near future.

Prospects of future uranium finds

Deffeyes and MacGregor 1980 [Q281] pointed out that the distribution of uranium in the earth's crust is not well investigated. In their view it's not possible to estimate the chance to find a uranium deposit with a given ore grade, within the accessible part of the lithosphere. They produced a diagram with a probable but speculative distribution of uranium in the various geologic reservoirs of the earth's crust (see Figure 8). Apparently this diagram has not been updated during the past 25 years.

Up until now, no indications of finds of new large rich uranium resources are published. The easily discoverable and easily mineable resources are already known and in production. Any nuclear renaissance scenario which would significantly contribute to the world energy supply and climate control, needs a large multiple (e.g. tenfold) of all rich ores currently known. Moreover, these new resources should be mineable as easily as the currently known ores. What are the chances of discovery? Which regions in the world are so poorly explored that major new discoveries seem probable? Tibet, Antarctica?

Figure 8



Distribution of uranium among the major geological reservoirs, according to Deffeyes & MacGregor 1980 [Q281]. It should be noted that both horizontal and vertical scales are logarithmic in this diagram. The rich deposits in Canada (more than 3% U) are lacking in the original pubication of Deffeyes & MacGregor and are added by the authors Storm & Smith [Q6] (two darkest shaded bars on the left). The lighter shaded bars in the mid represent geological reservoirs not yet exploited.

The diagram in Figure 8 persuaded MIT 2003 [Q280] and many others to the view that the amounts of uranium available for generation of nuclear energy are practically limitless.
From a geological point of view there are no reasons to dispute the accuracy of the diagram. However, the interpretation of the diagram in terms of energy resources is based on the misconception that every uranium atom in the accessible earth's crust would be extractable from its host rock at no energy cost.

The fallacy of this misconception will be explained in the next section.

7. Extraction of Uranium ore

To extract uranium from ores a number of physical and chemical processes are needed. The rock has to be excavated from the earth – in open-pit mines after removing thick layers (tens to hundreds of meters) of overburden, or in deep underground mines – and transported to the mill, where the rock is crushed and ground to powder.

Energy requirements

The specific energy requirements of mining and milling of uranium ore depend on several variables, for instance: type of rock, depth of the ore body, mining in open-pit mines or in underground mines. The energy consumption comprises not only direct energy inputs – e.g. diesel fuel for the excavators and trucks and electricity for the mills and other equipment – but also indirect energy inputs, embodied in chemicals and auxiliary materials, capital goods, equipment, human labour and services.

In-situ leaching (ISL)

About 20% of the world uranium production is extracted from the ground by an in-situ leaching process. Using this method, chemicals are pumped into the ground via injection wells and the uranium-containing solution is pumped up via production wells. Due to the high specific consumption of chemicals (e.g. sulphuric acid) the large number of wells to be drilled and the limited operational life of the wells, the specific energy requirements may become quite large. We found values as high, or even higher, as conventional mining + milling operations, starting from the study of Mudd 2000 [Q291]. Mortimer 1977 [Q98] found values in the same range as the combined energy requirements of mining and milling of soft ores.

A serious drawback of ISL is the large-scale and irreversible contamination of underground aquifers, not only by the added chemicals, but also by radioactive and non-radioactive toxic elements, such as radium, heavy metals and arsenic, which are mobilized from the parent rock as well.
In our view, the ISL method cannot be reconciled with any sustainability concept.

Physical basics
As is it a combination of physical and chemical processes, the extraction of uranium from rock obeys the basic physical laws. To judge the quality of uranium resources as energy resources, one has to take into account two basic parameters:

- the dilution factor,
- the extraction yield.

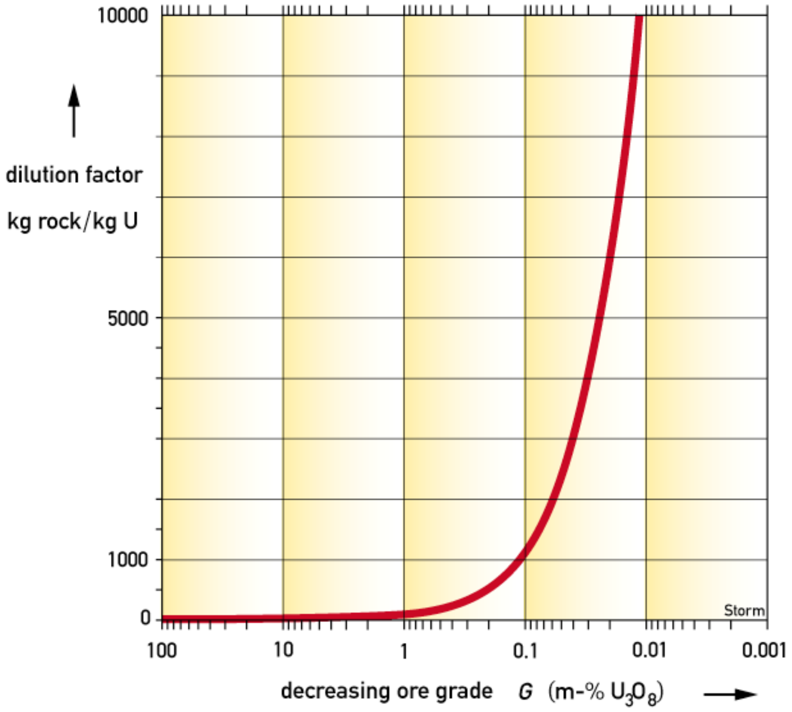
Application of these parameters on the nuclear energy system leads to the concept of the 'energy cliff'.

Dilution factor

Obviously the amount of rock to be mined and milled to obtain 1 kg uranium depends on the ore grade. For example:
At a grade of 0.1% uranium, one Mg rock has to be processed to obtain 1 kg uranium, ten times as much as from rock at a grade of 1%, containing 10 kg uranium per Mg rock.
If the grade falls to 0.01% uranium, 10 Mg rock has to be crushed, ground to powder and leached with chemicals.
In Figure 9 the dilution factor, that is the mass of rock to be processed per kg uranium, is presented as function of the ore grade. The dilution factor is a mathematical relationship and does not depend on technology or ore type.

