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Nuclear power: energy security and CO_2 emission

Submission to the Uranium Mining, Processing and Nuclear Energy Review Taskforce

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Introduction

The draft report to the Prime Minister of the Australian Government by the Uranium Mining, Processing and Nuclear Energy Review Taskforce appears to rely heavily on advices from the nuclear industry, taking little notice of evidence and opinions from sources who are not financially interested in new nuclear build.

The sole civil application of uranium is in its role as an energy source. Obviously, nuclear power should be judged on the amount of net energy obtainable from uranium resources present in the ground, in the perspective of a sustainable and climate-benign energy supply, and should not be judged solely on short-term economic considerations.

The study by Storm van Leeuwen & Smith [Q6] is one of the very few independent studies addressing nuclear power from a strictly scientific point of view. The ISA of The University of Melbourne [Q325] reviewed our report. In some respects the views of ISA and ours differ, not surprising in such a complicated matter as nuclear power. The numerical results of the ISA study only slightly differ from the results of Storm van Leeuwen & Smith.

Uncertainties

Uncertainty might be the key word in describing the future of nuclear power. Uncertainties – which already persist for more than half a century and most of which will persist for another half a century – crop up in many aspects of nuclear power, such as:

- safety (accidents, illegal trade of radioactive materials, terrorism)
- costs to be paid by the society
- environmental and health aspects
- uranium supply security
- climate control (greenhouse gas emissions)
- net energy return.

This paper addresses the last three of above mentioned aspects.

A nuclear reactor is not a stand-alone system. The generation of useful energy from uranium-bearing rock requires a very complex system of sophisticated industrial processes. The nuclear process chain will briefly be discussed in the next section. Several factors are contributing to the uncertainties:

1 Some waste streams from the nuclear system never have been investigated and/or published.

2 In most life-cycle assessments a number of processes in the nuclear process chain are not taken into account, often for unknown reasons.

3 A number of processes, which are vital with regard to safety and to environmental and health aspects, still exist only on paper.

4 Embarking upon a nuclear energy supply project implies an extremely long-term commitment (100-150 years). Will society have the skills and the ability to cope – a century from now – with the inevitable afermath of a nuclear project started today?

5 The chances of new discoveries of large high-quality uranium resources are unknown.

The next sections address each of these factors. First some basic features of the nuclear process chain will be explained.

The nuclear process chain

The nuclear reactor, in which a fraction of the uranium atoms are fissioned, generating heat, is one component in a chain of a number of processes. None of these industrial activities are located near the reactor. Some of these indispensable processes are running simultaneously with the reactor operation, other will start only decades after the reactor is closed down. To make things even more obscure, many processes are situated at large distances all over the world.

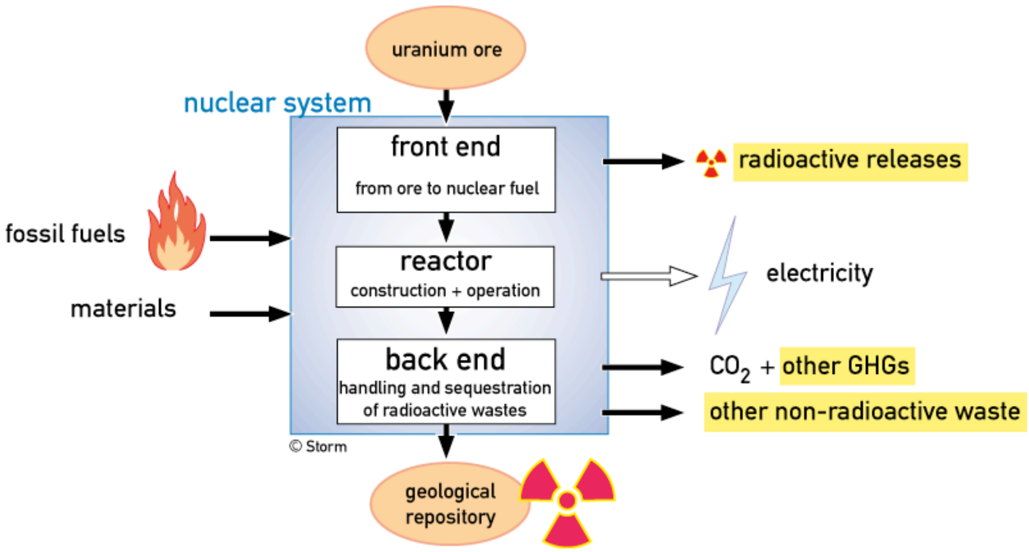

Figure 1
Outline of the nuclear process chain. Like any industrial process, the nuclear system consumes energy (electricity and fossil fuels) materials and labour, and emits CO_2, other greenhouse gases and other waste. A part of the waste is radioactive, which distinguishes the nuclear system from all other energy supply systems. The yellow marked releases by the nuclear system are not included in any assessment of nuclear power.

The nuclear process chain can be divided into three main parts:

- conversion of uranium ore in the ground into fuel elements for the reactor,
- construction of the nuclear power plant itself, maintaining and operating it during its operational lifetime, including refurbishments.
- handling of the radioactive wastes, decommissioning and dismantling of the (radioactive) nuclear power plant and sequestration of the radioactive waste in a save geological repository.

Each of the three main parts of the chain comprises a number of industrial processes. Each process consumes electricity, fossil fuels, materials and chemicals, and emits carbon dioxide and other greenhouse gases.
The reactor itself is the *only* part of the process chain which produces virtually no carbon dioxide (CO_2).

The full flowsheet of the nuclear process chain is shown in Figure 2. This flowsheet comprises all processes of the three main parts of the nuclear system – front end, reactor and back end – needed to generate nuclear power and clean up its waste.

