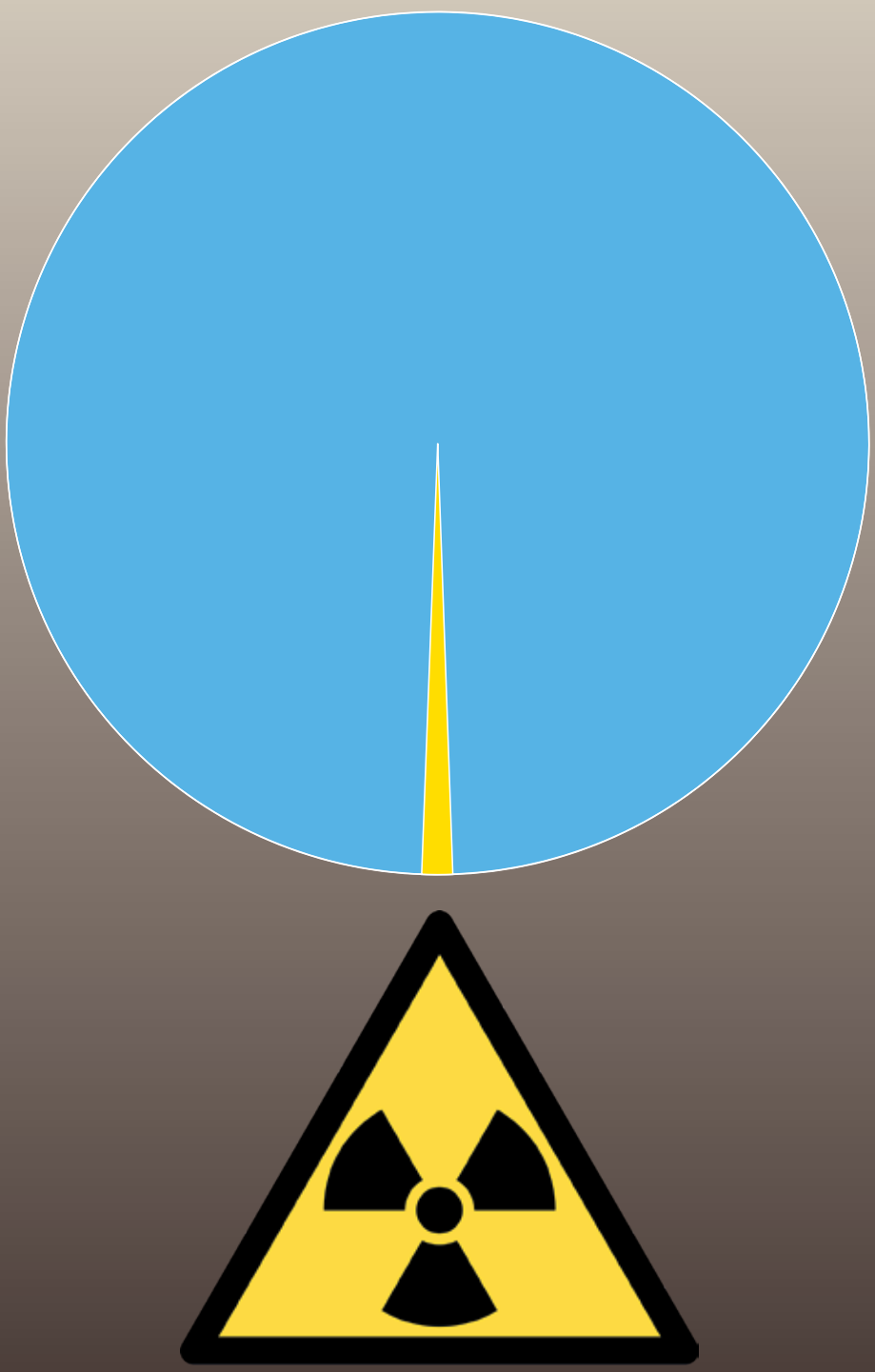
Can nuclear power slow down climate change?



An analysis of nuclear greenhouse gas emissions

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By Jan Willem Storm van Leeuwen

Ceedata Consultancy

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With this study WISE hopes to contribute to a thorough debate about the best solutions to tackle climate change. Nuclear energy is part of the current global energy system. The question is whether the role of nuclear power should be increased or halted. In order to be able to fruitfully discuss this we should at least know what the contribution of nuclear power could possibly be.

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Greens in the European Parliament

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Summary and conclusions

Starting point

Nuclear power is claimed to be nearly carbon-free and indispensable for mitigating climate change as a result of anthropogenic emissions of greenhouse gases.
Assuming that nuclear power really does not emit carbon dioxide CO_2 nor other greenhouse gases (GHGs), how large is the present nuclear mitigation share and how large could it become in the future? Could the term 'indispensable' in this context be quantfied? These issues are assessed from a physical point of view, economic aspects are left outside the scope of this assessment.

How large is the present nuclear mitigation share?

The global GHG emissions comprise a number of different gases and sources. Weighted by the global warming potential of the various GHGs 61% of the emissions were caused by CO_2 from burning of fossil fuels for energy generation. Nuclear power could displace fossil-fuelled electricity generation, so hypothetically the maximum nuclear mitigation share would be 61% if the global energy supply were to be fully electric and fully nuclear.
In 2014 the nuclear contribution to the global usable energy supply was 1.6% and consequently the nuclear mitigation share was 1.0%.
The International Atomic Energy Agency (IAEA) asserts that the nuclear contribution to the global energy supply was 4.6% in 2014. However, this figure turns out to be based on a thermodynamically inaccurate statistical trick using virtual energy quantities.

How large could the nuclear mitigation to climate change become in the future according to the nuclear industry?

