Powering the Future

But is nuclear energy the solution?

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Large-scale implementation of nuclear power cannot be the solution to the future energy and climate problems of the world. Costs, constraints on uranium supply and technological shortcoming, well known to the nuclear industry, undermine the case for a nuclear future. There are better and cheaper alternatives, starting with more efficient transport, biomass and photovoltaics.

Some facts, technical dreams and misconceptions are discussed in this article, from a physical point of view.

Nuclear share of the world energy mix

In 2003 nuclear power, almost exclusively generated by thermal-neutron fission reactors, provided 15.9 per cent of the world electricity production. World's electricity consumption in turn stands for 15.9 per cent of the world energy consumption (*see table 1 below*). The nuclear contribution to the world energy supply in 2004 amounted to 2.5 per cent.

Figure 1 shows electricity from renewables, mainly biomass, is not included, but may be a minor contribution: one to two per cent of the total electricity production. The amount is not exactly known. Source: *BP Statistical Review of World Energy* 2005 [1], comprises commercially traded fuels only.

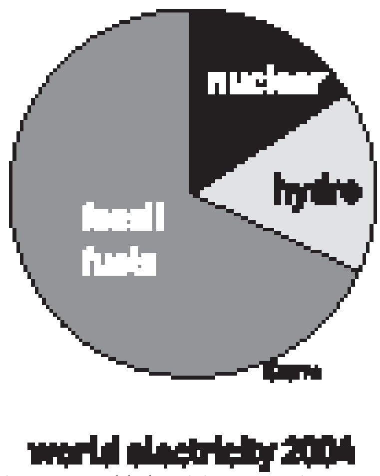

Figure 1 World electricity generation
(*Data from table 1*)

Figure 2 on page XX shows the nuclear share of the world electricity supply has been stable for about 14 years, but now it is slightly declining, because the growth of nuclear capacity is lagging behind the growth in the world electricity consumption.

Some confusion may arise about the figures on the contribution of nuclear electricity to the world energy supply. In the *BP Statistical Review of World Energy* 2005 (*see reference* [1]), and in many other statistical reviews, electricity generated by nuclear and hydro power stations is converted into primary energy equivalents (measured in tonnes oil equivalents) by multiplying the amount of electricity (measured in kilowatthour) by a factor of 2.6 (*cf. column 6 in table 2 pXX*). The factor 2.6 is based on an assumed average conversion efficiency of 38 per cent (heat into electricity) of thermal power plants, in effect, fossil-fuelled power plants. Doing so, the nuclear share becomes about six per cent of the world energy demand (*see column 7 in table 2, pXX*).

However, the nuclear contribution to the *actually* generated energy worldwide is 2.5 per cent, as summarised in columns 4 and 5 of table 2.

Figure 3 on page XX shows the energy generation in 2004 based on data from column 5 of table 2. It comprises commercially traded fuels only. The amount of biomass (wood, peat, dung) used in developing countries for heating and cooking, is not exactly known, but may be in the order of 12 to 13 per cent of the total energy consumption.

Conversion of nuclear electricity into oil equivalents is misleading in other senses as well: in the house of the consumer one joule electricity can be converted into one joule heat or one joule power, not into 2.6

Source	TWh	EJ	Fraction of world electricity (%)	Fraction of total world energy (%)
Nuclear	2758.4	9.930	15.8	2.5
Hydro	2803.2	10.092	16.1	2.5
Other	11890.4	42.805	68.1	10.8
Total electricity	17452	62.827	100	15.8
Total world energy (see Table 2, col. 4)		396.58		

Table 1: World electricity generated in 2004
1 TWh = 1 terawatthour = 1 billion kWh = 0.0036 EJ (exajoules). 1 EJ = 10E18 joule.
Source: *BP Statistical Review of World Energy* 2005 [1].