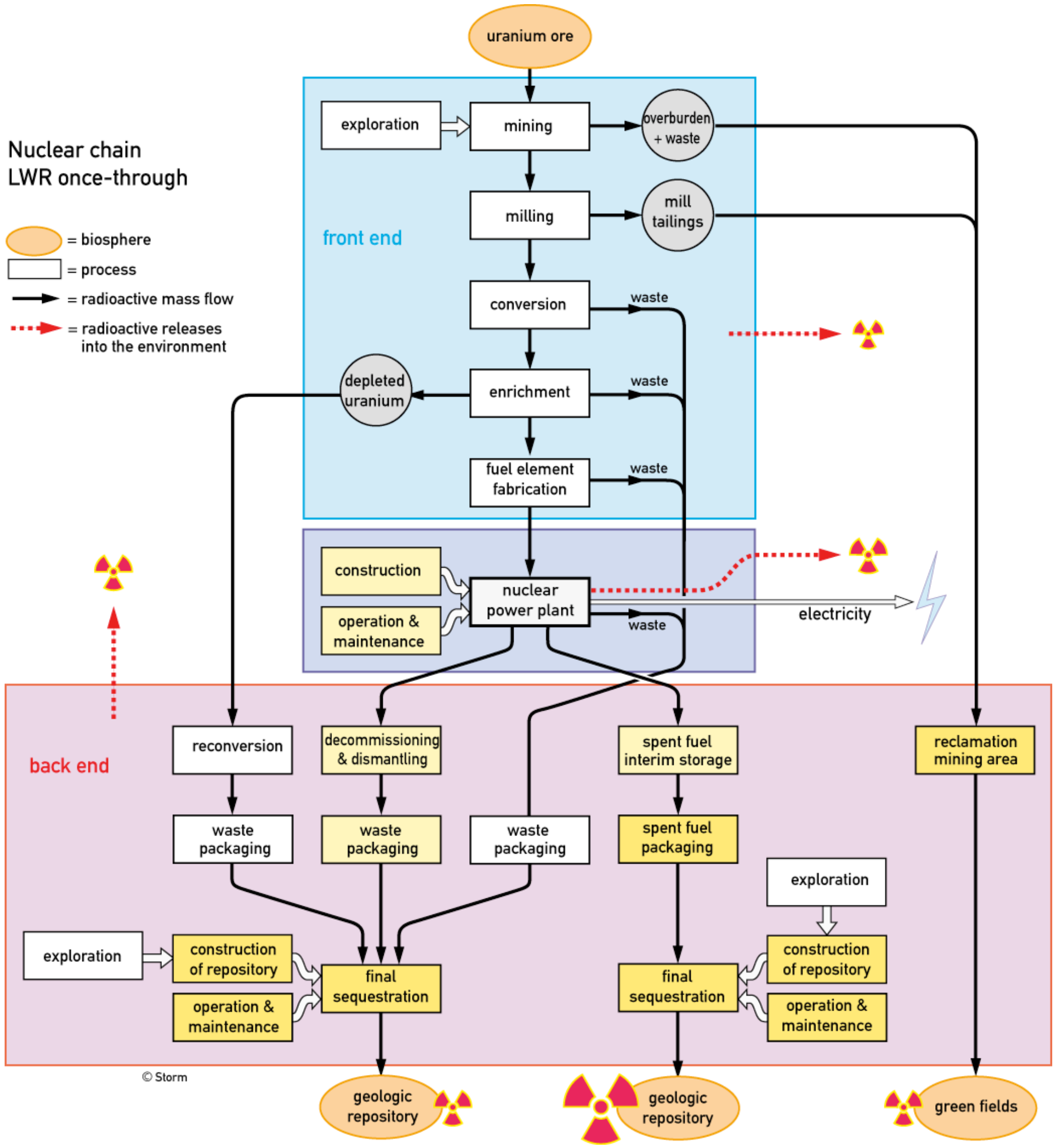

Figure 2
Flowsheet of the radioactive materials in the nuclear process chain. Not all radioactve materials extracted from the uranium ore and generated in de reactor end up in the geologic repositories. Considerable amounts are released into the environment. The study of Storm van Leeuwen & Smith 2005 [Q6] is based on this flowsheet.
The yellow-marked processes are either underestimated (light yellow) or absent (darker yellow) in other studies of the nuclear system.

Unknowns of the nuclear process chain

Besides heat, a nuclear reactor generates tremendous amounts of radioactivity, an irreversible process. Each reactor generates each year an amount of radioactivity hundreds of times as much as one exploding nuclear weapon. How to deal with these huge amounts is an unsolved problem, still after more than 60 years of nuclear power.

Unpublished waste streams

The nuclear system has waste flows which are surely there, but which never have been investigated and/or published. These quantitatively and qualitatively unknown emissions and releases are:
– Operational, so routine releases of radioactive substances. Also unknown is what happens with the radionuclides released into the air, water and soil.
– Emissions of other greenhouse gases than carbon dioxide.
– Releases of other, non-radioactive waste.
In Figure 1 these unknown emissions and releases by the nuclear system have been marked yellow.

Obviously lack of data does not mean the releases are absent. Lack of data introduces uncertainties with respect to climate, health and safety.

Omitted or non-existent processes

The nuclear process chain comprises a large number of industrial processes, as Figure 2 shows. Most processes in the back end are not pperational, exist only on paper or are not considered at all. In addition several processes are disputed with respect to their quantitative implications.

Non-existent (only on paper) are the processes:
• final sequestration of radioactive waste other than spent fuel, including construction and operation of the geologic repository
• final sequestration of spent fuel, including construction and operation of the geologic repository
• spent fuel packaging
• decommissioning and dismantling of a large power reactor after a full commercial lifetime.

Very scarce experience exists with regard to:
• spent fuel interim storage, other than
• reclamation of mining area. Most mines have no reclamation activities.
• packaging decommissioning waste.

Disputed processes, with respect to the numerical values, are
• construction of the nuclear power plant
• operation, maintenance and refurbishment of the nuclear power plant during its opersational lifetime.

In Figure 2 the problematic processes have been marked yellow. The light yellow-marked processes have been accounted for in the studies of ISA [Q325] and of Storm van Leeuwen & Smith [Q6], be it with different approaches and different results. The darker yellow-marked processes still exist only on paper, so no empirical data are available.

Usually the yellow-marked processes are left out of life cycle assessments (LCA), including the ISA study [Q325]. Storm van Leeuwen & Smith [Q6] did include all processes in their LCA and tried to estimate the energy intensity and CO_2 intensity of these processes, using data from similar, but known processes.
Obviously the numerical results of such a practice are no more than estimates, but they expose the uncertainties with regard to these vital processes. Omitting these processes from an LCA energy analysis must be considered scientifically bad practice and will result in wrongly accurate numerical results or expectations.

Long-term commitments: the energy debt

Once started a nuclear reactor becomes radioactive, the more so the longer the reactor operates. Even after one year of operation the reactor and its nearby equipment are so radioactive that decommissioning and dismantling will be a demanding process, requiring lots of energy, materials and manhours. Timescales published in the nuclear literature for the decommissioning process – cleanup of the reactor, cooling down (to let decay short-living radioniclides) and actual dismantling – range from decades to more than a century.

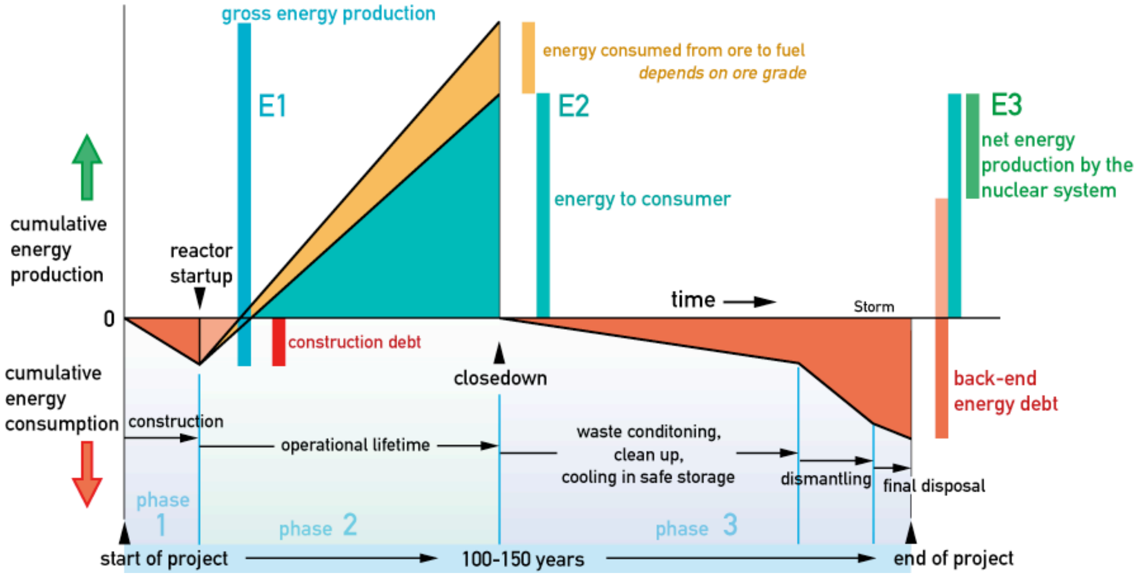

Figure 3
Dynamic energy balance of a nuclear power plant, the sequence in time of a nuclear project. Phase 1, construction. Phase 2, productive lifetime: energy generation until closedown of the reactor. Phase 3, cleanup of the reactor, safeguarding during cooling period, dismantling, packing wastes and disposing of in final repository.
Note that the diagram is not to scale and that the height of a curve indicates the cumulative energy (production or debt) and not the area beneath a curve.
E1 = gross energy production: the electricity put into the grid. This is the quantity listed in the energy statistics (for example *BP Statistical Energy Review*).
E2 = E1 minus the operational energy costs, these are ore grade-dependent. In the study of Storm van Leeuwen & Smith 2005 [Q6] this quantity has been marked: with partial debt.
E3 = net energy production of the nuclear system, freely usable and not needed to maintain the production system itself.