We found no hard figures on this issue, for that reason this study analyses the mitigation consequences of the envisioned developments of global nuclear generating capacity. During the past years the International Atomic Energy Agency and the nuclear industry, represented by the World Nuclear Association (WNA), published numerous scenarios of global nuclear generating capacity in the future, measured in gigawatt-electric GWe. Four recent scenarios are assessed in this study, as these can be considered to be typical of the views within the nuclear industry:

- IAEA low: the global nuclear capacity remains flat at the current level until 2050.
- IAEA high: the global nuclear capacity grows to 964 GWe by 2050, nearly three times the current global capacity of 333 GWe.
- WNA low: the global nuclear capacity grows to 1140 GWe by 2060 and to 2062 GWe by 2100.
- WNA high: the global nuclear capacity grows to 3688 GWe by 2060 and to 11046 GWe by 2100.

The nuclear mitigation share in the four scenarios depends not only on the nuclear generation capacity, but also on the growth rate of the global GHG emissions. The IAEA expects a growth rate of the global energy consumption of 2.0-3.5% per year until 2050. This study assumes that global GHG emissions will grow during the next decades proportionally to global energy consumption: also at 2.0-3.5% per year. Based on this assumption – and still assuming nuclear power is free of CO_2 and other GHG emissions (which it is not) – the mitigation shares would be as follows, the high figure at a global growth of 2.0%/yr, the low figure at 3.5%/yr:

- IAEA low: 0.5-0.3% by 2050.

- IAEA high: 1.4-0.9% by 2050.
- WNA low: 1.4-0.7% by 2060 and 1.1-0.3% by 2100.
- WNA high: 4.5-2.4% by 2060 and 6.2-1.8% by 2100.

What next after 2050?

The IAEA scenarios are provided through 2050. Evidently the nuclear future does not end in 2050. On the contrary it is highly unlikely that the nuclear industry would build 964 GWe of new nuclear capacity by the year 2050 without solid prospects of operating these units for 40-50 years after 2050.
How does the nuclear industry imagine development after reaching their milestone in 2050?
Further growth, leveling off to a constant capacity, or phase-out? Or: let tomorrow take care of itself?

What global construction rates would be required?

By 2060 nearly all currently operating nuclear power plants (NPPs) will be closed down because they will reach the end of their operational lifetime within that timeframe. The current rate of 3-4 GWe per year is too low to keep the global nuclear capacity flat and consequently the global nuclear capacity is declining. To keep the global nuclear capacity at the current level the construction rate would have to be doubled. The average global construction rates that would be required in the industry scenarios are:
- IAEA low: 7-8 GWe per year until 2050.
- IAEA high: 27 GWe/yr until 2050.
- WNA low: 25 GWe/yr until 2060 and 23 GWe/yr from 2060 until 2100.
- WNA high: 82 GWe/yr until 2060 and 184 GWe/yr from 2060 until 2100.

In view of the massive cost overruns and construction delays of new NPPs that have plagued the nuclear industry for decades it is not clear how the required high construction rates could be achieved.

How are the prospects of new advanced nuclear technology?

The nuclear industry promises the application within a few decades of advanced nuclear systems that would enable mankind to use nuclear power for hundreds to thousands of years. This promise concerns two main classes of closed-cycle reactor systems: uranium-based systems and thorium-based systems:
– uranium-plutonium recycle in conventional reactors, generally light-water reactors (LWRs)
– fast reactors, that are uranium-plutonium breeder reactors
– thorium reactors.

Because of the complexity of this matter the three options are briefly discussed below, starting with a brief description of a crucial component common to all three systems, reprocessing.

Reprocessing
A crucial technical component of the advanced reactor systems is the reprocessing of spent fuel, that is the sequence of physical and chemical processes required to separate spent nuclear fuel into a number of fractions: unused uranium, newly formed plutonium, actinides, fission products and other fractions. The reprocessed uranium and plutonium would be used to fabricate new nuclear fuel to be placed into reactors. In case of a thorium-based system the spent fuel would be separated into unused thorium-232, newly formed uranium-233, fission products and other fractions.
Reprocessing is a complicated, highly polluting, and very energy-intensive process. Decommissioning and dismantling of a reprocessing plant after it has to be closed down requires massive investments of materials, energy and financial resources and likely will take more than a century of dedicated effort.

U-Pu recycle in LWRs

The first option, uranium-plutonium recycle in conventional reactors (LWRs), relates to the use of plutonium as fissile material in nuclear fuel instead of uranium-235, as in enriched uranium; this kind of fuel is usually called MOX: Mixed OXide fuel. If all spent fuel discharged from the current global nuclear fleet (all conventional reactors except one) were to be reprocessed and the plutonium obtained were to be used in conventional reactors, the global uranium demand would decrease by some 18%.

Physical analysis of U-Pu recycle in LWRs proves that the energy balance of the system is negative, meaning that the system is actually an energy sink instead of an energy source. The main cause of this is the required energy input of reprocessing and of the decommissioning and dismantling of the reprocessing plant at the end of its service life.

Fast reactors: uranium-plutonium breeders

The term 'fast reactor' usually refers to the breeder system, a closed-cycle system that would generate (breed) more fissile nuclei from uranium than consumed in the fission process by converting non-fissile uranium-238 nuclei into fissile plutonium nuclei. During the 1980s and 1990s this type of reactor was usually called a 'breeder' or 'fast breeder reactor' (FBR) but this term has disappeared from the publications of the IAEA and the nuclear industry. Now the breeder concept is part of the so-called Generation IV program. This program also includes other types of fast reactors without a breeding capacity that are not discussed here.

The envisioned breeders would be able to extract 50-100 times more energy from a kilogram of natural uranium than the current conventional reactors, that cannot fission more than about 0.6% of the nuclei in natural uranium. The prefix 'fast' refers to the fact that this type of reactors operate with fast neutrons, contrary to the currently operating commercial reactors in which fission occurs by thermal (slow) neutrons.