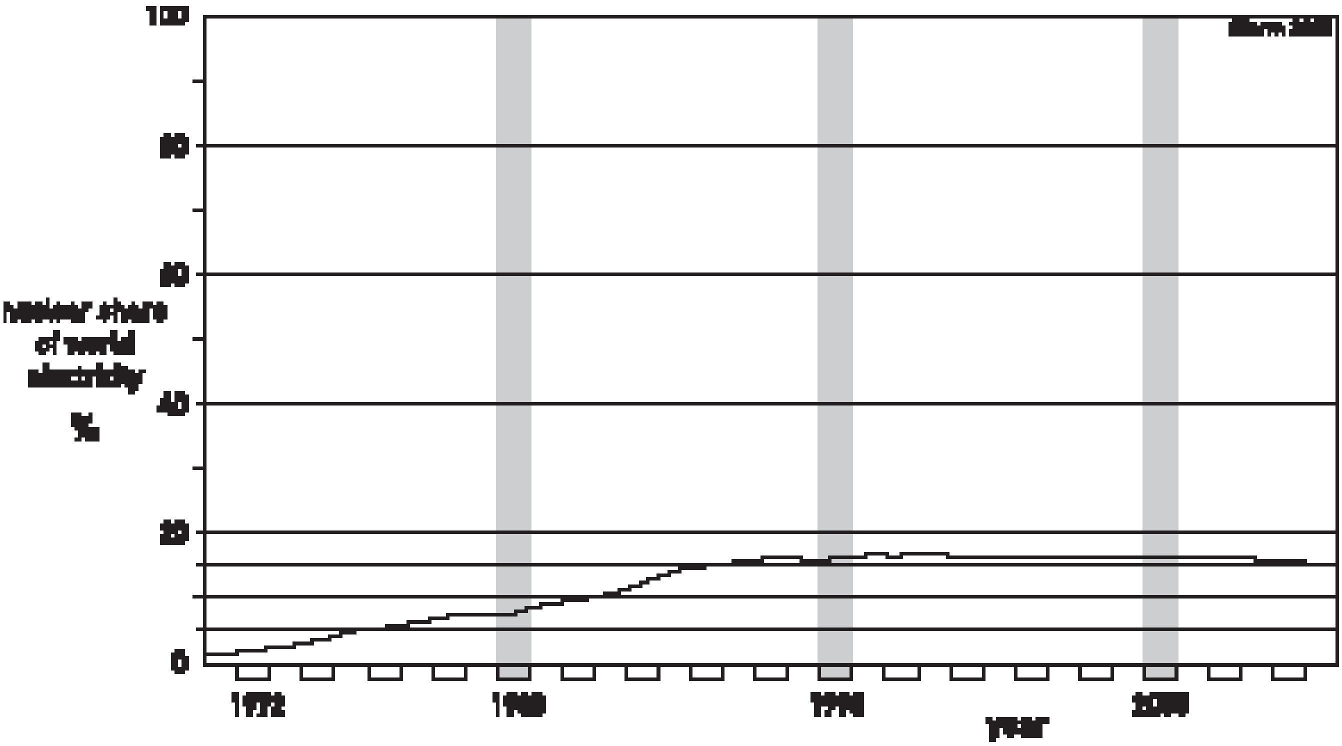

Figure 2: Nuclear share in world electricity production.
Sources: Flin 2002 (*see reference* [2]) and *BP Statistical Review of World Energy* 2004 & 2005 (*see reference* [1]).

joule heat or power.

The sole usable energy product of nuclear power stations is electricity. In a hypothetical all-nuclear society the full 397 EJ of energy should be generated, as electricity.

Nuclear system

A nuclear power plant often is viewed as a 'black box', a mysterious and large concrete building which injects electricity into the grid,without fuel, such as oil, gas or coal.

Technically, a nuclear power plant is not a stand-alone system, but is part of a large chain of industrial processes. Generally, these processes are 'invisible', because they proceed in areas other than the location of the nuclear power plant and often at other times than the electricity generation. Some processes will start only decades after the the reactor put its last kilowatthour into the grid.

Figure 4 shows the nuclear system is a complex of industrial processes, of which the nuclear reactor is the pivot process. Together all these processes can be seen as the 'black box', extracting raw materials from the biosphere, as any industrial process in our economy does, and producing

1	2	3	4	5	6	7
	Energy actually generated				Primary energy	
Energy source	TWh	MTOE	EJ	fraction (%)	MTOE	fraction of total (%)
Nuclear	2758,4		9.930	2.5	624.3	6.1
Hydro	2803,2		10.092	2.5	634.4	6.2
Oil		3767,1	158.22	39.9	3767.1	36.8
Natural gas		2440,4	101.66	25.6	2440.4	23.7
Coal		2778,2	116.68	29.4	2778.2	27.2
Total			396.58	100	10 224.4	100

Table 2 Energy mix of the world energy consumption in 2004.
Comprises commercially traded fuels only. MTOE = million (metric) tonnes oil equivalents, 1 MTOE = 0.042 EJ.
Columns 2 and 3 contain data from [1]. In column 4 these data are converted into exajoules (EJ). Columns 2 to 5 represent the energy actually generated in 2004. Columns 6 and 7 represent the world energy consumption in primary energy, as presented in *BP Statistical Review of World Energy 2005*.
Source: *BP Statistical Review of World Energy 2005* (*see reference* [1]).

Figure 3: Energy generation in 2004
(*Data from table 2 column 5*)
Source: *BP Statistical Review of World Energy* 2005 [1].

electricity as its sole product. All wastes will return into the biosphere inevitably. The – still unresolved – problem is to isolate the dangerous wastes long enough from the biosphere (thousands to millions of years).