The main differences between the nuclear system and other energy systems are:
- its extremely long-term commitments,
- the irreversibility of the sequence once the reactor started up and
- the huge unavoidable efforts (manpower, materials and energy) required for safely winding up a nuclear project once started.

Since no commercial power plant project ever reached its completion, large uncertainties exist regarding the final energy costs.

Will the society have the skills and the ability to cope with the inevitable afermath of the nuclear project a century from now? The nuclear industry has proven to be unable to solve the waste problems from the past. The legacy of more than 60 years nuclear technology is still waiting for safe isolation from the biosphere.

Figure 4 shows the the way the energy debt of the nuclear system has been accounted for in the study of Storm van Leeuwen & Smith [Q6]. Energy is a conserved, physical quantity and cannot be treated in the same way as a monetary debt. An energy debt cannot be written off as ‘uncollectable’. It has to paid, sooner or later.

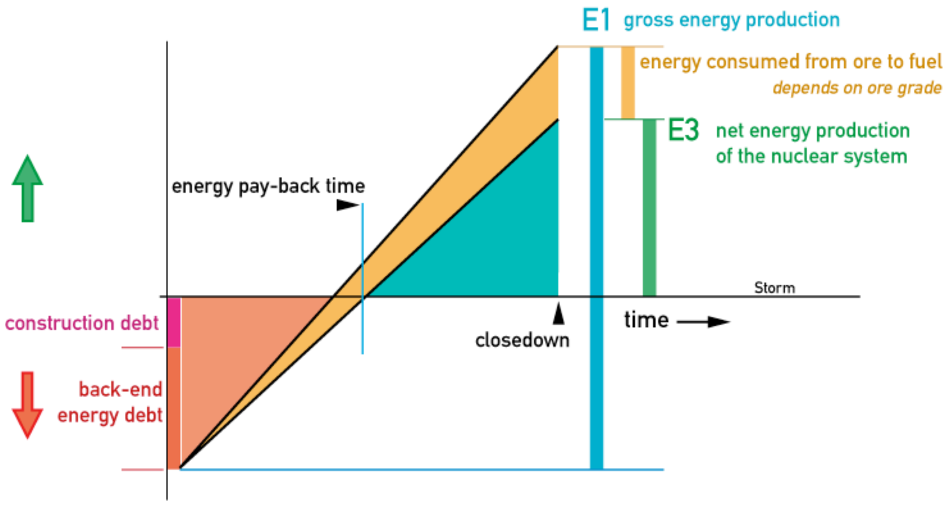

Figure 4
Definition of the energy payback time. The energy debts are ‘capitalized’ at the start of the project. This virtual dynamic energy balance has been used in the study of Storm van Leeuwen & Smith 2005 [Q6].

Storm van Leeuwen & Smith ‘capitalized’ the energy debt of the future – emerging after the closedown of the reactor – at the start of its operational lifetime. In other words: they compressed the time-axis. In that way, they eliminate the factor of time and are able to define the energy which is available for free use: that is E3 in this diagram. In this way the nuclear system becomes comparable with other energy systems, especially renewable systems. In the long run only the lifetime energy investments count, not the initial ones.

The diagram of Figure 4 shows the definition of the energy payback time of the nuclear system. For a given type of reactor and average burnup, the energy payback time depends on the grade of the uranium ore used. The operational energy inputs (orange-coloured in Figure 4) depend heavily on the grade at values below 0.1% U. The energy pay-back time of the nuclear system is about 6-14 years using the currently mined uranium ores.

Figure 5 presents the way the nuclear industry seems to see a nuclear project: a short construction period (4-5 years), 60 years operational life, negligible costs of the fuel cycle and a financial reservation of a small, say, 100 million dollars to pay for the dismantling of the reactor. After closedown, the nuclear industry considers the project finished.

In the UK for example the closed down nuclear power stations become property of the government. The UK government has the responsibility and the burden of the decomissioning task. The taxpayer pays and the utilities can claim low electricity prices.

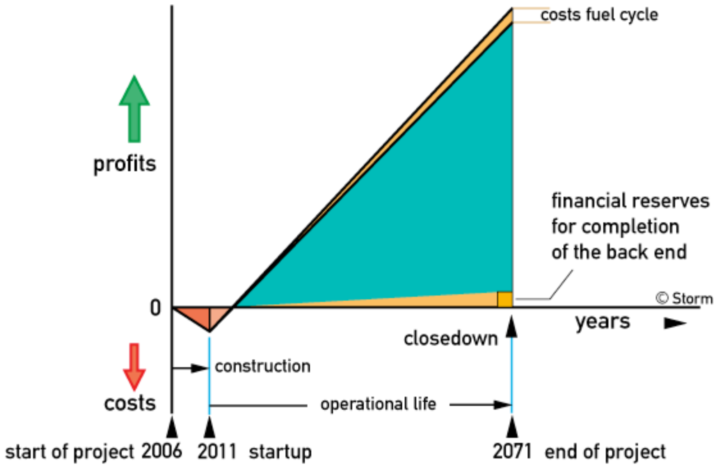

Figure 5
A nuclear project as viewed by the nuclear industry.

Dismantling of power reactors

A potentially large energy debt arises after closedown of the reactor. Apart from the extremely long-term aspect (100-150 years) the height of the energy debt might be considerable.
No experience exists with the dismantling of the reactor after an normal operational lifetime. Some small experimental reactors with very short operational lifetimes and a couple of other nuclear facilities have been dismantled so far. None of these projects included permanent sequestration of the radioactive debris, so the final costs of even these pilot projects still are unknown. The published data on the actual dismantlements indicate very large efforts needed and high costs, sometimes several times the construction costs.
There are no reasons conceivable why the dismantling of large commercial nuclear power reactors would be much easier and cheaper than the pilot projects. On the contrary, the radioactive inventories of large power reactors (after removal of the spent fuel) will be a great many higher than those of small experimental reactors. The higher inventory is caused by a larger neutron flux, longer exposure time and more radioactive CRUD (Corrosion Residuals and Unidentified Deposits). This implies more robotic operations, larger volumes of radioactive debris and scrap, with a higher specific activity and more long-living isotopes.

Based on the scarce reported experiences, Storm van Leeuwen & Smith [Q6] assume the decommissioning costs to be 200% of the mean construction costs. This assumption appears to be confirmed by recent British figures. The British industry estimates the costs of clean-up of a number of British nuclear facilities at 34-68 billion GBP, excluding the Sellafield reprocessing facility (*Nature*, 23 November 2006).
Scientifically, no sound arguments have been published which would make plausible the figures of 10-35% of the construction costs, as the nuclear industry assumes.