The uranium grade of the deposits considered in energy resource discussions varies over a range of five orders of magnitude: from nearly 100% through 0.001% uranium, or 1 kg U per kg rock to 10 mg U per kg rock. The richest parts of known ore bodies contain some 0.5 kg U per kg rock. Consequently, the minimum energy consumption and the CO_2 emission of the mining process per kg mined uranium follows a similar curve as the dilution factor as function of the ore grade.

Figure 9



The dilution factor: mass of rock to be mined and milled to obtain 1 kg uranium, as function of the ore grade. Please note that the horizontal axis has a logarithmic scale and the vertical one a linear scale.

Example

An example may clarify the consequences of the dilution factor. Assume that common granite, with an average content of 4 grams of uranium per Mg granite, were to be used as uranium ore. The amounts of granite on earth are immeasurable and so the amounts of uranium. What's the problem?

To fuel one reference reactor with a nominal capacity of 1 GW(e) each year about 162 tonnes natural uranium have to be extracted from earth's crust. The mass of 162 tonnes uranium is in 40 million tonnes of granite. The rock has to be crushed, transported, ground to fine powder and chemically treated with sulfuric acid and other chemicals to extract the uranium compound from the mass. Assumed an overall extraction yield of $Y = 0.50$, a very optimistic assumption, 80 million tonnes granite have to be processed. This is a block of 100 meters width, 100 meters height and three kilometers length. Each year, for one reactor. For comparison: a coal-fired power station of 1 GW(e) consumes about 2 million tonnes of coal each year.

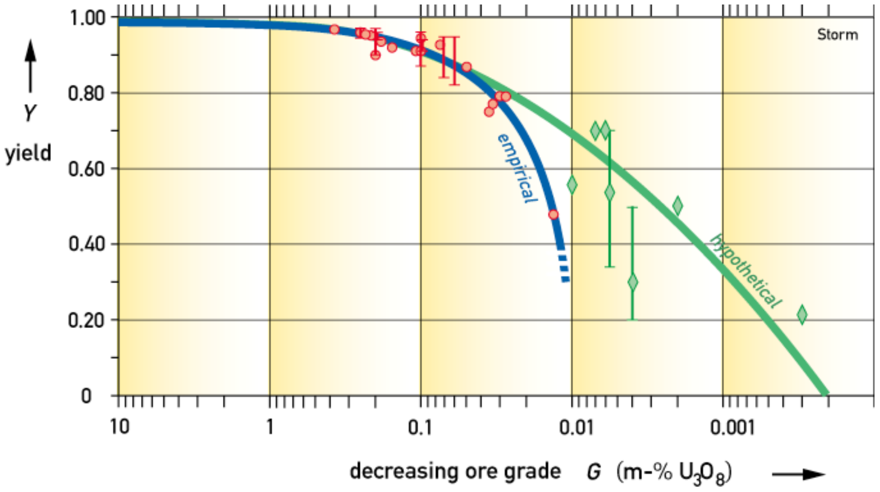
How much energy (fossil fuels) and chemicals would be needed for processing 80 million tonnes granite?

To fuel the current world nuclear power plant fleet of 400 GW – supplying 2.5% of the world energy demand –, each year 12 cubic km of granite would have to be processed each year. That would be a mountain with a base of 4x4 km and a height of 2.3 km

Extraction yield

After grinding the uranium-bearing rock, the resulting powder is treated with chemicals, to dissolve the uranium compound from the host rock. The resulting solution goes through a number of chemical processes to extract the uranium from the raw solution, to separate it from other dissolved species and to concentrate and refine the product, called yellow cake.

Figure 10



The extraction yield, also called recovery, Y, of uranium from ore, as function of the ore grade G. The red dots are empirical values from the literature, based on actual mining operations. The diamonds are taken from hypothetical mining and milling studies. The blue curve (empirical) shows the empirical relationship between Y and G. The green curve represents the hypothetical relationship between, which is used in our study [Q6

In Figure 10 the red dots represents the empirical extraction yields of uranium mines, as reported in the literature. With the currently used extraction methods the yield drops to very low values at grades below 0.02% uranium oxide U_3O_8 (blue curve). In a small number of studies on mining and milling of unconventional ores some extraction yields are mentioned, either based on small-scale laboratory experiments or on undisclosed assumptions. These values are represented by the diamonds in Figure 10. The references on which this diagram is based, are listed in Chapter 2 of Q6.

In our study we chose to use the hypothetical relationship to stay at the safe side of the yield estimates. In this way we anticipate development of advanced technologies in the future. At low ore grades this relationship leads to significant overrating the yield and consequently underrating the specific energy requirements of uranium extraction from ore.

Equilibria and mixing entropy

The extraction of the uranium from the raw solution involves a number of chemical equilibria. Extraction equilibria never go to completion and the extraction yield – the fraction extracted from the mother liquid into the extraction solvent – decreases with decreasing concentration of the uranium ions in the mother liquid. This problem is aggravated by the presence of many other ions in the solution, with competing equilibria, the more the higher their concentrations and the lower the uranium concentration.

Technically it is possible to extract uranium from rock with very low grades, but at the expense of higher consumption rates of materials and energy. The lower the uranium concentration in a matrix of many other ions, often with much higher concentrations, the higher the mixing entropy of the uranium and the more work is required for its extraction and purification. More work means that the specific energy requirements of extraction will rise with decreasing ore grade, independently on the applied technology. Advanced technology only can come closer to the thermodynamic minimum at a given ore grade.

The energy cliff

The quantity of energy which can be generated from 1 Mg natural uranium has a fixed value in a given reactor type. The amount of energy needed to convert a uranium-bearing rock in the ground into nuclear fuel, depends on the ore grade: the lower the grade the more energy the extraction of uranium from its ore consumes. Applying any technology, the extraction energy requirements heavily depend on the dilution factor and the extraction yield.