The nuclear process chain can be divided into three main parts (*see figure 5*):

- conversion of uranium ore in the ground into fuel elements for the reactor,

- construction of the nuclear power plant itself, and maintaining and operating it during its operational lifetime

- handling of the wastes, decommissioning and dismantling of the (radioactive) nuclear power plant and sequestration of the wastes in a save geological repository.

Each of these three main parts comprises a number of processes.

Misunderstandings may arise when the system boundaries are not clearly defined (*see figure 5*). Sometimes, only the first phase of the process chain is considered: from ore to fuel. Sometimes construction and operation of the nuclear power plant

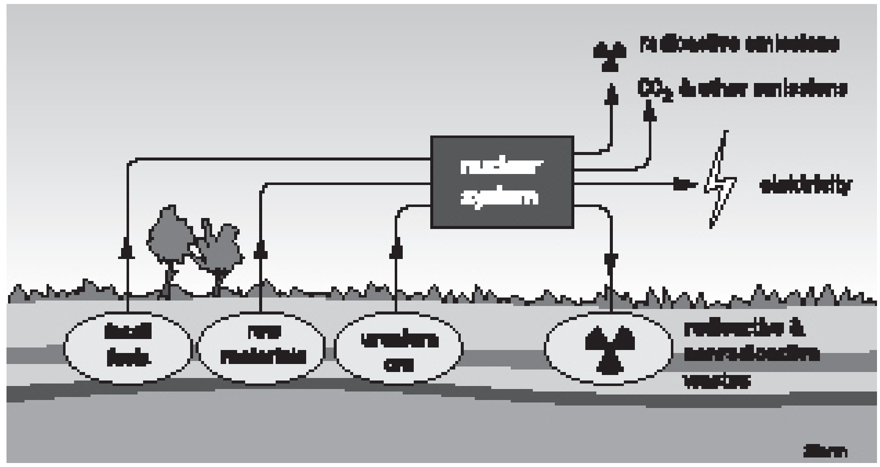

Figure 4: The 'nuclear black box'

are included as well. Seldom or never the third phase is included fully. The reason for that is simple: we have practically no experience with the third phase. But it will come, inevitably.

Figure 5 shows inside the nuclear black box. To proceed from uranium ore in the ground to a safe and permanent sequestration of the radioactive wastes; three groups of processes should be completed.

Energy debt

Completion of the whole nuclear chain will take 100 to 150 years, from start of construction of the power plant through the disposal of the last wastes. Figure 6 represents a dynamic energy balance of the complete nuclear chain. At the moment the experiences with nuclear technology extend no further than the first two phases in the diagram. No experience exists with final sequestration of nuclear wastes, other than dumping into the sea.

Figure 6 on page XX shows the dynamic energy balance of the LWR once-through process chain.

The last phase comprises a number of processes:

- decommissioning of the reactor,

- safe storage for several decades to a century of reactor and spent fuel to let decay a large part of the radioactivity,

- dismantling the radioactive part of the nuclear power plant

- packing spent fuel and other radioactive wastes, including dismantling wastes, into suitable containers,

- construction of a safe geological repository

- final disposal of all radioactive wastes into the repository.

Each of these processes will require materials, energy, capital goods and skilled personel. The amounts of materials and energy required can be roughly estimated, because volumes, masses and radioactive