Anyway this phase of the nuclear process chain is beset with uncertainties.

Uranium

Energy from uranium

Uranium can be found only in the form of numerous different chemical compounds (minerals), embedded in many different types of rock.
An uranium-bearing deposit is called an 'ore' if the uranium can be recovered from that deposit economically. The definition of 'uranium ore', or 'recoverable uranium', at first is based on economic concepts, not on physical parameters.

Net energy extractable from a uranium-bearing deposit depends on its physical *quality*, the main parameters being:

- ore grade
- type of rock
- size of deposit
- depth of deposit
- location of the deposit
- transport distamces

In this section two basic process parameters of the extraction of uranium from rock are discussed: the dilution factor and the recovery yield. Applying these parameters on the net energy from uranium generates the concept of the 'energy cliff'. Combination of the energy cliff and the known uranium resources gives insight in a crucial question: how much freely usable energy can we extract from uranium in the earth's crust?
Here another misconception frequently appears: *uranium resources are not the same as energy resources*.

Dilution factor

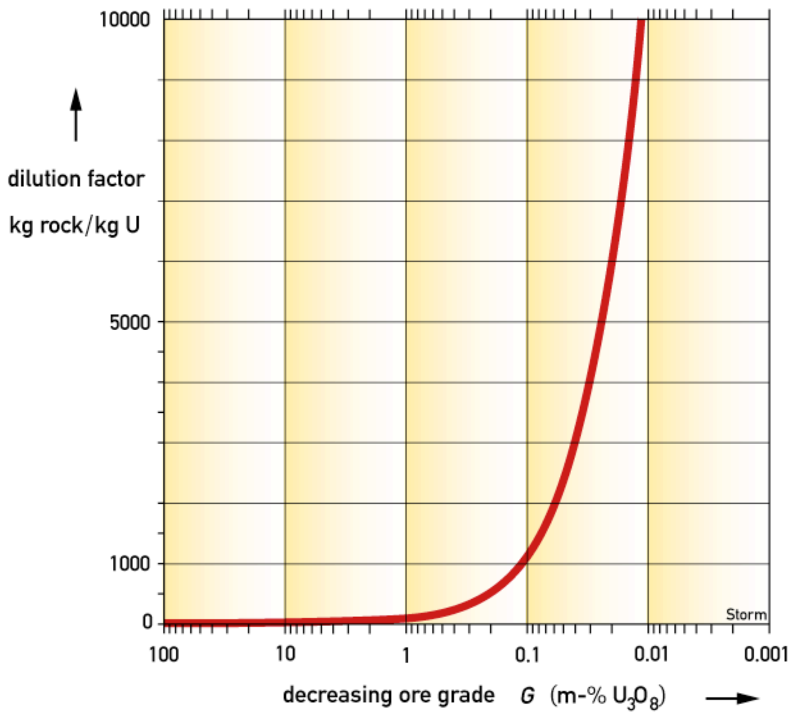

Figure 6
The dilution factor. Note that the horizontal axis, plotting the decreasing ore grade, has a logarithmic scale. Obviously the more rock has to be mined and milled, the lower the grade of the wished-for element in the rock.

Recovery yield

The extraction of uranium from its host rock is a complex chemical process. The consumption of energy and chemicals depend in the first place on the ore grade, but also on the geochemical characterics of the rock. Moreover, extraction becomes increasingly difficult the lower the uranium content. More 'difficult' means more energy and chemicals per kg uranium.

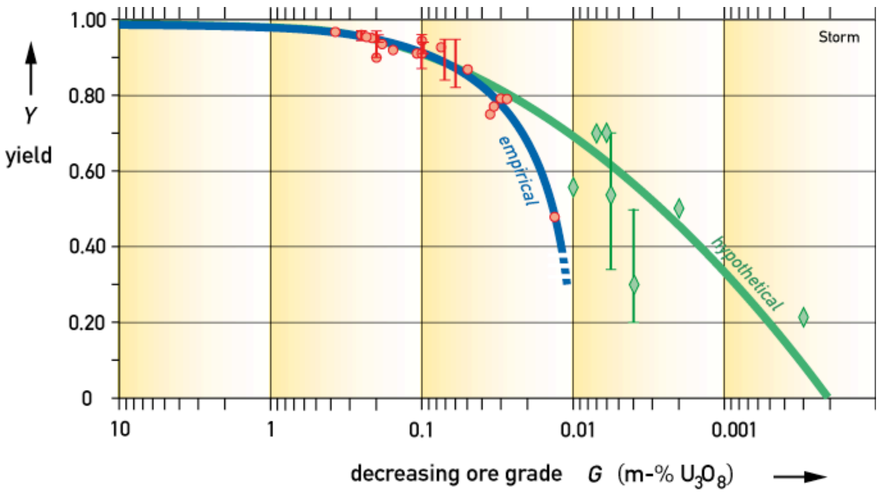

Figure 7
The extraction yield *Y* is defined as the fraction of the uranium, as present in the mined rock, actually being extracted and leaving the mill as yellowcake.
The red dots represent empirical values, as reported in the nuclear literature. The green diamonds originate from studies of hypothetical extraction plants, based on small-scale laboratory experiments or untested concepts.

The study of Storm van Leeuwen & Smith [Q6] used the values according to the theoretical curve (marked green in Figure 7), to be sure not to overrate the specific energy requirements of uranium mining and milling.
At ore grades below 0.05%, this choice leads to significantly overrating the extraction yield and so to underrating the specific energy requirements of the mining and milling operations. For example: the empirical curve (blue in Figure 7) suggest a recovery yield approaching zero at an ore grade of about 0.01%, the theoretical curve (green) suggests a yield of about 70% at that grade.
As most chemists know, extraction processes seldom go to completion. Because of the inherent properties of chemical equilibria, the extracted fraction decreases as the concentration of uranium in its natural matrix decreases. Extraction is some kind of enrichment. The larger the concentration gradient, the larger are the process losses and energy requirements.
We have to deal with thermodynamic constraints and chemical extraction equilibria.

The minimum energy requirements of the extraction of uranium from the earth's crust are governed by basic physical and chemical principles. By advancement of technology we can come nearer to the thermodynamic limits, but never reach them, let alone surpass them. The thermodynamic laws can be circumvented neither by advanced technology nor by bookkeeping tricks.

The energy cliff

The quantity of energy that can be generated from 1 kg of natural uranium, with the isotopic composition as found in nature, essentially has a fixed value. The energy needed to recover the uranium from the rocks in the earth's crust increases with decreasing ore grade. At a certain grade the extraction energy equals the gross energy production of the reactor. Using ore at that critical grade the nuclear system as a whole produces no net energy. The relationship between net energy production and ore grade is here called the 'energy cliff', see Figure 8.