A breeder (FBR) is not just a reactor but a cyclic system consisting of a fast-neutron nuclear reactor plus a reprocessing plant plus a fuel fabrication plant. Each of the three components of the cycle would have to operate flawlessly and finely tuned to the two other without any interruption. If one component fails in any respect, the whole system fails and breeding is out of question. Operation of the cyclic system is further complicated by the high radioactivity of the materials to be processed, increasing with each following cycle. Four decades of intensive research in several countries and investments of some $100bn, have proven that the breeding cycle is technically unfeasible. The failure to materialize the U-Pu breeder concept can be traced back to fundamental laws of nature, especially the Second Law of thermodynamics. Thermodynamics is the science of energy conversions; it is at the basis of physics, chemistry and biology. From the Second Law follows, among other consequences, that separation processes of mixtures of different substances never go to completion and consequently perfect materials are not possible. Critical in the breeder cycle is the reprocessing of the spent fuel as soon as possible after unloading from the reactor.

Thorium reactors

Thorium is a radioactive metal, more abundant in the Earth's crust than uranium. The concept of the thorium reactor is based on the conversion by neutron capture of non-fissile thorium-232 into uranium-233, which is as fissile as plutonium-239. Application of thorium-based systems would make nuclear power independent of the uranium supply, according to the promises of the nuclear industry.

The fundamental obstacles that render the U-Pu breeder technically unfeasible apply also to the thorium breeder. Another drawback of the thorium cycle is that a thorium reactor cannot sustain a fission process in combination with breeding uranium-233 from thorium-232, but always would need an external accelerator-driven neutron source, or the addition of extra fissile material, such as plutonium or uranium-235 from conventional reactors.

Conclusion

In the end the breeder concepts, U-Pu as well Th-U, turn out to be based on inherently unfeasible assumptions. *Conditio sine qua non* for closed-cycle nuclear generating systems is the availability of:

- perfect materials
- fail-safe and fool-proof technical systems with perfectly predictable properties across decades
- perfect separation of strongly radioactive, complex mixtures of numerous different chemical species into 100% pure fractions.

None of these conditions is possible, as a consequence of the Second Law of thermodynamics, and for that reason materialization of the breeder concept is inherently unfeasible.

From this observation it follows that nuclear power in the future would have to rely solely on once-through reactor technology based on natural uranium. As a consequence the size of the uranium resources will be a restricting factor.

How much uranium would be needed to sustain the various scenario's?

As pointed out above the nuclear generating capacity in the scenarios will not fall to zero at their end date. The minimum amounts of uranium that would be required in the IAEA scenario's are estimated here by assuming no new NPPs would be build after 2050 and consequently the nuclear power plants operational in 2050 would be phased out by 2100. In case of the WNA scenario's extension after 2100 seemed too speculative. The masses of uranium are given in teragram Tg, 1 Tg is 1 million metric tonnes .

- IAEA low: 2.3 Tg until 2050 plus 1.7 Tg during phase-out by 2100, total 4.0 Tg uranium
- IAEA high: 4.5 Tg until 2050 plus 4.8 Tg during phase-out by 2100, total 9.3 Tg uranium
- WNA low: 6.6 Tg until 2060 plus 12.7 Tg from 2060 until 2100, total 19.3 Tg uranium
- WNA high: 17.5 Tg until 2060 plus 58.4 Tg from 2060 until 2100, total 75.9 Tg uranium.

Obviously the uranium demand in the IAEA scenarios would be higher if the nuclear capacity were to remain flat after 2050, as opposed to phasing out after 2050 as assumed above; in case of a constant capacity after 2050 the total demand would be about 5.7 Tg in IAEA low and 14.1 Tg in IAEA high.

The known recoverable uranium resources of the world in the cost category of up to 130 USD/kg U amounted to 5.9 Tg in 2013 according to the IAEA; the market price in september 2015 was about 82 USD/kg U. An additional amount of 1.7 Tg of uranium is known to exist in the higher cost category 130-260 USD/kg U.

How are the prospects of the global uranium supply?

Uranium in the earth's crust is unevenly distributed among the rocks comprising the crust. The grade distribution of uranium in uranium-bearing rocks in the earth's crust show a geologic pattern common to other metals: the lower the grade of uranium the larger the amounts of uranium present in the crust. The size distribution of uranium deposits show a similar pattern as a result of the geologic ore-forming mechanisms: the larger the size, the more rare the deposits. From this observation it follows that the chance of discovering new resources increases with lower grades and smaller sizes of the deposits. One may assume that the most easily discoverable resources have been found already and that most easily minable deposits are already being mined. The chances of discovering new large high-grade resources seem low; in reality no such discoveries have been reported during the past two decades.

Based on a simple economic model the nuclear industry states that the global uranium resources are practically inexhaustable, apparently suggesting that any scenario could be materialized. However, the generation of nuclear energy from uranium resources is a physical phenomenon governed by the laws of nature, not by economic notions. The economic model does not include physical and chemical realities with regard to uranium deposits in the earth's crust. Thermodynamics sets the boundaries for the resources that fit the conditions of uranium-for-energy resources.

What are the thermodynamic boundaries of uranium-for-energy resources?

Energy cliff

The energy content of natural uranium that is in any sense extractable is limited: the nuclear power stations that would form the backbone of future nuclear capacity could not fission more than about 0.6% of the nuclei in natural uranium.

The thermodynamic boundaries of the uranium-for-energy resources are determined by the energy required to extract uranium from the resources as found in nature. Analysis of the physical and chemical processes needed to recover uranium from the earth's crust and all the processes needed to release the potential energy in uranium and convert it to useful energy proves that the amount of energy consumed per kg recovered natural uranium rises exponentially with declining ore grades. Below a grade of 200-100 ppm (0.2-0.1 grams U per kg rock) no net energy can be generated by the nuclear system as a whole from a uranium resource, this relationship is called the *energy cliff*. From this conclusion it follows that only uranium resources at grades higher than 200 ppm (0.2 g U/kg rock) are actually energy sources.

The ore grades of the known uranium resources which are by definition economically recoverable varies widely: from about 200 down to 0.1 gram uranium per kg rock. A part of the resources classified by the IAEA as 'recoverable' falls beyond the thermodynamic boundaries of uranium-for-energy resources.