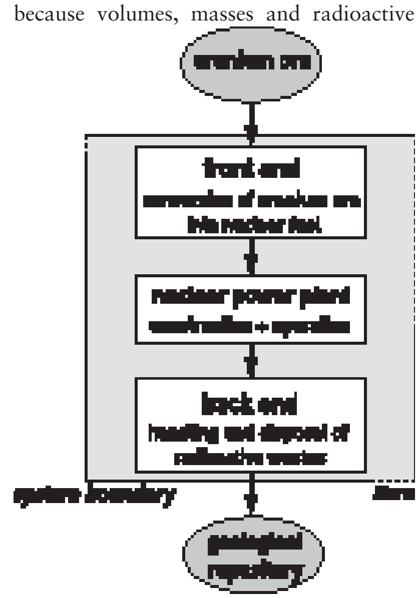

Figure 5: The nuclear process chain

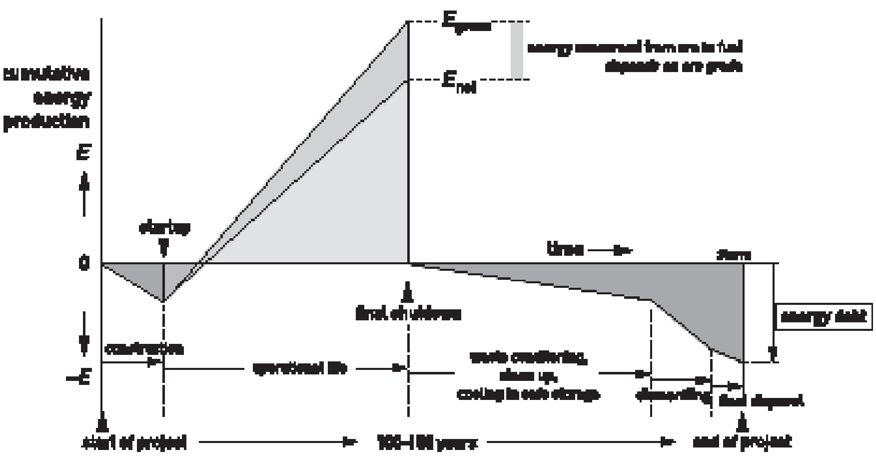

Figure 6: Dynamic energy balance of the LWR once-through process chain.

properties of the materials to be handled after final shutdown of a reactor, are known.

Each nuclear power plant leaves behind an energy debt. That may be large, or very large. The time at which the debt must be paid is irrelevant, quite differently than monetary debts. The latter are, in economic calculations, discounted at an assumed interest rate, and are further subject to the variations in the value of money. Energy is a conserved quantity, whereas the value of money is unpredictable beyond a short time horizon. Energy debts cannot just be written off as uncollectable.

Costs

In the nuclear world a strong belief in future technical solutions for today's problems seems to lead to systematically underestimating or even ignoring the problems to be solved, in spite of 60 years of very intensive research without acceptable results.

For instance, one of the proposed 'solutions' to mitigate the radioactive waste problem is transmutation, which will be discussed in the following section.

Figure 7 illustrates the dynamic financial balance of the LWR once-through process chain, as viewed by the nuclear industry. At final shutdown a small financial reserve is created to cover the completion of the nuclear project.

Studies of the RAND Corporation from 1979 and 1981 (*references* [3] and [4], pXX) show that the costs of complex projects with new technologies at completion, are *always* much higher than estimated at the start of the project, often by a factor of two to five. The nuclear industry offers ample examples of this phenomenon: cost escalations with a factor of 10 were not uncommon.

The back-end of the nuclear chain comprises new technologies. Numerous paper concepts are circulating within the nuclear industry and reassuring reports are being disseminated among the general public, stating that the waste problem 'has been solved'. The fact is that completion of the back-end of the nuclear chain never has been done in practice. One may wonder if the nuclear industry wants to complete the back-end at all.

As long as no full nuclear chain has been completed anywhere, the real costs of nuclear energy, that are the costs to be be paid by society sooner or later, cannot be figured out with any confidence. Those costs will come, without doubt, and they will be higher than estimated nowadays. At least, if we want not to compromise the safety and health of our children and grandchildren.

Transmutation

Transmutation is a hypothetical concept to transmute (convert) long-living radionuclides (radioactive atoms) into short-living or stable nuclides by irradiation with neutrons.

In practice, the reduction of radioactivity will be limited, because during the transmuting process in the reactor new long-living nuclides are generated from stable nuclides. Even theoretically it is not possible to convert all long-living nuclides originating from the fission and activation processes in a nuclear reactor into short-living or stable nuclides.

A transmuter is not a single, stand-

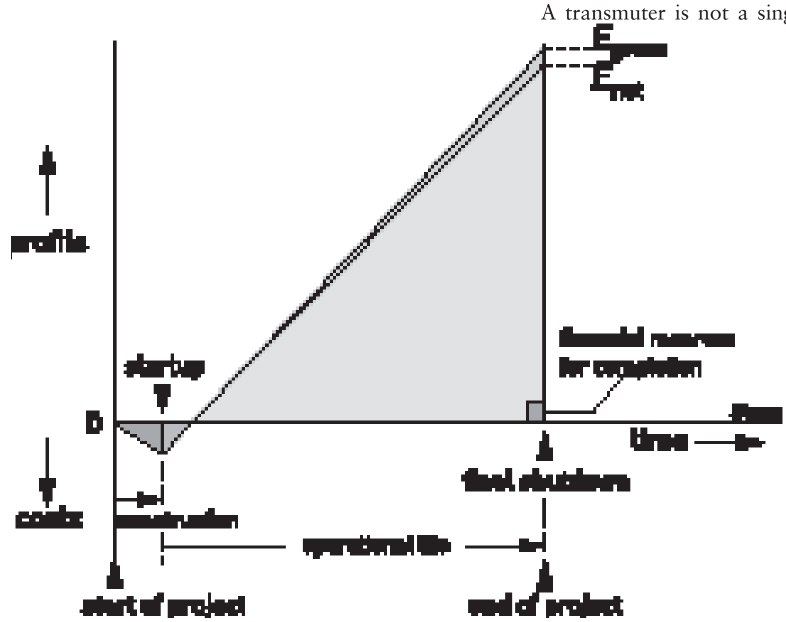

Figure 7: Dynamic energy balance of the LWR once-through process chain. (viewed by nuclear industry)

alone machine but is a system comprising transmuter reactor, reprocessing plant and fuel fabrication plant. All three components should operate flawlessly and exactly tuned to each other, before any reduction of the amount of long-living radionuclides would be achieved. If one component fails, the whole cycle fails.