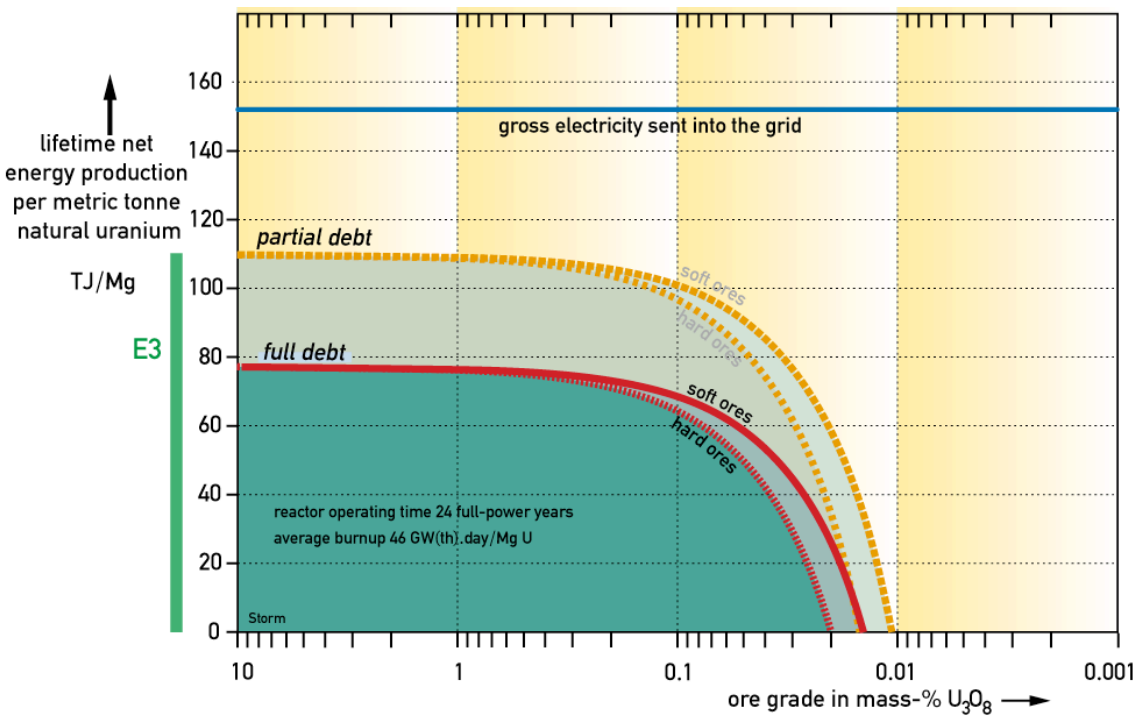

Figure 8
The energy cliff. The horizontal axis represents the decreasing uranium ore grade on a logarithmic scale. On the vertical axis the value of the net energy extractable from a kilogram of uranium, as found in the earth's crust, is presented at a given ore grade. The net energy content is defined as the gross energy production per kilogram natural uranium minus the the energy consumption of the nuclear system itself. The energy consumption of the system is dependent on the grade of the used uranium ore. The green bar E3 represents the net energy from the nuclear chain, as defined in Figures 3 and 4. The blue line represents the gross electricity production of the nuclear power station, measured at its connection with the grid.
The curve 'partial debt' refers to the case the decommissioning and dismantlement of the reactor is excluded, 'full debt' to the case this final part of the nuclear process chain is included in the calculations.

Ores with grades of 0.02% (0.2 grams of uranium per kilogram rock) or lower are no net energy sources. A nuclear chain based on these poor ores consumes as much energy as can be generated from the extracted uranium.

It is important to note that the energy cliff, hardly depends on the value of the assumed energy requirements of the back end of the nuclear chain, especially the decommissioning and dismantlement of the reactor.
The curves are based on the theoretical extraction yield curve presented in Figure 7. At ore grades below 0.05% U_3O_8 this relationship leads to underestimating the energy requirements of the extraction process, the more so the lower the ore grade. In effect, no practical data justify application of the theoretical curve from Figure 7. The actual energy cliff reaches zero value at a higher ore grade than indicated in the diagram of Figure 8. Even if the energy requirements of construction and dismantling are much lower than estimated in the study of Storm van Leeuwen & Smith [Q6], say 10%, the energy cliff will remain at the indicated grade of about 0.02%. In addition, the low grade ores tend to be hard ores, so the lower curves in Figure 8 should be applied.
Moreover the energy cliff does not depend on the state of extraction technology either, for it is rooted in basic physical, chemical and geochemical principles.

There's another phenomenon fixating the energy cliff. At a grade about 0.02-0.01% uranium meets its mineralogical barrier. Below this grade, no separate uranium minerals will be formed. The uranium ions are present as a solid solution in its host rocks. Examples are shales and phosphate ores.
To recover uranium from this kinds of rocks, no process to concentrate the uranium mineral is possible, so the whole mass of rock has to be treated chemically to extract the uranium. Beyond this mineralogical barrier the specific energy requirements of the extraction of uranium may jump with a factor of ten, according to Skinner 1979 [Q322].

Uranium supply

The security of the nuclear energy supply in the future is set by two parameters: The quantuty of the accessible uranium resources and the quality of the resources.

Figure 6 gives the world known uranium resources in 2006, in relation with the ore grades.

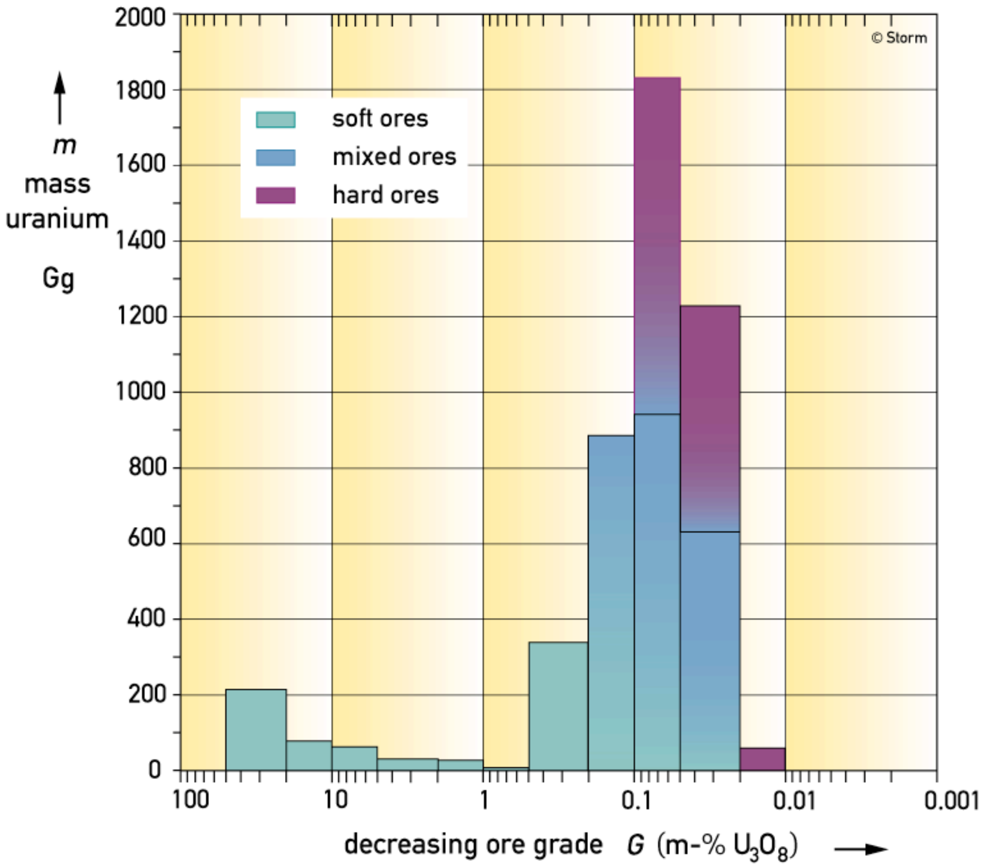

Figure 9
The world known recoverable uranium resources – according to Red Book 2006 [Q90] – as function of decreasing ore grade. Note that the horizontal coordinate has a logarithmic scale and the vertical one a linear scale. The quantity of uranium is represented by the height, not the area of a bar. The width of a bar represents only the range of ore grades.
The largest resources happen to be present in rocks with low ore grades, a common geologic feature of metal ores. We distinguish between soft and hard uranium ores, the latter being harder to mine and mill than the soft ores. Poorer ores tend to be harder.
The total amount of uranium represented by this diagram is 4.7 Tg, or 4.7 million metric tonnes.