*Unconventional uranium resource*s

The nuclear industry classifies the global uranium resources into two categories: conventional and unconventional resources. Phosphates are the main constituent of unconventional uranium resources, other types of uranium-bearing resources (e.g. black shales) are insignificant on global scale.

Phosphates are irreplaceable for agricultural use, so mining of these minerals should be tailored exclusively to agricultural needs. Moreover, the thermodynamic quality of phosphates as a uranium-for-energy source lies beyond the energy cliff: no net energy generation is possible by exploitation of phosphate rock; this holds true also for other unconventional uranium resources, including uranium from seawater.

How much CO_2 does nuclear power emit?

Nuclear CO_2 emission originates from burning fossil fuels in all processes and factories needed to extract uranium from the ground, prepare nuclear fuel from the recovered uranium, construct the nuclear power plant and to safely manage the radioactive wastes. The fission process in the nuclear reactor is the only process of the nuclear system that has (virtually) no CO_2 emission. In addition CO_2 is generated by chemical reactions during the production of necessary materials and chemicals, for example cement (concrete) and steel. A generic NPP contains some 150 000 tonnes of steel and 850 000 tonnes of concrete, in addition to several thousands of tonnes of other materials. The sum of all materials consumed by an NPP during its operational lifetime is about 76 grams per kilowatt.hour delivered to the grid, excluding the mass of rock displaced for mining and final sequestration of the radioactive wastes.

By means of the same thermodynamic analysis that revealed the energy cliff, see above, the sum of the CO_2 emissions of all processes constituting the nuclear energy system could be estimated at 88-146 gram CO_2 per kilowatt.hour. This figure is based on the assumption that all electric inputs of the nuclear process chain are provided by the nuclear power plant itself, to avoid discussions of the local fuel mix of electricity generation.

The large uncertainty range is chiefly caused by uncertainties regarding the processes of the back end of the process chain, these are the processes needed to safely isolate the inevitable radioactive wastes from the biosphere, including the dismantling of the NPP after its service life. The emission figure will rise with time, as will be explained below.

CO_2 trap

The energy consumption and consequently the CO_2 emission of the recovery of uranium from the earth's crust strongly depend on the ore grade, and several other physical and chemical factors that are not discussed here. In practice the most easily recoverable and richest resources are exploited first, a common practice in mining, because these offer the highest return on investment. As a result of this practice the remaining resources have lower grades and uranium recovery becomes more energy-intensive and more CO_2 intensive. Consequently the specific CO_2 emission of nuclear power will rise with time; when the average ore grade approaches 200 ppm, the specific CO_2 emission of the nuclear energy system will surpass that of fossil-fuelled electricity generation. This phenomenon is called the *CO_2 trap*.

If no new major high-grade uranium resources are found in the future, nuclear power will run aground in the CO_2 trap within the lifetime of new nuclear build.

Does nuclear power also emit other greenhouse gases?

No data are found in the open literature on the emission of greenhouse gases other than CO_2 by the nuclear system, likely such data never have been published. Assessment of the chemical processes required to produce enriched uranium and to fabricate fuel elements for the reactor indicates that substantial emissions of fluorinated and chlorinated gases are unavoidable; some of these gases may be potent greenhouse gases, with global warming potentials thousands of times greater than CO_2.

Unknown are the GHG emissions of the construction of a nuclear power plant, with its large mass of high-quality and often exotic materials. Unknown are the GHG emissions of the operation, maintenance and refurbishment of nuclear power plants. Unknown are the GHG emissions of the backend of the nuclear process chain: the handling and storage of spent fuel and other radioactive waste.

It is inconceivable that nuclear power does not emit other greenhouse gases, this matter is still a well-kept secret. Absence of published data does not mean absence of emissions.

Does nuclear power emit other climate changing gases?

Nuclear power stations and reprocessing plants discharge substantial amounts of a number of fission products, one of them is krypton-85, a radioactive noble gas. Krypton-85 is a beta emitter and is capable of ionizing the atmosphere, leading to the formation of ozone in the troposphere. Tropospheric ozone is a greenhouse gas, it damages plants, it causes smog and health problems. Due to the ionization of air krypton-85 affects the atmospheric electric properties, which gives rise to unforeseeable effects for weather and climate; the Earth's heat balance and precipitation patterns could be disturbed. Would nuclear power exchange alleged mitigation of CO_2 emissions for enhanced emissions of climate changer krypton-85?

Are the published nuclear GHG emission figures comparable to renewables?

Scientifically sound comparison of nuclear power with renewables is not possible as long as many physical and chemical processes of the nuclear process chain are inaccessible in the open literature, and their unavoidable emissions cannot be assessed.

When the nuclear industry is speaking about its GHG emissions, only its CO_2 emissions are involved. Erroneously the nuclear industry uses the unit gCO_2eq/kWh (gram CO_2-*equivalent* per kilowatt-hour), this unit implies that other greenhouse gases also are included in the emission figures, instead the unit gCO_2/kWh (gram CO_2 per kilowatt-hour) should be used. The published emission figures of renewables *do* include all greenhouse gases. In this way the nuclear industry gives a false and misleading impression of things, comparing apples and oranges.

A second reason why the published emission figures of the nuclear industry are not scientifically comparable to those of renewables is the fact that the nuclear emission figures are based on a very incomplete analysis of the nuclear process chain, for instance the emissions of construction, operation, maintenance, refurbishment and dismantling, jointly responsible for 70% of nuclear CO_2 emissions, are either not taken into account, or use unrealistically low figures. It is these exact components that are the only contributions to the published GHG emissions of renewables. Solar power and wind power do not consume materials for conversion into electricity, as nuclear power does.

What is the energy debt and what are the delayed CO_2 emissions of nuclear power?