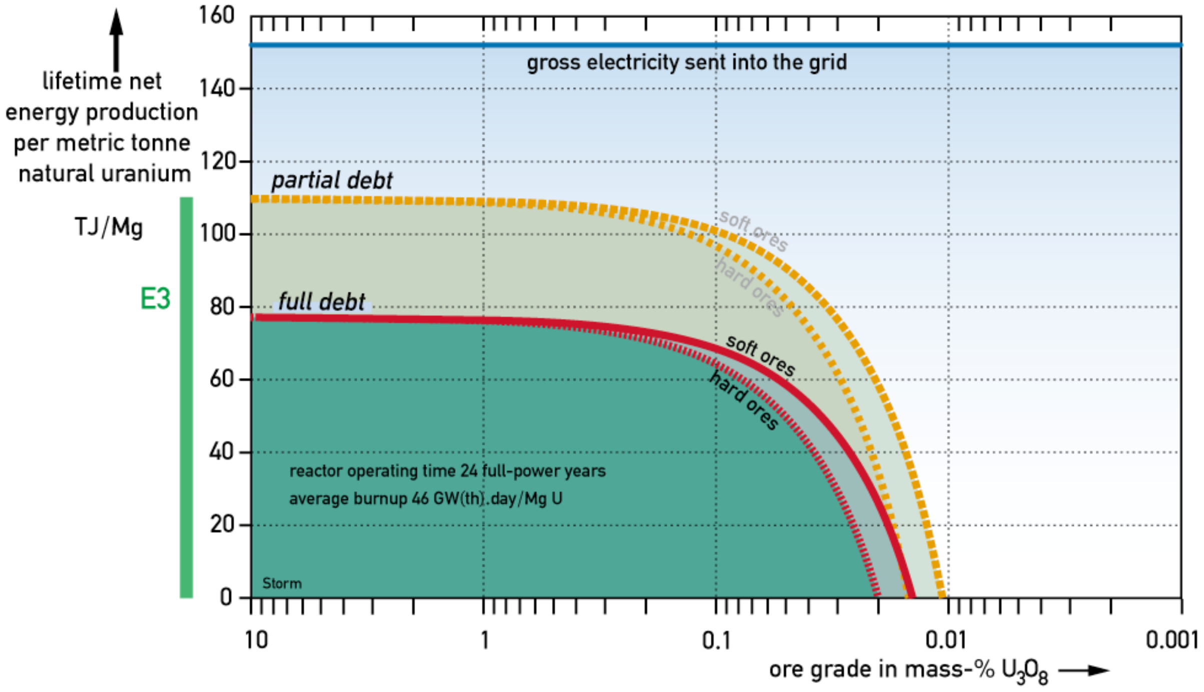
The curves in figure 11 result from subtracting the energy requirements (per Mg natural uranium) of the full nuclear process chain from the electricity put into the grid by the nuclear power plant (value represented by the horizontal line at top of the diagram). All energy inputs of the nuclear system are averaged on a operational lifetime of 24.6 full-power years (FPY), or 30 reload periods, corresponding with about 31 calendar years at a lifetime average load factor of 80%.

The height of the green areas in Figure 11 represent the net energy production by the nuclear system (E3 in Figures 5 and 6) at a given grade of the used uranium ore. The difference between soft ores and hard ores becomes prominent at low ore grades.

The construction of a nuclear power plant requires a fixed amount of energy, materials, etcetera, independent on the operational lifetime of the reactor. The effort needed to dismantle the reactor after its retirement may partially depend on the operational lifetime, due to the increasing radioactivity of the reactor and associated parts of the construction with increasing neutron flux and leakages. We assumed a fixed quantity of energy and materials needed for decommissioning and dismantling after one year of operation: the ‘energy debt’. The energy costs of construction and dismantling are averaged on the lifetime of the reactor. ‘Partial debt’ in Figure 11 means that dismantling is not taken into account and ‘full debt’ means it is.

The range between full debt and partial debt may also be viewed as an uncertainty range in the results of our analysis. Major causes are uncertainties regarding average operational lifetime and the energy costs of dismantling and final disposal of all contained radioactive wastes in a safe geologic repository.

Figure 11



The 'energy cliff'. This diagram shows the net energy production possible per megagram (see page 2) natural uranium, averaged over the reactor lifetime. This corresponds with E3 in Figures 5 and 6.

As it turns out, the grade at which the energy consumption of the full nuclear fuel chain equals the gross energy production and the net energy production falls off the cliff and plunges into the sea of zero, little depends on the size of the energy debt. Between ore grades of 0.02 and 0.01 the nuclear system meets its zero net energy limit.

These values would also follow from the relationship between the recovery yield *Y* and ore grade alone (see Figure 10). Using conventional extraction techniques the extraction yield *Y* approaches zero at that ore grades.

Application of advanced techniques may shift the zero-energy grade to somewhat lower values, but the gain would be not significant. Even an improvement of energy efficiency with a factor of two would fall within the uncertainty range posed by other variables (soft or hard ores, full or partial debt).