Even if the transmutation cycle would work as advertised, it would take many centuries (!) to reduce the amount of actinides and transuranics a hundredfold, leaving aside the unavoidable process losses (*see reference* [5], pXX). The remaining one per cent of the long-living nuclides would be still dangerous.

The transmutation concept is a technical dream and will remain so.

Emissions of greenhouse gases from fission power

As is pointed out earlier, the nuclear system consists of a chain of, mainly conventional, industrial processes, which all consume

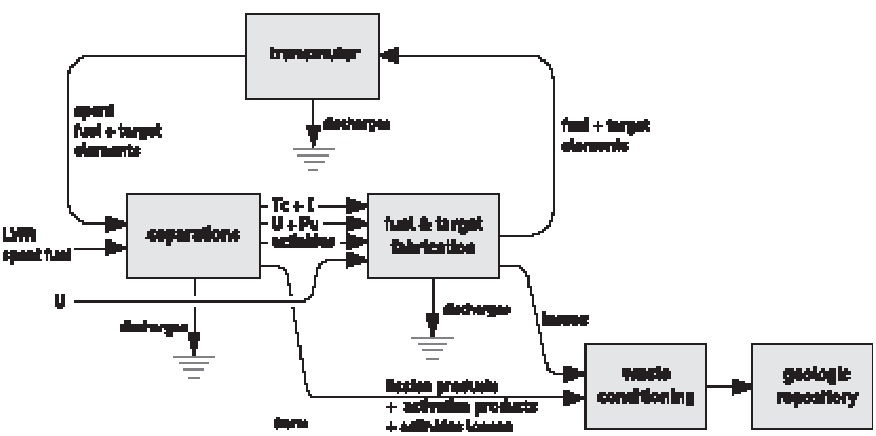

Figure 8: Transmuter system

fossil fuels. The reactor is the only part of the process chain which produces virtually no carbon dioxide (CO_2).

A complete Life Cycle Analysis (LCA) shows that generating electricity with nuclear power emits 15 to 40 per cent of the CO_2 per kilowatthour (kWh) of a gas-fired system when the whole system is taken into account, *if the uranium is extracted from rich ores* (*see reference* [6], pXX). Using ores with grades lower than 0.1 per cent (that means 1kg uranium per tonne of rock), the specific CO_2 emission rapidly rises with decreasing ore grade and surpasses that of a gas-fired power plant at grades of about 0.02 to 0.01 per cent (200 to 100 grams uranium per tonne rock).

The nuclear process chain emits other greenhouse gases (GHGs) as well, apart from carbon dioxide, with far stronger greenhouse effect potential, such as chloro- and fluorohydrocarbons. In the processes needed to convert uranium from ore to fuel, very large quantities of fluorine, chlorine and compounds of these elements are used. No chemical plant is leakproof, so significant amounts of organic fluorine and chlorine compounds *may* be emitted into the atmosphere.

The emissions of other greenhouse gases by the nuclear process chain are very difficult to quantify from the open literature, but the specific emission of CO_2-*equivalents* by the nuclear system must be significantly higher than the 15 to 40 per cent of a gas-fired system cited above.

The energy required to extract uranium

Nuclear power stations are fuelled by uranium, an element found in the earth's crust in various chemical compounds. The metal is extracted from ore by mechanical and chemical processes, like copper from copper ore. The energy requirements of the extraction process depend on the grade of the uranium ore. For example, the extraction of one kilogram of uranium from ore containing one kg U per tonne rock consumes ten times as much than from ore of 10 kg U per tonne rock.

Moreover, the extraction yield falls with the ore grade, an unavoidable chemical phenomenon. At high ore grades (10 kg U per tonne rock or more) about 99 per cent of the uranium can be extracted from the rock, but at low grades (eg 0.2 kg U per tonne rock) not more than about half of the uranium present in the rock can be extracted in practice.

Both factors – increasing specific energy consumption, and falling yield with decreasing ore grade – pose a limit below which an uranium-bearing rock can no longer be considered a net source of energy. This *threshold grade* happens to be about 200 grams U per tonne rock (*see reference* [6], pXX).