Only a minor fraction of the back end processes of the nuclear chain are operational, after more than 60 years of civil nuclear power. The fulfillment of the back end processes involve large-scale industrial activities, requiring massive amounts of energy and high-grade materials. The energy investments of the yet-to-be fulfilled activities can be reliably estimated by a physical analysis of the processes needed to safely handle the radioactive materials generated during the operational lifetime of the nuclear power plant. No advanced technology is required for these processes.
The energy investments for construction of the nuclear power plant and those for running the front end processes are offset against the electricity production during the operational lifetime. The future energy investments required to finish the back end are called the *energy debt*.

The CO_2 emissions coupled to those processes in the future have to be added to the emissions generated during the construction and operation of the NPP if the CO_2 intensity of nuclear power were to be compared to that of other energy systems; effectively this is the *delayed CO_2 emission* of nuclear power. Whether the back end processes would emit also other greenhouse gases is unknown.
Claiming that nuclear power is a low-carbon energy system, even lower than renewables such as wind power and solar photovoltaics, seems strange in view of the fact that the CO_2 debt built up during the past six decades of nuclear power is still to be paid off.

What consequences of the energy debt could be expected?

As a result of the living-on-credit paradigm prevailing in the nuclear industry, all human-made radioactivity ever generated is still stored in makeshift facilities, if not already dumped into the sea, lakes, rivers or unattended landfills. The isolation from the biosphere of all radioactive materials in the least risky way is a *conditio sine qua non* to secure our children, grandchildren and future generations against the insidious hazards of the tremendous quantities of human-made radioactivity.

Realization of the nuclear scenarios combined with the currently prevailing après nous le déluge culture of the nuclear industry would greatly enhance health hazards and risks of accidents and terrorism. We could expect increased dispersion of radioactive materials into the environment due to the unavoidable and progressive deterioration of the materials housing the radioactive wastes of the nuclear chain, combined with increasing amounts of radioactive wastes, stored at an increasing number of temporary storage facilities.
The risks of severe accidents like Chernobyl and Fukushima would increase due to an increasing number of nuclear power plants and spent fuel cooling pools, this in combination with the progressive ageing of nuclear power plants and reprocessing plants. Other hazards are posed by an increasing number of transports of radioactive materials. If reprocessing of spent fuel were to be continued in the future the risks of nuclear terrorism would grow day by day, because an increasing amount of plutonium and other fissile materials would be transported and stored at different places.

Economic preferences and commercial choices can greatly increase nuclear hazards, the more so if the global economy stagnates or declines. There is the relaxation of the official standards for operational routine discharges of radionuclides into the environment by nuclear power plants and reprocessing plants. Due to ageing the frequency of leaks and spills will rise at an accelerating rate and so will the costs to repair the leaks and to prevent their occurrence. Raising allowable radioactive discharge limits for the nuclear operators keeps their costs down, while resulting in higher exposure standards for the general public, often by large factors, without scientific justification. Similar relaxation of exposure standards may be expected in case of a future nuclear accident, as occurred after the Fukushima disaster.
Another example is the relaxation of standards for clearance of radioactive construction materials for unrestricted use in the public domain. This will become a hot issue when heavily contaminated nuclear installations are dismantled; safe guardianship and disposal of the massive amounts of radioactive debris and scrap will be very expensive.

How independent is the information supply to the public on nuclear matters?

Communication between the nuclear industry and the general public is dominated by the International Atomic Energy Agency (IAEA). The authoritative 'nuclear watchdog' IAEA has the promotion of nuclear power in its mission statement. Moreover, official publications of the IAEA have to be approved by all member states of the IAEA. For these reasons it is a misconception to regard the IAEA as an independent scientific institution.
The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has strong connections with the IAEA and the World Health Organization (WHO) cannot operate independently of the IAEA with respect to nuclear issues. As a consequence statements of the WHO concerning health effects of radioactivity and nuclear activities do not deviate from the offical position of the IAEA.

Are releases of radioactive materials into the human environment really of minor importance?

From the reports of the IAEA, UNSCEAR and WHO on the subject of health effects, especially concerning the disasters of Chernobyl and Fukushima, a picture emerges of the nuclear world marked by *downplaying* and even *denial of health effects* caused by exposure to radiation and contamination by radioactive materials.
Non-cancerous diseases are not recognized as radiation-induced health effects, attention is paid only to acute radiation syndrome (ARS, radiation sickness). Conspicuous are the downplaying and denial of health effects caused by radioactivity using unscientific methods, committing elementary scientific flaws.

Full reliance is placed on (old) models for assessment of exposure doses and of dose-effect relationships, with little or no input of empirical evidence. Biochemical behaviour of radionuclides inside human body are not included. Chronic exposure to a mix of different radionuclides inside the body, via ingestion (food and water) and inhalation (gases, dust) are also not covered. The radiological models applied by the IAEA and nuclear industry turn out to be easily adaptable to economic and financial considerations.

Important international studies on health effects of radiation and contamination by radioactive materials with results diverging from the IAEA viewpoint are not discussed in the official IAEA publications and are even not mentioned.

Conclusions

- Assuming nuclear power emits no greenhouse gases (which is not true), the nuclear mitigation share would grow from the present level of less than 1% to at most 1.4% of the global greenhouse gas emissions by 2050-2060, if the global nuclear capacity were to grow according to scenarios projected by the nuclear industry.

- Materialization of the nuclear capacity scenarios proposed by the nuclear industry are doubtful because of the unrealistically high construction rates of new nuclear power plants that would be required.

- Nuclear generating capacity in the future will have to rely completely on reactors in the once-through mode, because closed-cycle systems, including the thorium cycle, are inherently unfeasible. As a consequence future nuclear power depends exclusively on the availability of natural uranium resources.

- Net energy contribution to the global energy supply by nuclear power is limited by the availability of uranium-for-energy resources. Exploiting resources at ore grades below 0.02-0.01% uranium the nuclear system becomes an energy sink instead of an energy source: nuclear power falls off the energy cliff.

- The average ore grade and other qualities of the yet-to-be exploited global uranium resources decline with time, because the highest quality resources available are always mined first.