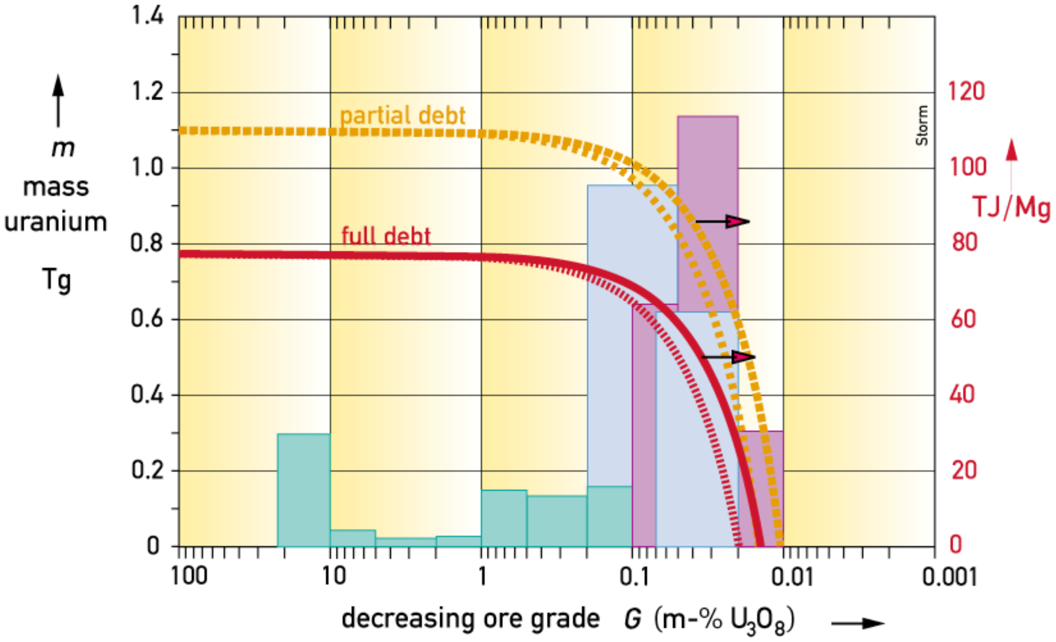
The existence of the energy cliff implies that no net energy from uranium is possible below an ore grade of about 0.02-0.01% U_3O_8. This limit hardly depends on the state of technology nor on the assumptions on which the energy analysis of this study is based.

The uranium peak

Projection of the curves of the energy cliff from Figure 11 onto the diagram of the world known recoverable uranium resources (Figure 7), gives the picture in Figure 12. By chance or not, it turns out that no 'known recoverable resources' are reported at grades below the 'cutoff grade' of 0.02-0.01% U_3O_8 (200-100 grams U_3O_8 per Mg rock).

The size of uranium resources increases exponentially with decreasing ore grade, a common geologic feature of mineral resources. Due to the dilution factor and the extraction yield, the net energy content falls exponentially with decreasing ore grade. Consequently the total net available energy in uranium resources, as function of the ore grade, reaches a peak at some ore grade. In Figure 13 a roughly calculated curve shows such a peak. The net energy content of a given deposit, *E*, is found by multiplying the amount of uranium in that resource with the specific energy content (TJ/Mg U nat) of the uranium from that ore. The sole civil use of uranium is an as energy resource, so an energy balance defines the value of an uranium deposit for the energy supply.

Figure 12

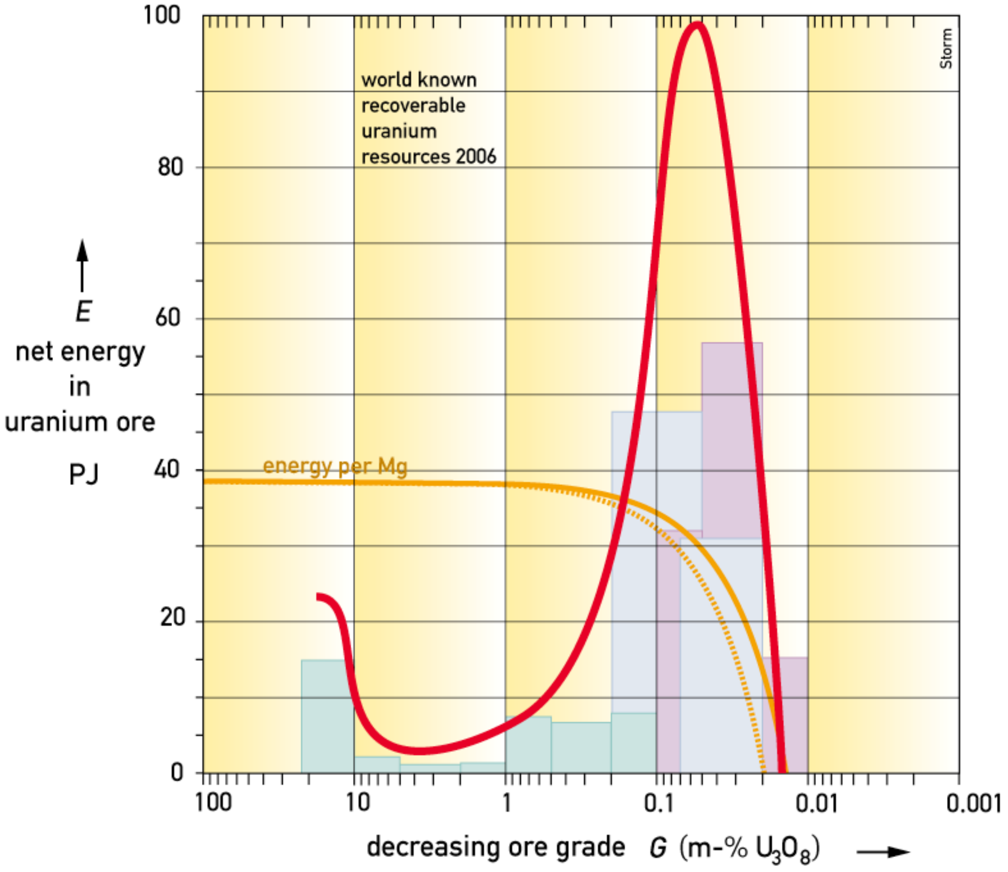


The 'energy cliff' from Figure 11 is projected onto the figure of the world known recoverable uranium resources from Figure 7.

In Figure 13 the peak of the potential net energy in the currently known recoverable energy resources from uranium appears between 0.05 and 0.06% U_3O_8. Obviously the peak would become higher when new resources are discovered. The peak ore grade may shift somewhat to higher grades when large rich and easily mineable deposits are discovered, or to lower grades if very large poor ore deposits are found, but not much. Below G = 0.05% U_3O_8 the energy cliff becomes very steep.