Technically, it is possible to extract uranium from leaner ores, but the energy consumption of the extraction of one kilogram uranium will surpass the amount of energy which can be generated from that kilogram in the nuclear system.

The specific energy requirements of extraction of an element from a matrix rise exponentially with falling concentration of that element in its matrix. This is inherent to any extraction process. Advanced technology may lower the threshold grade from, for example, 0.02 per cent to 0.015 per cent (200 and 150 grammes uranium per tonne rock respectively), but that wouldn't add much uranium resources to the energy resources.

Figure 9 shows the energy threshold; the net energy from uranium depends on the grade of the ore from which the uranium is extracted.

In view of the nuclear industry, the energy content of uranium is independent of ore grade, ignoring the energy requirements of the processes needed to convert uranium ore into nuclear fuel.

How much uranium is there?

In 2004, some 440 power reactors were operating worldwide, with a combined capacity of some 363 GW(e) (*see reference* [7], pXX), requiring about 67,000 tonnes

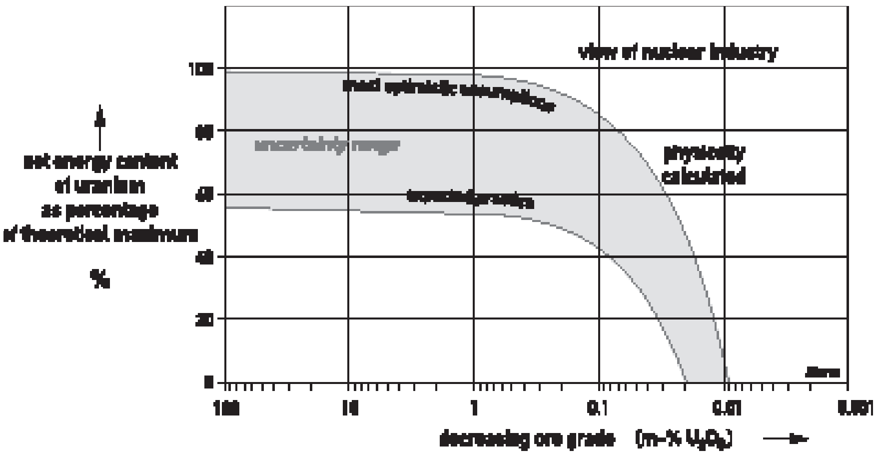

Figure 9: The energy threshold

of natural uranium per year. The present reserves and resources (to 80 US$/kg U) are about 3.5 million tonnes (*see reference* [7], pXX). This is enough to last some 50 years at the aforementioned consumption rate.

Uranium from granite

To fuel one reactor with a nominal capacity of one GW(e), each year about 162 tonnes natural uranium has to be extracted from earth's crust. If the ore is granite, with an average uranium grade of four gram U per tonne rock, 162 tonnes uranium is in 40 million tonnes of granite. The rock has to be dug up, ground to fine powder and chemically treated with sulfuric acid and other chemicals to extract the uranium compound from the mass. Assumed an extraction yield of 50 per cent (an unrealistically high estimate), 80 million tonnes of granite have to be treated. This is a rock of 100 metres wide, 100 metres high and three kilometres long. Extracting the uranium from this huge rock would consume more than 30 times the energy generated in the reactor from the extracted uranium.

For comparison: a coal-fired power station of one GW(e) consumes about two million tonnes of coal each year.

Uranium from seawater

Seawater contains 3.3 milligrams of uranium per cubic metre of seawater. The total volume of seawater of the world is estimated at 1.37 billion cubic kilometres, so the oceans contain some 4.5 billion tonnes of uranium. Technically, it is possible to extract uranium from seawater.

To obtain 162 tonnes uranium (for one reactor for one year), about 162 cubic kilometers of seawater (about 162 billion tonnes) have to be treated (if an extraction yield of 30 per cent can be achieved). Looking at it another way, this is equivalent to 5,140 cubic meters per second (two to three times the flow rate of the river Rhine at its debouchement) continuously during a whole year. The dimensions of such an extraction plant should be measured in kilometres.

The first stage of the extraction process is adsorption of the dissolved uranium from the seawater on specific adsorption beds. Several methods have been proposed (*see a US study from 1974* [8], pXX) and a Japanese study from 2001 (*see reference* [9], pXX), none of which have been actually tested other than in some small-scale laboratory experiments. The adsorption stage requires very large facilities, either with pump-fed beds or with beds anchored on buoys in a sea current. At least four additional processes are needed to obtain the uranium: elution of the adsorbed uranium ions from the adsorption beds, purification of the eluent (removal of other desorbed compounds) concentrating the solution, extraction of uranium from the solution, concentrating and purification of the extracted uranium compound. Each stage has its unavoidable losses. The overall yield of the processing, excluding the first stage (adsorption), may be no higher than 20 to 40 per cent. Large amounts of adsorbent are lost in the process; at least 15 kg titanium per kg uranium in the ORNL process (*see reference* [8], pXX) and at least eight to 24 kg amidoxime polymer per kg uranium in the Japanese process (*see reference* [9], pXX).