As Figure 9 shows the largest resources happen to be present in rocks with low ore grades, a common geologic feature of metal ores.
We distinguish between soft and hard uranium ores, the latter being harder to mine and mill, cunsuming more energy ans materials, than the soft ores. The purple colored bars represent resources of hard ores. There are also ores with mixed properties in this respect, indicated by the changing colors. Poorer ores tend to be harder.
In Figure 10 the diagram of the 'energy cliff' (Figure 8) is plotted with the diagram of the world known recoverable uranium resources. As it turns out, the largest known recoverable resources are nearest to the verge of the 'energy cliff'.

The world nuclear potential is set by the *quality* of the uranium resources, NOT the *quantity*.
The higher the thermodynamic quality of an uranium deposit, the lower the energy requirements of the extraction of uranium from that deposit.

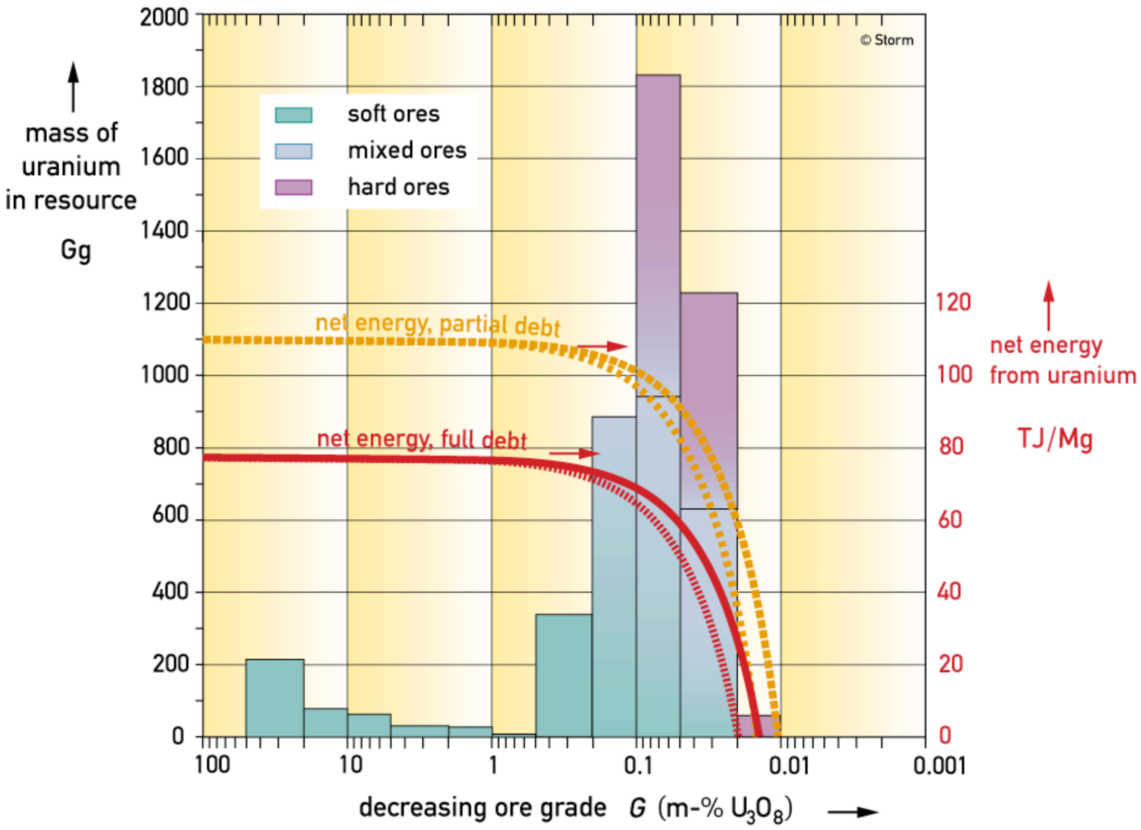

Figure 10
Plotting the diagram of the 'energy cliff' on to the diagram of the world known recoverable uranium resources, results in this picture. As it turns out the largest known recoverable resources are nearest to the verge of the 'energy cliff'.

Obviously, the CO_2 intensity of nuclear power increases with decreasing grade of the uranium ore from which the uranium is extracted, due to higher energy inputs from fossil fuels. Figure 11 depicts this effect.

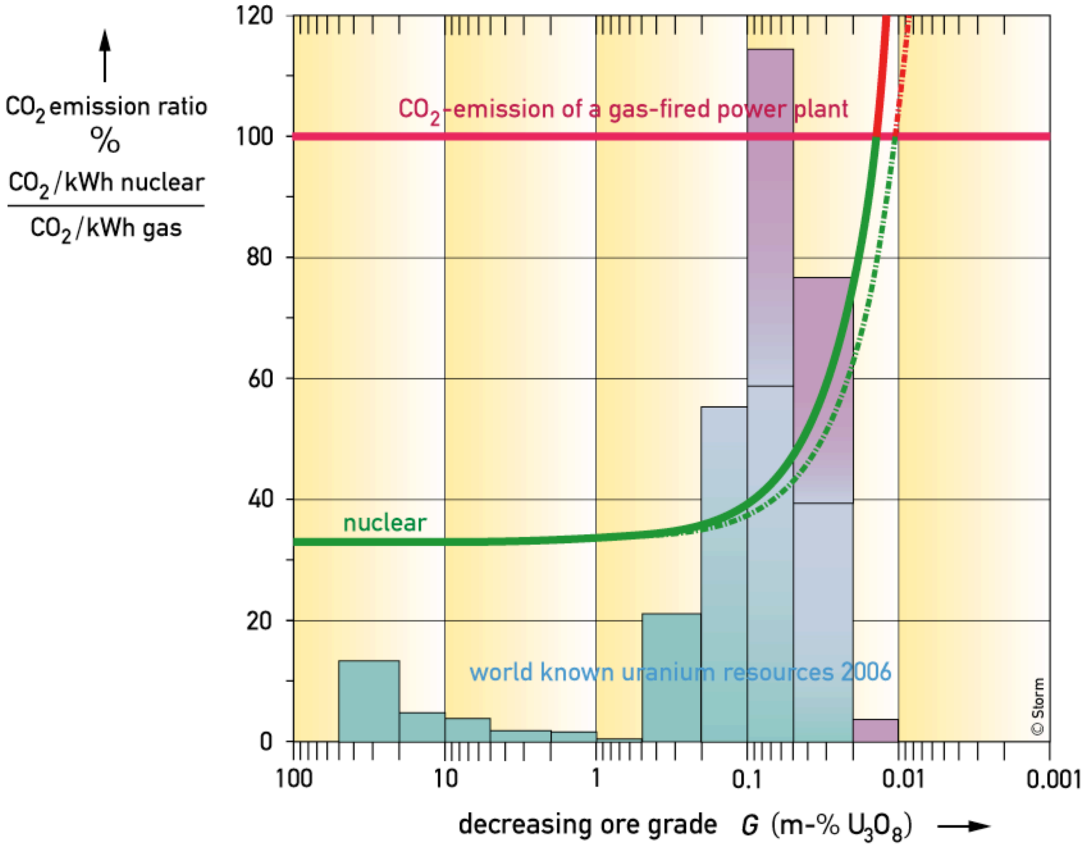

Figure 11
The CO_2 intensity of the nuclear system as function of the ore grade.