- The chances of discovering new major uranium-for-energy resources are bleak.

- Mining of phosphates should be tailored exclusively to agricultural needs, for phosphorus is irreplaceable in agriculture.

- Uranium from seawater is no option. If feasible at commercial scale at all, this resource lies far beyond the energy cliff: no net energy generation is possible.

- From a practical viewpoint only the low IAEA scenario seems feasible, resulting in a mitigation share of 0.5-0.3% of the global GHG emissions by 2050, provided nuclear power is GHG free. The mitigation share would become negligible if the nuclear GHG emissions are taken into account.

- At present nuclear power emits 88-146 gCO_2/kWh. Likely the nuclear CO_2 emissions will grow from the current level to values approaching fossil fuel generation within the lifetime of new nuclear builds in the scenarios of both the IAEA and WNA.

- Emissions of GHGs other than CO_2 by nuclear power are not reported, but are almost certain from a technical point of view.

- Krypton-85, discharged by all nuclear power plants and reprocessing plants, generates greenhouse gases in the troposphere, in addition it causes other weather and climate changing effects.

- The published figures of nuclear GHG emissions are not comparable to the figures of renewables, because different quantities and estimation methods are applied.

- Due to the après nous le déluge culture of the nuclear industry the health hazards posed by radioactive materials in the human environment will increase with time, in addition to risks of Chernobyl-like disasters and of nuclear terrorism.

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Introduction

Nuclear power is, according to the nuclear industry, nearly carbon-free and indispensable for mitigating climate change as a result of anthropogenic emissions of greenhouse gases (GHGs).
This study examines this claim from a physical and thermodynamic viewpoint, economic aspects remain outside the scope; the flow chart below represents the outline of the analysis of this report.

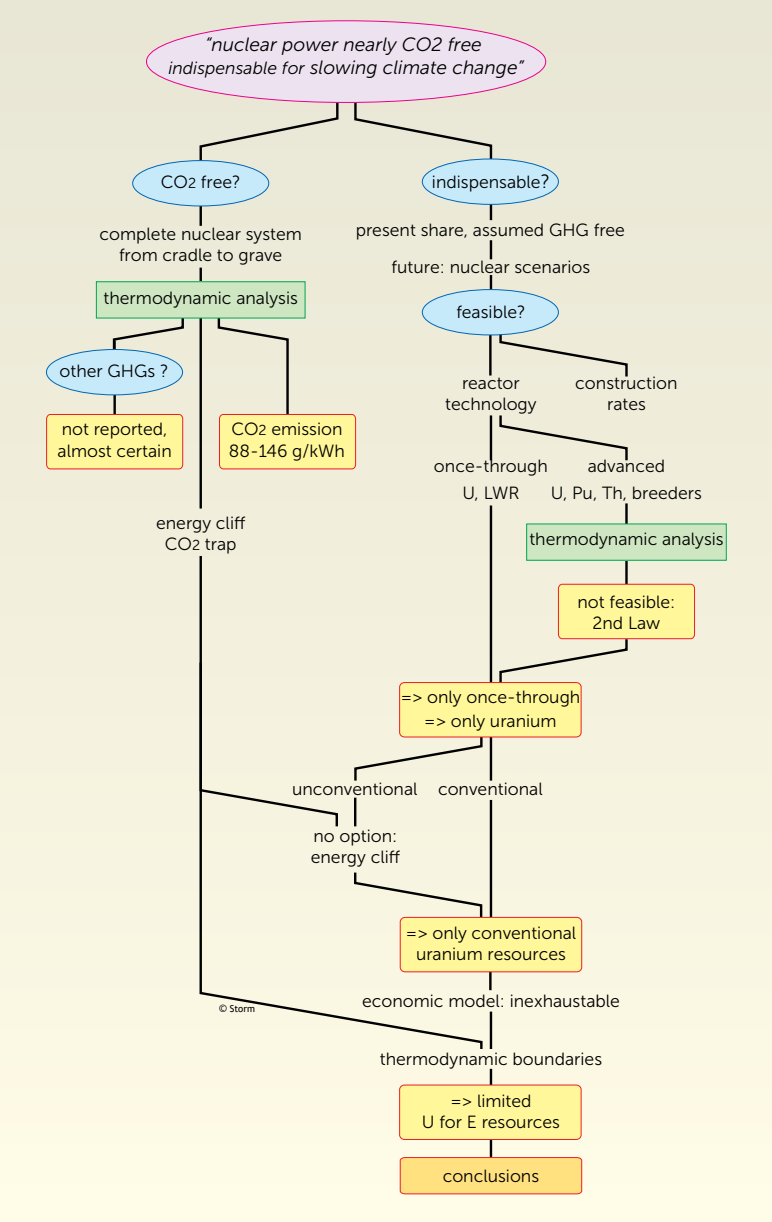

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Figure 1
Outline of the assessment of this study, with two independent analysis lines.

The assessment of the issue of the nuclear GHG mitigation share comprises two independent lines:

- quantification of the nuclear emissions of CO_2 by means of a thermodynamic analysis of the complete system of industrial processes required to make nuclear power possible
- assessment of the nuclear mitigation share at present and in the future, based on the global nuclear

capacity growth according to scenarios proposed by the nuclear industry; this part of the study is independent of the results from the first line.

As climate change, sustainability and energy security are global issues this study starts with outlining the global context of nuclear power: the present state of the global greenhouse gas (GHG) emissions and of the world energy suppy. The most recent data on the global GHG emissions are from 2010. Published trends indicate that the mutual proportions of the various contributors are changing slowly, so the results of this study may still be valid for the year 2014, the base year of this study, all the more since the uncertainty range of the numerical results is not negligible. The scope of the analysis is limited to the emission of carbon dioxide (CO_2) from burning fossil fuels for generating useful energy, because nuclear power is an energy supply system and could only substitute fossil fuels as energy source. Emissions of other GHGs are briefly addressed.