The largest operating uranium mine in the world, Olympic Dam in Australia, produces uranium from ores with grades of 0.06% down to 0.03% U_3O_8. This mine contains some 30% of the world known recoverable resources and is represented by the highest purple bar in Figure 7 and 12, very near the verge of the energy cliff and at the downhill side of the uranium peak in Figure 13.

Figure 13



The uranium peak. The red line represents a rough estimate of the net energy content E (in petajoules PJ) of a given ore deposit with a given ore grade. E is found by multiplying the amount of uranium in a given resource with the specific energy content (TJ/Mg U nat, orange line, for the scale see Figures 11 and 12), from ore at the given grade. The calculations are based on the lower curve of Figure 11, the net energy accounting for the full energy debt. Using the upper curve (partial debt) would result in a higher peak, but at about the same ore grade (0.05-0.06% U_3O_8*).*

Improvement of the energy efficiency of uranium extraction with, say, a factor two would not add much energy-from-uranium resources.

Shift effect

It should be noted that, apart from the ore grade, the peak curve is affected by a second effect. Table 4 includes resources with higher production costs and less degree of assured quality (e.g. Inferred Resources an Estimated additional Resources) than Table 3, the official figures of WNA. In practice that means that such deposits are less accessible and harder to mine and consequently have higher specific energy requirements for mining plus milling than the currently mined deposits of the same ore grade. This effect, here called the shift effect, causes the zero-level grade of the energy cliff to shift to higher ore grades, as the easier-mineable ores are getting depleted.
The shift effect is not accounted for in our study, because very few quantitative data are available.

Consumption and supply of uranium

The current world nuclear fleet of 367 GW has an annual natural uranium consumption of about 68000 Mg/a. How long will the currently known uranium resources last?

The largest known resources have ore grades below 0.05% U_3O_8 and are more or less near the verge of the energy cliff. The sum of the resources of Olympic Dam, South Africa, Namibia and Kazakhstan is about 2.6 Tg uranium. These resources are marginal is respect to their net energy content and would cause a significantly higher specific CO_2 emission than the currently mined ores.

The remaining higher-grade resources have a mass of 1.9 Tg and will be sufficient to feed the current nuclear capacity for 28 years. Then the specific CO_2 emission will rapidly rise and may approach the value of a gas-fired station in about 65 years, when the poorest ores will get exploited. However, the net energy production of the nuclear system will approach zero in the same time. One may wonder how the nuclear future will look after 2034.

Conclusions

Future reactor type

- Generation of nuclear power in the foreseeable future has to rely on thermal-neutron reactors, mainly light-water reactors. These reactors cannot fission more than about 0.7% of the atoms in natural uranium, the uranium as extracted from ore.
- Even if the breeder cycle starts working flawlessly next year, the share of breeder power could not become significant before the end of this century.

Carbon dioxide and other greenhouse gases

- Under the most favourable conditions, the nuclear system emits 90-140 grams carbondioxide per kilowatt-hour.
- It is not possible to give one value of the specific emission, due to the large uncertainties in many processes of the nuclear process chain.
- The specific emission of carbon dioxide by the nuclear system strongly depends on the grade of the uranium ore used to fuel the system. At grades below about 0.01% uranium, the nuclear chain emits more CO_2 than a gas-fired power station.
- Emissions of other greenhouse gases by the nuclear system, especially chloro- and fluorohydrocarbons, are not published and likely never analysed. Absence of reports does not mean absence of emissions.
- Considering the large amounts of fluorine and chlorine being used in the processes needed to convert uranium ore into nuclear fuel, it seems inconceivable that such emissions are absent.
- Enrichment facilities in the USA emit about 5 grams CO_2-equivalents per kWh as CFC-114.

Operational life

- Nuclear reactors cannot be operated during an indefinite number of years, due to deterioration of materials and accumulation of radioactive substances in the system. The construction materials of the nuclear reactor and associated systems become more radioactive and less reliable, the longer the reactor operates.
- More significant than the life in calendars years is the lifetime energy production of a reactor. A few reactors may have achieved a lifetime production equivalent to about 24 full-power years.

Energy debt

- A distinct feature of the nuclear energy system is its extremely long time scale (100-150 years).
- Completion of a nuclear project, after retirement of the reactor, involves a number of energy-intensive activities, which together form a large energy debt.
- Likely, energy costs will increase in the future. Consequently the burden for the economy to pay off the energy debt will become heavier, not lighter.
- Energy debts cannot be written off as ‘uncollectable’.

Technical and economic uncertainties

No nuclear project ever has been completed, from ore to geologic repository, consequently large unknowns still exist concerning the technical feasibility and economic aspects of the back end of the nuclear process chain.

Energy cliff

- To make energy available from uranium resources significant energy inputs are required.
- Besides on ore type and accessibility of the ore body, the energy requirements of the extraction of uranium from its ore strongly depend on the ore grade.
- The relationship between the energy requirements of the extraction of uranium and the ore grade is determined by two factors:

  - The dilution factor, which increases exponentially with decreasing uranium ore grade. The dilution factor is a mathematical relationship, independent of ore type.
  - The extraction yield, which decreases exponentially with decreasing uranium ore grade.
- The thermodynamic minimum of work (useful energy) needed for extraction increases exponentially with decreasing ore grade, due to the increasing mixing entropy of the uranium. Advancement of technology means coming closer to the thermodynamic minimum.
- The net energy production of the nuclear system depends on the grade of the uranium ores which feeds the system. Below grades of 0.1% uranium, the curve representing the relationship between net energy and ore grade, steeply declines and reaches zero value at grades of 0.02-0.01% uranium: the energy cliff.
- The existence of the energy cliff implies that no net energy from uranium is possible below an ore grade of about 0.02-0.01% U_3O_8. This limit hardly depends on the state of technology nor on the assumptions on which the energy analysis of this study is based.
- Uranium resources are not the same as energy resources.