Depletion scenarios

To address the potential contribution of nuclear power to the world energy supply, hence to the mitigation of the CO_2 emissions, I use two simple scenarios.

Scenario 1

World nuclear capacity remains constant at current level, 370 GW(e).
Share declines to < 1% of world energy supply by 2050, due to rising world energy demand.
Scenario 1 implies a new nuclear build as large as during the past decades. Nuclear power plants cannot be refurbished anymore beyond a certain life span, due to increasing radioactivity, wear, corrosion and deterioration of materials. During the next decades almost all existing NPPs have to be replaced to keep the world nuclear capacity at a constant level.

Scenario 2

World nuclear share remains constant at current level, 2.2% of world energy supply, from 2012 on.
World nuclear capacity increases by 2-3% a year (7.5-10 GW/a), to keep pace with rising world energy demand.

This scenario roughly corresponds with the 'High' scenario of the IAEA in 2005.

In addition to the new buil in scenario 1, 7-10 GW capacity has to be added each year to keep growing the nuclear capacity with 2-3% a year.

In the scenarios we assume the highest quality uranium ores being mined first, as these will usually generate the largest profits for the mining companies. Actually a mix will be mined, but the general trend of decreasing mean ore quality will be correct.
The recovery of uranium requires more energy, materials and equipment the lower the ore grade and quality.

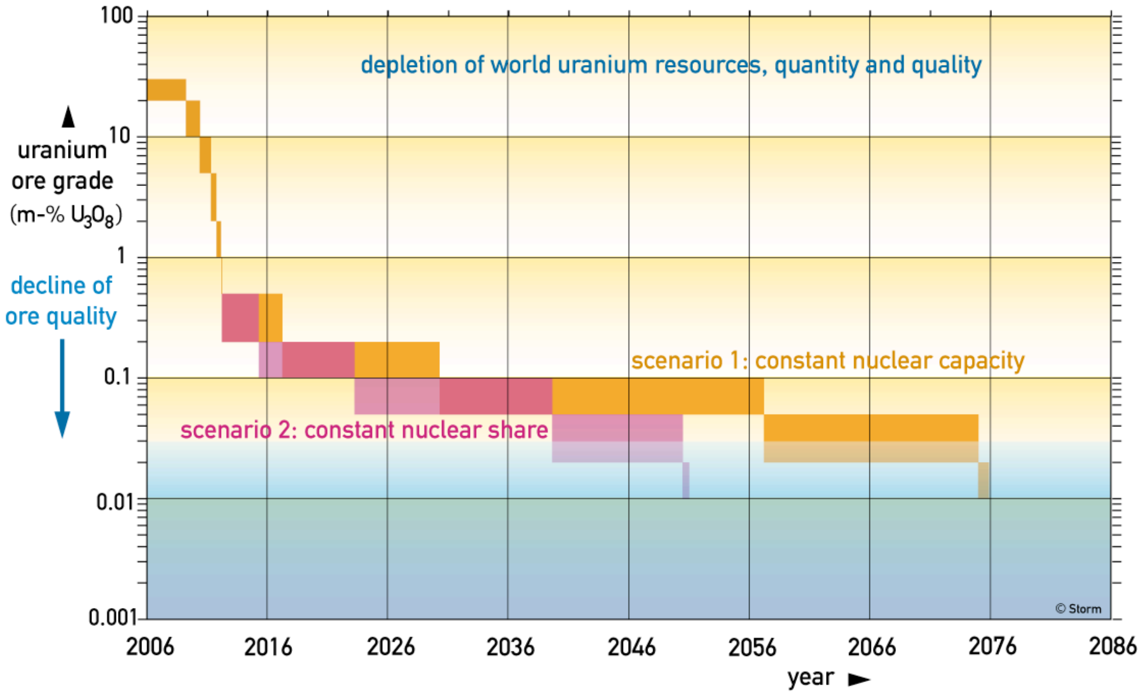

Figure 12
The depletion of the currently known uranium reserves in two simple scenarios. With time the mean quality of the mined uranium ores will decline. On the vertical axis the ore grade is plotted in a logarithmic scale. Going down means decreasing ore grade, each division with a factor 10, and consequently decreasing ore quality.
Significant is the drop of the average ore grade below the 0.1% boundary. At ore grades below 0.1% the energy requirements of extraction rapidly rise with declining ore grade.
At grades of about 0.02% the energy cliff is reached: using that lean ores the nuclear system no longer produces net energy from uranium ore.
In an all-nuclear world electricity scenario the uranium resources would be depleted within a decade.

Leaner ores require more energy to exploit, hence more CO_2 is produced by the extraction per kilogram uranium. As the mean ore grade drops with time, the specific CO_2 emission rises. In about 70 years (scenario 1) to 45 years (scenario 2) the nuclear CO_2 emission surpasses that of the gas-fired electricity generation, see Figure 13.

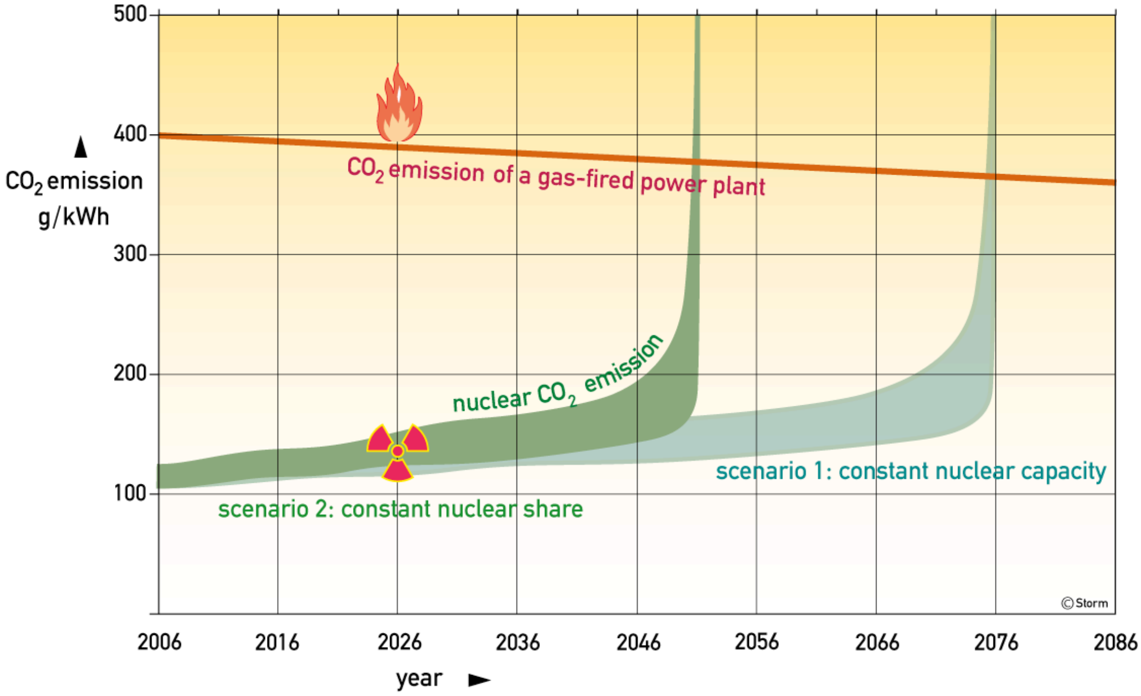

Figure 13
The green area represents the uncertainty range in the calculated values. Due to some optimistic assumptions in the analysis, the higher boundary may be more plausible than the lower one. The energy conversion efficiency of gas-fired electricity generation is expected to increase by time, hence the slope in the red line.