Based on the very optimistic assumptions of the theoretical studies, the energy requirements may be roughly estimated at least two to four times the energy generated in the reactor from the extracted uranium.

A nuclear renaissance?

Assume a thousand new nuclear power plants (NPP) with a combined capacity of 1,500 GW(e) will be built during the coming decades, as proposed in an MIT study in 2003 (*see reference* [10], pXX). A park of of this capacity would supply about 10 per cent of the present world energy consumption, but much less than 10 per cent by the time the new NPPs should come on line, because the world energy consumption will grow considerably during the next period.

The annual uranium consumption of the 1,500GW(e) park will be some 250,000 tonnes and the known uranium reserves and resources will be exhausted in about 14 years.

No problem, says MIT, the economic market mechanism will do the job.

Higher prices: more energy?

When uranium becomes scarce, its price will rise. Higher price means that leaner, but more abundant ores would become economically mineable. These ores, such as phosphates, shales and granites, would last for hundreds of years.

This is a fallacy *when viewed* in terms of energy. The sole civil application of uranium is its use in power reactors to generate useful energy. The huge amounts of very lean 'ores' (*see reference* [10], pXX) and (*see reference* [7], pXX) refer to, have grades well below the energy threshold, discussed in a previous section. That uranium-bearing rocks may be uranium ores in economic sense, but they never will be a net *energy source*, whatever extraction technology would be invented.

Even if large new rich uranium deposits are found, doubling the known reserves, which is not very probable from a geological point of view (*see reference* [11], pXX), the total reserves will last for less than 30 years in the scenario of the nuclear renaissance.

Breeder reactors

Theoretically, the breeder would be able to fission about 60 per cent of natural uranium atoms, via conversion into plutonium. All power reactors nowadays operating are thermal reactors, most of them LWRs (light-water reactors), which can fission only 0.6 to 0.7 per cent of natural uranium. The high figure of the breeder is the source of old nuclear dreams; an 'all nuclear society' and 'burning the rocks'. Dreams that are still alive today.

What is called 'breeder' is not just a reactor type, it's a system, a *cycle* made up of three components. All three components should operate flawlessly and exactly tuned to each other, before any breeding would be achieved.

- First, the breeder reactor, which generates more fissile atoms (plutonium) from non-fissile uranium-238 atoms than it consumes by fissioning.

- Second, the reprocessing of the spent fuel to separate the plutonium and remaining uranium from the fission products and unusable, but nasty and dangerous transuranic elements.

- Third, the fuel fabrication facility, to make new fuel elements from the highly radioactive plutonium and recycled uranium from the reprocessing plant.

The breeder cycle is *similar* to the transmutation cycle, discussed above.

Neither of the three components ever demonstrated operation as needed, let alone the three components together as a fine-tuned continuously operating system.

Fifty years of intensive research in seven countries, with investments of tens, if not hundreds, of billions of dollars have so far failed to demonstrate that the breeder cycle is feasible.

The same holds true for the thorium cycle, which is even more difficult to develop.

At the moment only three fast-neutron reactors, prototypes of breeder reactors, are operable in the world: Rhapsodie in France, Monju in Japan and Beloyarsk-3 in Russia. It's doubtful wether the French and Japanese reactors ever will be restarted. The Russian reactor is not a breeder and is operating intermittently, with a long history of serious accidents.

The MIT study (*see reference* [10], pXX) does not expect breeders (in effect, breeder cycle) will come into operation during the next three decades.

Thermonuclear fusion

Thermonuclear fusion is the energy source of the sun. For man-made fusion reactors only the D-T reaction (deuterium-tritium) is practicable. No uranium nor plutonium are needed for this kind of nuclear reactions. Deuterium can be extracted from seawater, tritium has to be breeded from lithium. Although the principle of controlled fusion (other than explosions of hydrogen bombs) has been demonstrated, still no reactor exists which produces more energy than it consumes.

For 50 years, research on nuclear fusion has been ongoing in the USA, Europe, Japan, and Russia, with investments of many tens of billions of dollars. A German study in 2002 (*see reference* [12], pXX) concludes that the first fusion reactor producing net electricity may be built around 2050. As the study put it:

'To achieve this programme, very substantial scientific and technical challenges must be met. The R&D required will take several decades and demand funding on a large scale. Over almost 50 years in which fusion research has been going on, the difficulties in developing a fusion plant have been repeatedly underestimated, with the result that the horizon for implementation had to be pushed further and further into the future, becoming in effect a "moving target".'