Uranium peak

- The currently known recoverable uranium resources will be depleted in about 50 years, if the world nuclear capacity remains at the current level.
- The easily discoverable and easily mineable uranium resources are already known and in production.
- The mines with relatively rich uranium ores currently in production will get depleted in about 28 years.
- During the years after 2034 the specific CO_2 emission of the nuclear process chain will rapidly rise, if the world nuclear capacity remains at the current level and if no new large uranium resources will be discovered, which are as easily accessible and mineable as the current rich ores.
- During the same years after 2034, under the same conditions, the net energy production of the nuclear system will decline and fall off the energy cliff by the year the currently known resources will get depleted.

Prospects

- Up until now, no indications of finds of new large rich uranium resources are known or published.
- The chances of discovery of new large resources as easily mineable as the currently known ores are unknown.

Appendix 1

Breeders

The only fissile nuclide in nature is uranium-235, accounting for 0.7% of the atoms in the uranium as found in nature (called: natural uranium). The remaining 99.3% are uranium-238 atoms and traces of uranium-234, both of which are not fissile.

In an operating nuclear reactor a part of the abundant and 'fertile' uranium-238 in natural uranium is converted by neutron capture into plutonium-239, which is fissile. Theoretically, in a fast breeder reactor (FBR), more plutonium-239 atoms (and higher isotopes) are formed than are fissioned.
In this way, via conversion into plutonium, some 30-60% of the atoms in natural uranium could be fissioned in a breeder reactor. That would mean 50 to 100 times the fissioned amount in conventional (thermal-neutron) reactors.

The high fissionable fraction of natural uranium theoretically achievable by the breeder system is the source of the old nuclear dreams from the 1950s: 'all nuclear society', 'too cheap to meter' and 'burning the rocks'. Today these unproven figures still give rise to the technical dreams of untold quantities of cheap, clean nuclear energy for all mankind for the next centuries.

However, two obstacles are blocking the road to materialization of these dreams: the technical unfeasibility of the breeder system and the logistic problem of plutonium availability.

Breeder system

What is called a 'breeder' is not just a reactor type or a stand-alone system. To exploit fully the promised potential of natural uranium, a complex breeder cycle is prerequisite. The cycle (see Figure A1) comprises three components: the breeder reactor, a reprocessing plant and a fuel fabrication plant.

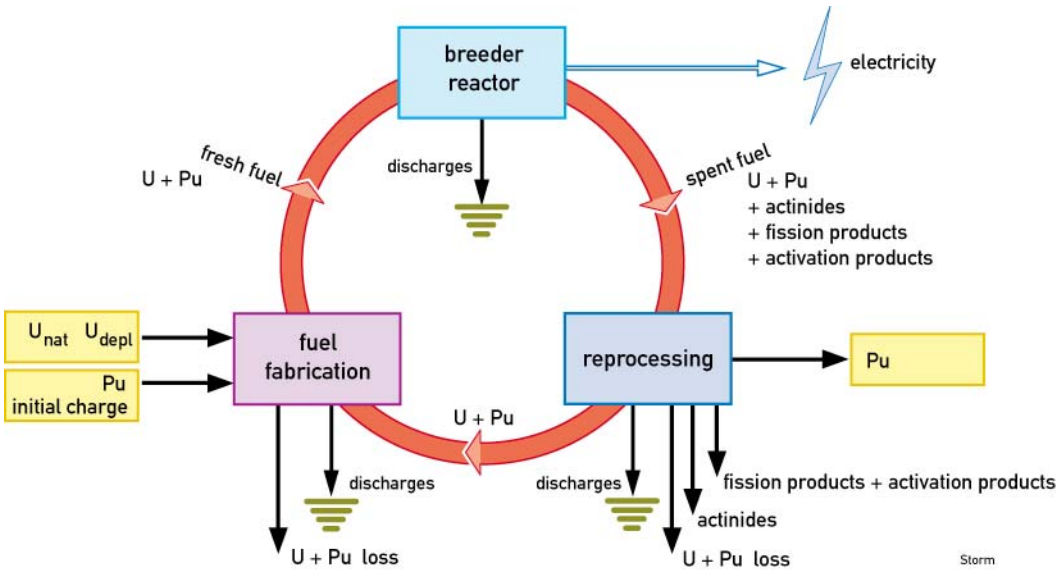
Important parameters of the breeder system are, among other:

- initial inventory of plutonium in Mg/GW, should be as low as possible
- breeding ratio, should be as high as possible
- full-power operating time of the reactor, should be as long as possible
- out-of-pile time of the plutonium, should be as short as possible
- plutonium losses in the cycle, should be as low as possible.

The first three are reactor parameters, the latter two are determined by two of the other components of the cycle: reprocessing and fuel fabrication.

All three components of the breeder cycle must operate flawlessly, continuously and exactly tuned to the other two components, before any breeding can be achieved. If one component fails, the whole system fails. In fact, none of the three components have ever demonstrated operation as required, let alone the three components together as one integrated continuously operating system.

Figure A1



General outline of the breeder system in steady state. By repeatedly recycling spent fuel, it would be theoretically possible to fission the main part of natural uranium. If all goes well, the cycle produces during its operational life a plutonium gain, large enough to start up two or more new breeders: one to replace the closed down unit, and one or more additional breeders. The cycle represents the mass flows of uranium and the nuclides originating from the nuclear processes in the reactor (fission, activation and decay). The initial plutonium charge to start up the breeder reactor is about 3 Mg Pu for a 1 GW(e) FBR.

Fifty years of intensive research in seven countries (USA, UK, France, Germany, former USSR now Russia, Japan and India), with investments of many of tens of billions of dollars so far have failed to demonstrate that the breeder cycle is technically feasible.

Problems of the breeder system are discussed in more detail by, among others, UNIPEDE/CEC 1981 [Q58] and Lidsky & Miller 1998 [Q301]. The authors concluded that the breeder system is not feasible, not only due to the technical hurdles, but also because the system cannot meet the requirements of safety, proliferation and economy. The MIT 2003 study *The Future of Nuclear Power* [Q280], does not expect breeders (in effect the breeder cycle) to come into operation during the next three decades.