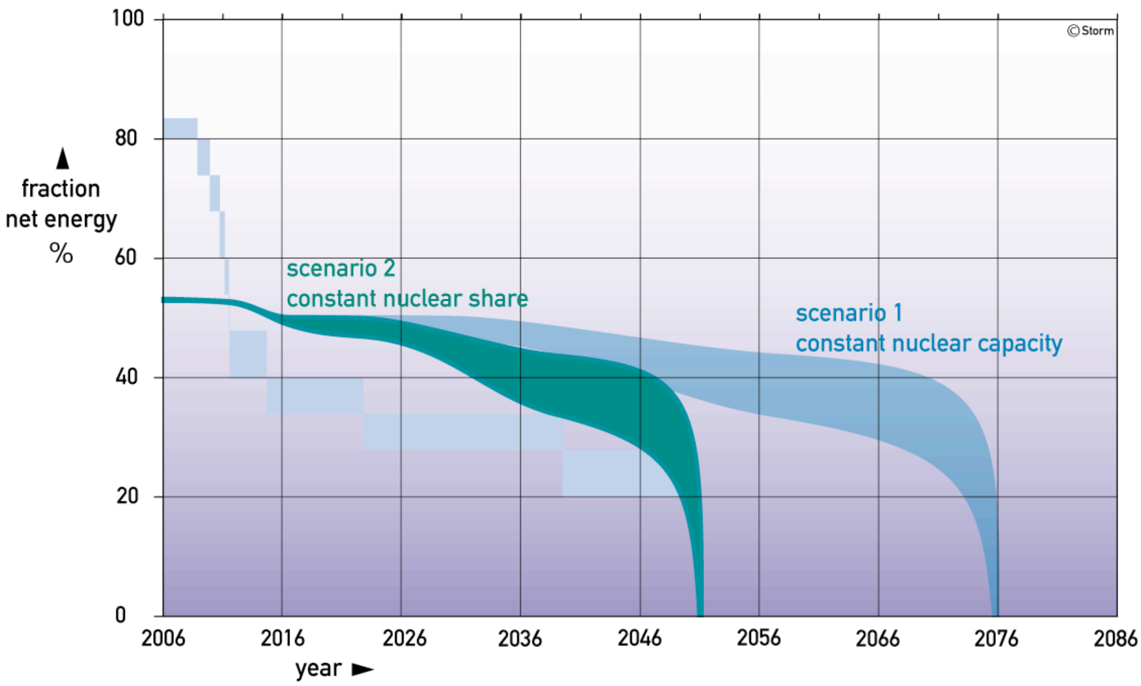

Figure 14
Another hockey stick.
The blue area represents the uncertainty range in the calculated values. Due to some optimistic assumptions in the analysis, the lower boundary may be more plausible than the higher one.

Gradually the net energy extracted from uranium ore will decrease with time. In addition the uncertainty range increases. Due to optimistic assumptions regarding lean ores, the lower boundary of the uncertainty range may be more realistic.
The drop of the mean ore grade below 0.1%, with three decades, incurs a significant drop of the net energy from uranium.
The nuclear system may fall off the energy cliff by about 2050 or 2070, dependent on the scenario.

Outlook

Both scenarios in this paper are based on the currently known recoverable uranium resources. How is the outlook on not-yet discovered uranium resources?

New uranium deposits almost certainly will be found. Higher uranium prices will stimulate more exploration and more exploration might lead to new discoveries. That's the economic part of the story.

The highest quality uranium deposits, that is the easiest discoverable and easiest accessible (physically and chemically) and mineable deposits are known already. From a geologic point of view the chances of finding new, large, high-quality deposits seem slim. No indications on the existence of such deposits have been published up to now. Even if a new 'Canada'-sized rich deposit would be discovered, it would add only 6-7 years of high-quality uranium supply to the current world demand.

Most likely new finds of large deposits will have lower energy quality than currently known deposits of the same ore grade, due either to lower grade, greater depth, longer transport distances or other causes. Lower quality means more energy consumed per kg extracted uranium. So new finds of uranium deposits might be closer to the energy cliff.
It is important to distinguish between *high-grade ores* (that is, ores with a high uranium content) and *high-quality ores* (that is, ores with low extraction energy).

Summarized

- The highest-quality uranium deposits are already known and in production.
- The chances of finding new large high-quality deposits are unknown, but might be very slim.
- Lower quality of uranium ore means more energy consumed per kg extracted uranium.
- From a geologic point of view new finds will be of lower quality. the larger the deposit.
- New finds of uranium deposits will be closer to the energy cliff.

Conclusion
The time of depletion of net nuclear energy from uranium ores may not change significantly in the future, nor by new finds, nor by advanced technology.

Studies of ISA and Storm&Smith compared

Both studies are based on the lght-water reactor (LWR) in the once0through mode. The ISA study also analysed the heavy-water reactor, with slightly different results.

The numerical results of the study by ISA, The University of Melbourne 2006 [Q325], as quoted in the UNPNER Draft Report [Q326], p 121-124, are close to the results of Storm van Leeuwen & Smith 2005 [Q6], as Table 1 shows. This despite of a methodological disagreement with regard to the energy requirements of construction and decommissioning.

As explained in the section 'The energy cliff' the value of the energy requirements of construction and decommissioning of the reactor have little impact on the zero net energy ore grade: about 0.02-0.01% U_3O_8.

Table 1
Comparison of the numerical results of the study by ISA, The University of Melbourne 2006 [Q325], as quoted in the Draft Report of the Taskforce [Q326], with results of the study by Storm van Leeuwen & Smith 2005 [Q6]. The results refer to an LWR with an operational lifetime of 35 years at a mean load factor of 85%. The figures of Storm van Leeuwen & Smith 2005 have been adjusted to this lifetime and load factor.

	unit	ISA [Q325]	Stormsmith [Q6]
energy intensity	kWh_{th}/kWh_e	0.16 – 0.40	0.38 – 0.55
greenhouse gas intensity *	g CO_2-e/kWh_e	10 – 130	85 - 125
energy payback time	years	5.6 -14.1	6.2 – 14.4

* See text below.

The ISA study uses the unit gCO_2-e/kWh, meaning gram CO_2-equivalent per kilowatt-hour. Using this unit would imply other greenhouse gases being investigated as well as carbon dioxide. Neither ISA [Q325] nor Storm van Leeuwen & Smith 2005 [Q6] did investigate greenhouse gas emissions other than CO_2 by the nuclear chain. Storm van Leeuwen & Smith [Q6] found no data on other greenhouse gases in the open literature. Vattenfall 2005 [Q152] states no data were made available by the nuclear industry.

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