Nuclear power - from the sun

Mankind has a perfectly functioning thermonuclear fusion reactor at his disposal. The reactor delivers its energy to man in a constant, abundant flow of clean, benign electromagnetic radiation, without radioactive wastes and harmful radiation. The only hurdle man has to take for exploiting that free energy source is collecting its energy. That hurdle is not technical, but paradigmatic.

Potential

Solar energy can be harvested in several ways: eg biomass, wind, hydropower and photovoltaic (PV) panels. The intensity of the solar energy reaching the earth's surface varies from some 3.6 GJ/m^2/year (gigajoule per square meter per year) in the temperate zones to 7.2 to 8.6 GJ/m^2/year in the tropics. To illustrate the possibilities of harvesting solar energy, two rough calculations are given here: biomass and photovoltaics (PV).

Biomass

Vegetable material from trees and crops can be converted directly into *liquid fuels, via relatively simple chemical processes*. The conversion efficiency of solar energy into biomass by selected crops varies from one per cent in the temperate zones to some three per cent in some tropical regions. Depending on place and climate, on each square kilometer 20 to 120TJ (terajoules) energy is fixed by the photosynthesis reaction in vegetable material.

An efficient way to harvest the energy in biomass is to gasify all organic material. The resulting synthesis gas can be burned directly in highly efficient power stations, but can be converted relatively easily into liquid fuels or even

to meet the present world energy demand of roughly 400EJ/a (exajoules per year), some 10 million square kilometers with energy crops would be needed. The surface area available for growing biomass for energy purposes is estimated at six to 13 million square kilometers, without competition with agriculture (*see reference* [13], pXX).

Photovoltaics

Photovoltaic (PV) panels convert light directly into electricity. Because of the intermittent production, the electricity has to be stored in a medium, an energy carrier, such as hydrogen. The hydrogen, to be produced from water by electrolysis can be used as chemical feedstock as well.

Current PV panels have a system efficiency of some 12 per cent. Firm expectations are that this value will double during the next two decades. Based on the low efficiency figure, an area of less than 700km by 700km (about the area of Spain) covered with PV panels in the deserts of the earth at low latitudes, would produce sufficient hydrogen to meet the world energy demand. The total area of appropriate deserts in the USA, Africa, Asia and Australia is large multiple of the required area. The energy supply of USA and China, for instance, could become independent of energy sources on foreign soil.

Initial costs of energy from fission and PV

To get a financial impression, we compare the costs of electricity generated by photovoltaic (PV) panels with the costs of nuclear-generated electricity. We start this rough calculation at the nuclear renaissance scenario of MIT, as described earlier.

It seems highly unlikely that the construction costs of new nuclear power plants will be lower than those during the last construction period in the USA in the 1980s. Based on those empirical values, the construction costs of 1,500GW(e) nuclear capacity may be estimated at some 7,500 to 15,000 billion US$, the higher figure being the most probable.

An investment of US$15,000 billion would be sufficient to construct a solar photovoltaic (PV) system with an electricity generating capacity of about 23EJ/a (exajoule per annum), calculation based on the current state of technology, costs and efficiency (*see reference* [14], pXX). The total world energy consumption in 2004 was around 400EJ/a, excluding biomass (wood, peat, dung). Accounting for the learning curve effect and the expected doubling of the conversion efficiency of PV systems within two decades, a system with a capacity of some 90EJ/a can be built with the same investments. This may be 15 to 20 per cent of the world energy consumption by 2030.

A nuclear park with a capacity of 1,500GW(e) produces about 38EJ/a electricity, assuming an average load factor of 80 per cent. *This is well under half of what we could expect from the same investment in photovoltaics.*

Lifetime costs

The energy source of the PV system, the sun, is free and has a constant flow and a constant quality. During the lifetime of the PV system no costs other than for maintenance of the system are required.

Nuclear power, on the other hand, consumes uranium, which has to be mined from ever deeper mines and extracted from ever leaner ores. It produces an ever growing mass of hazardous, radioactive wastes, that has to be packed and sequestered in safe repositories. The lifetime costs of all processes needed to run the nuclear system, apart from operation and maintenance, and to clean up its wastes, will rise to a multiple of the initial construction costs.

Assuming the lifetime costs of the nuclear park are three times the initial construction costs (in constant monetary units), a PV system (current technology) with a production rate of at least 70EJ/a could be built for the same costs. In such a large development and contruction project the expected higher efficiency and lower specific costs almost certainly will be achieved. If the calculation is based on the higher efficiency figures, a solar nuclear energy conversion system with a capacity of about 270EJ/a can be built and operated – seven times the capacity of the fission power system.

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