Plutonium availability

Even if the breeder system starts working according to the textbooks from now on, a logistic problem is limiting the set up of a large-scale breeder-based energy system: the plutonium availability. The first breeders are to be fueled with plutonium from LWRs. At present about 240 Mg reactor-grade plutonium is in stock world wide, in addition to 150-200 Mg weapons-grade plutonium, according to WNA-inf15 2005 [Q313]. Assuming an initial load of 3 Mg plutonium per 1 GW breeder reactor, these inventories would be adequate to start up about 140 breeder reactors.

Two scenarios may demonstrate the potential of the breeder system as part of the world energy supply. Both scenarios are based on the following assumptions:

- the breeder system works according to the textbooks,
- the doubling time of the system is 40 years (a survey based on the state of technology in the early 1980s estimated a doubling time of 87 years [Q58]),

- in 2006 the construction programme of the maximum number of breeder systems starts, the number only limited by the available plutonium,
- in 2016 all breeders come on line and keep operating without interruptions,
- the world economy keeps strong enough during the next century – the build-up phase of the breeder systems – to support the huge investments of money (order of magnitude: a thousand of billions of US dollars each year), materials, energy and manpower, needed for construction of 140 breeder reactors and associated reprocessing facilities and fuel fabrication plants,
- decommissioning and dismantling are ignored.

In scenario 1 (see Figure A2) a phase-out of LWR fuel reprocessing is assumed. The combined gross electricity generating capacity of the first batch of breeders would be some 140 GW, 38% of the current world nuclear fleet or 6% of the world electricity generating capacity in 2005. From 2016, the doubling time of the breeder system would be the pacing factor of the extension of the breeder capacity, if the LWRs were to be phased out, e.g. because of depletion of the rich uranium ores.

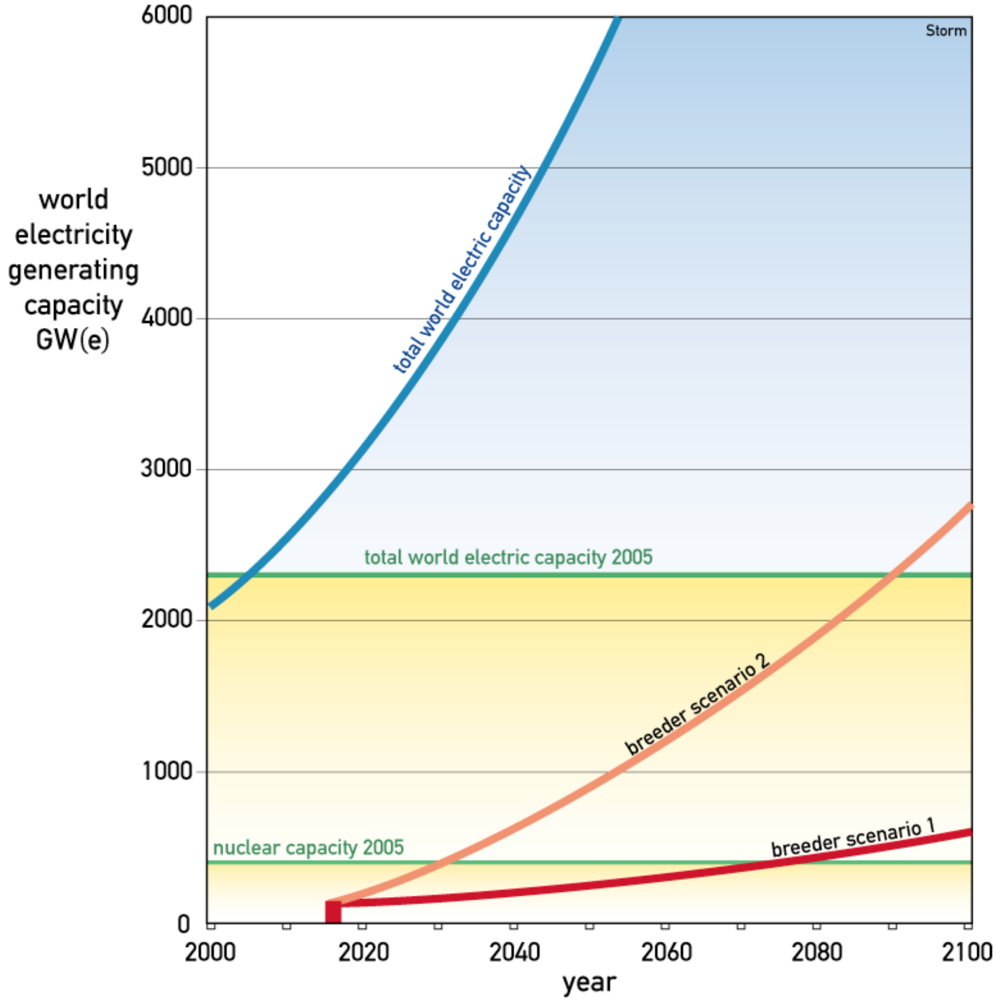
In scenario 2 the world LWR fleet is assumed to remain constant through 2056 and to be phased out after that year, because of depletion of rich uranium ores. In 2100 all LWR would be closed down. During the operating time of the LWRs all spent fuel of the world LWRs would be reprocessed from 2016 on. About 60 Mg plutonium each year would become available, enough to start up 20 new breeders.

It should be emphasized that none of the assumptions on which the scenarios are based are backed by any empirical or probable fact.

Thorium breeder

The thorium breeder is based on the conversion by neutron capture of non-fissile thorium-232 into fissile uranium-233, by a similar system as the uranium-plutonium breeder. The feasibility of the thorium breeder is even more remote than that of the U-Pu breeder. Besides, only minute quantities of U233 exist in the world at this moment. It would take decades to obtain sufficient U233 from special reactors to start up the first operating Th232–U233 breeder system. It would take 9 doubling times to attain a thorium breeder capacity equalling the current nuclear capacity. Even with an unrealistically assumed short doubling time of 20 years that would mean two centuries.