In the first analysis line this study assesses the specific CO_2 emissions of nuclear power and the long term global perspective of its relationship to climate change mitigation. The specific nuclear emissions of CO_2 and other GHGs are assessed by means of a thermodynamic analysis coupled to a life cycle assessment (LCA) of the complete system of industrial activities required to generate electricity from uranium and to safely manage the radioactive wastes.

In the second line of analysis the hypothetical contributions of nuclear power to mitigation of GHG emissions in the future are discussed in several scenarios proposed by the nuclear industry.
How large could the nuclear contribution to mitigation of global greenhouse gas emissions in the scenarios hypothetically become, ignoring the nuclear emissions of CO_2 and other GHGs?
Factors limiting the application of advanced nuclear technology are identified by means of thermodynamic analyses of advanced nuclear systems.

Uranium is a mineral, so it is not a renewable energy source. The amounts of uranium in the accessible part of earth's crust are immense. However, an amount of uranium *in situ* (just being present in the earth's crust) is not by definition an energy source. The size of the uranium resources usable as energy source are limited by boundaries determined by the thermodynamic properties of the uranium resources in situ. These boundaries are revealed by a thermodynamic analysis.
This observation raises the question: for how long could the known uranium-for energy resources supply the nuclear energy system with fissile material in various scenarios? This issue can be addressed independently of the analysis of the real emissions of GHGs by the nuclear energy system.

1 Global context of nuclear power

Global greenhouse gas emissions

Anthropogenic global warming is understood to be caused by the emission of greenhouse gases (GHGs). The global warming potential (GWP) of the gases released into the air vary widely and are measured as a multitude of the GWP of carbon dioxide and expressed in the unit gramCO_2-equivalent. Figure 2 shows the shares of the main categories of GHGs: carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O and fluorinated compounds, see also Table 7..

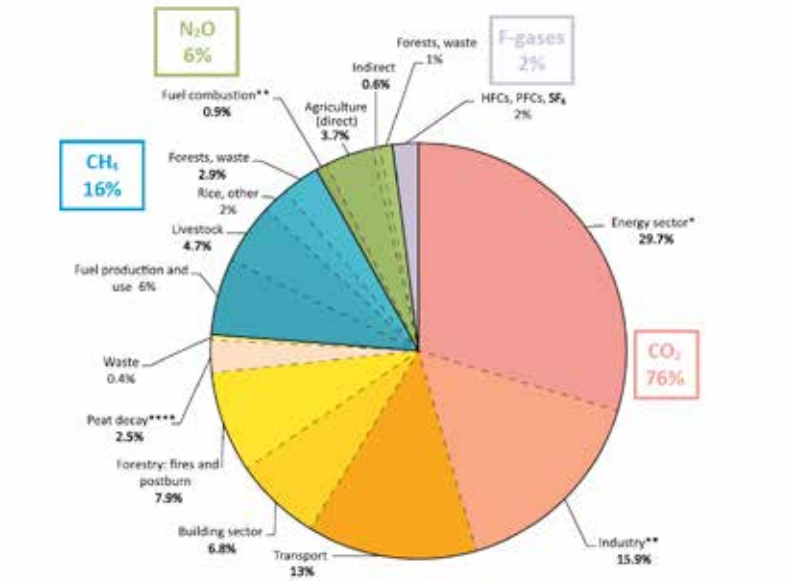


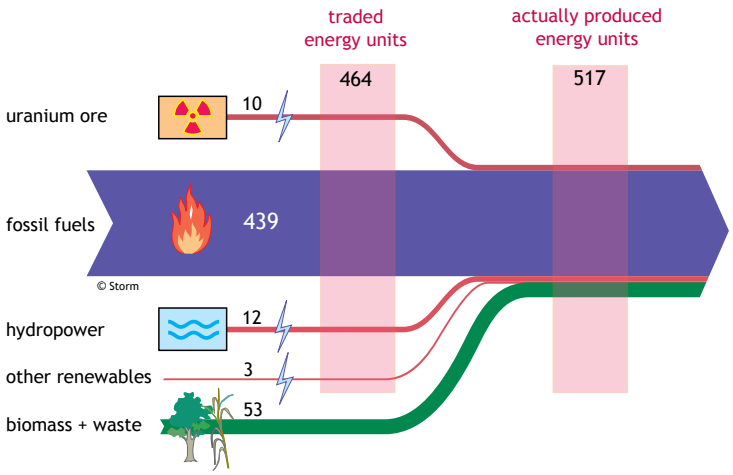
Figure 2.2b. *Shares of sources of global greenhouse gas emissions in 2010 by main sector and gas type (in CO_2e using GWP values as used for UNFCCC/Kyoto Protocol reporting). Source: JRC/PBL (2012) (EDGAR 4.2 FT2010)*

* Power generation, refineries, coke ovens.
** Including non-combustion CO_2 from limestone use and from non-energy use of fuels and N_2O from chemicals production.
*** Including wastewater.
**** Including peat fires.

Figure 2
Sources of global GHG emissions in 2010, weighted by their global warming potential (GWP). F-gases are fluorinated gases. Source: UNEP 2012.

World gross energy supply

In 2010 the world gross energy production was about 517 EJ, that is the sum of the combustion heat of fossil fuels and biomass plus the electricity generated by hydropower, nuclear power and modern renewables. The total world energy production is not exactly known, for the energy consumption of traditional biomass (wood, dung, straw, peat, organic waste) in a number of developing countries can only be roughly estimated. In the energy statistics of BP 2011 only traded energy flows are listed: fossil fuels, hydro power and nuclear power and modern renewables. Data on non-traded combustibles, especially biomass and waste, are taken from IEA 2012.



Gross world energy production 2010, physical flows (EJ)

Figure 3

Actually delivered usable energy (in exajoules EJ) to the world economy in 2010. This diagram is based on Table 1. The numbers are rounded. Source of traded energy figures: BP 2011 [Q91]. The figure of traditional biomass (53 EJ) is not accurately known, source: IEA 2012. Other renewables comprise: solar (PV and CSP), wind, small hydro, geothermal and 'modern' biomass.