Figure A2



Two breeder construction scenarios. De blue line represents the world electricity demand, assuming an average annual growth of 2%. Both scenarios start with 140 GW breeder reactor capacity in 2016 and are based on a doubling time of 40 years. In fact these scenarios do not depend on the assumed breeder system technology (except the doubling time), only on plutonium availability.

References

Q6
Storm & Smith 2005
Storm van Leeuwen J W & Smith Ph B,
Nuclear power - the energy balance
August 2005
www.stormsmith.nl

Q53
NAC 1982
Data world uranium mines outside China and Sovietunion,
Nuclear Assurance Corporation, Zürich, 1982
personal communication via PJ vander Hulst, KEMA, Arnhem.

Q58
UNIPEDE/CEC 1981
UNIPEDE/CEC Breeder Reactor Study Group,
Role of breeder reactor system in the European Community,
International Union of the Electric Power Producers and Distributors (UNIPEDE),
Fast Reactor Coordinating Committe (FRCC) and Commission of the European Community (CEC),
Published by ENEL, Roma, September 1981.

Q85
WNA-75 2004
Supply of Uranium,
Appendix: The sustainability of mineral resources
World Nuclear Association, August 2004
www.world-nuclear.org/info/inf75.htm
or
www.uic.com.au/nip75.htm
based on OECD, NEA & IAEA, Uranium 2003, per 0101003.

Q86
UIC-34 2005
Geology of uranium deposits,
Uranium Information Centre, Nuclear Issues Briefing Paper # 34, November 2001 (site visit 8sept2005)
www.uic.com.au/nip34.htm
= [WNA26 2005]
World Nuclear Association, Information Paper # 26
www.world-nuclear.org/info/inf26.htm

Q87
WNA-mining 2005
Uranium mining in Australia and Canada
World Nuclear Association, June 2001 (2005)
www.world-nuclear.org/education/mining.htm

Q89
WNA-23 2005
World uranium mining,
World Nuclear Association, Information paper # 23, July 2005
www.world-nuclear.org/info/inf23.htm

Q98
Mortimer 1977
Mortimer N D,
The Energy Analysis of Burner Reactor Power Systems,
PhD dissertation, Milton-Keynes Open University, UK, December 1977.

Q152
Vattenfall 2005
Vattenfall AB Generation Nordic Countries,
EPD: Certified Environmental Product Declaration of Eelectricity from Forsmarks Kraftgrupp AB (FKA),
S-P-00021
June 2004, updated 2005.
www.environdec.com

Q155
WNA-11 2005
Energy analysis of power systems,
Info Paper #11*,*
World Nuclear Association, 2005
http://www.world-nuclear.org/info/inf11.htm

Q210
WNA-48 2006
Australia's uranium and who buys it,
World Nuclear Association, February 2006
www.world-nuclear.org/info/inf48.htm.
identical with:
Uranium Information Centre, Nuclear Issues Briefing Paper 1, February 2006,
www.uic.com.au/nip01.htm

Q211
UIC-emine 2005
Australia's uranium mines,
Uranium Information Centre, December 2005
www.uic.com.au/emine.htm

Q212
WNA-49 2006
Canada's Uranium production and nuclear power,
World Nuclear Association, February 2006,
www.world-nuclear.org/info/inf49.htm

Q213
UIC-pmine 2005
Australia's uranium deposits and prospective mines,
Uranium Information Centre, May 2005
www.uic.com.au/pmine.htm

Q280
Deutch J, Moniz EJ, et al.
The Future of Nuclear Power. An interdisciplinary MIT study,
Massachusetts Institute of Technology, Cambridge MA, USA, 2003
ISBN 0-615-12420-8
www.mit.edu/afs/athena/org/n/nuclearpower

Q281
Deffeyes & MacGregor 1980
Deffeyes K S & MacGregor I D
'World Uranium Resources',
Scientific American, **242** (1), 1980, pp 50-60.

Q283
DOE-NERAC 2001
A roadmap to deploy new nuclear power plants in the United States by 2010,
Volume I, Summary Report
US Department of Energy (DOE), Office of Nuclear Energy Science and Technology,
and; Nuclear Energy Research Advisory Committee (NERAC). Subcommittee on Generation IV technology planning,
October 31, 2001
http://nuclear.gov/nerac/ntdroadmapvolume1.pdf

Q291
Mudd 2000
Mudd G M,
Acid in-situ leach uranium mining: 2 - Soviet Block and Asia,
paper for: Tailings and Mine Waste '00,
Fort Collins, CO, USA, January 23-26 2000,
proceedings AA Balkema, Rotterdam, pp.527-536.

Q301
Lidsky LM & Miller MM,
Nuclear power and energy security. A revised strategy for Japan,
PARESWorkshop: Energy Security in Japan, Tokyo, Japan, 13 July 1998.
www.nautilus.org/archives/papers/energy/LidskyPARES.pdf

Q302
Thorium
Uranium Information Centre, November 2004
UIC Nuclear Issues Briefing Paper # 67
www.uic.com.au/nip67.htm

Q313
WNA-inf15 2005
Plutonium
World Nuclear Association, June 2005
www.world-nuclear.org/info/inf15.htm

Q314
WNA-27 2003
In situ leach (ISL) mining of uranium
World Nuclear Association, June 2003
www.world-nuclear.org/info/inf27.htm

Q316
EIA-DOE 2005
Checklick N, Lead Environmental Analyst, EIA-DOE
email dated 25 August 2005, from nancy.checklick@eia.doe.gov via NPRI to <storm@ceedata.nl>
File: CFC Uranium Enrichment.xls
US Department of Energy, Energy Information Administration
Data from: www.eia.doe.gov
and: www.afeas.org