Table 1

Energy actually made available in 2010 to the global economic system. Sources: BP 2011 and IEA 2012.

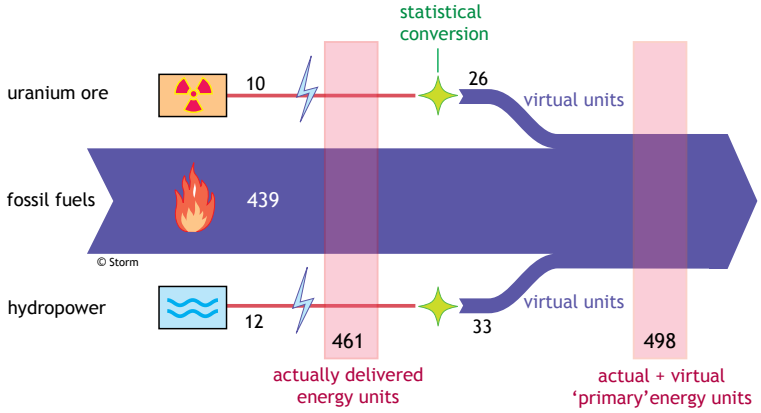
	energy source	electricity TWh	combustibles MTOE	EJ	fraction (%)
1	nuclear	2762.2		9.944	1.9
2	hydro	3427,7		12.340	24
3	other renewables	701.0		2.524	0.5
4	oil		4028.1	169.18	32.7
5	natural gas		2858.1	120.04	23.2
6	coal		3555.8	149.34	28.9
7	sum fossil fuels (3+4+5)		10442,0	438.56	84.9
8	sum traded energy units (1+2+3+7)			463,37	
9	biomass + waste		1271.7	53.41	10.3
10	world total (8+9)			516.78	100.0

Thermodynamic inaccuracies

Often the energy flows are given in million tonnes oil equivalent (1 Mtoe = 42 petajoule PJ). In most statistical energy reviews, e.g. BP 2011 and IEA 2012, and in publications of the nuclear industry the electricity generated by nuclear and hydro is converted into thermal equivalences, measured in 'primary energy' units, by multiplying with a factor $f = 2.64$, as if the electricity has been generated from fossil fuels at a conversion efficiency of 37.8% (currently operating nuclear power plants operate at 30-34% thermal efficiency). In its statistics before 2001 BP applied the factor $f = 3$ for nuclear and $f = 1$ for hydro; in other publications these conversion factors may still be used. Electricity from photovoltaics (PV), wind or Concentrating Solar Power (CSP) is usually not converted into 'primary energy' units Mtoe.

The heat from a nuclear reactor cannot be used directly, like the combustion heat of gas or oil. The only form

of usable energy from a nuclear power plant is the electricity it delivers to the grid. A hydropower plant does not produce heat at all. Applying this statistical conversion the contribution of nuclear power to the world energy supply seems to be nearly 3 times larger than the actually delivered quantity of useful energy units.



World energy production 2010 (EJ): the nuclear view

Figure 4

World energy production in 2010 in the statistical approach of BP 2011 and the nuclear industry. The unit of energy is the exajoule EJ. This diagram comprises only traded energy flows. The electricity produced by nuclear power and hydro power is converted into virtual energy units, called 'primary energy' units. The virtual energy units are added to the actually delivered energy units. The numbers are rounded. Not indicated here are wind, solar, geothermal power, (modern) biofuels and traditional biomass.

Conversion to thermal equivalence units implies that 1 joule electricity from a nuclear power plant equals nearly 3 primary energy units and that 1 joule electricity from a wind turbine equals 1 primary energy unit. Electricity is not labeled: 1 joule nuclear electricity has exactly the same work potential as 1 joule wind-generated electricity. One joule of electricity, from whatever source, can be converted into not more than exactly one joule of heat, as follows from the First Law of thermodynamics.
Another questionable aspect is that above conversion introduces variable and arbitrary assumptions, making the energy statistics unreliable for physical computations, because virtual energy units are added to actually delivered energy units. In thermodynamics you cannot add quality to quantity. Quality is not a conserved quantity in physics, like mass and energy, and it cannot be defined unambiguously.

This study presents all physical energy quantities of the world energy flows in exajoules (1 EJ = 10^{18} joule), as shown in Table 1, without using the notion 'thermal equivalence'.

Inconsistencies

The energy statistics of BP 2011 and IEA 2012 prove to be inconsistent. The figures of the world energy flows for the year 2010 are different in both publications. Obviously different definitions and probably also different statistical data bases are used. This study uses the figures of BP 2011 and the figure for biomass + waste from IEA 2012, which is not listed in the BP publication. The uncertainty range in the figures used in this study may be as large as 6% as a result of the inconsistencies.

Final energy use

A portion of the fossil fuels are used to produce asphalt, solvents, lubricants and chemical feedstock. In 2000 this non-energy use of fossil fuels amounted to 22 EJ, some 6% of the fossil fuel production, according to Weiss et al. 2009. IEA 2012 determined a non-energy use fraction of 6.3% of the total primary energy supply (fossil fuels plus biomass) in 2010, but it is not clear how the IEA arrived at this figure.

There are three kinds of energy losses in the world energy system:

- Upstream fossil fuel losses. The recovery from the earth (production), refining and transport of the fossil fuels consumes some 23% of the energy content of the fuels. Indirect energy use and losses due to flared and spilled fuels are not included so it may be a low estimate. This loss fraction will increase with time, as the most easily recoverable resources available are exploited first and will be depleted first; the remaining resources are less easy to exploit and consequently will consume more useful energy per unit of extracted fuel. In addition the share of liquified natural gas (LNG) is increasing, leading to higher upstream energy losses.
- Conversion losses. In 2010 the average conversion efficiency of fossil fuels into electricity was about 38% BP 2011, so 62% of the energy content of the fossil fuels are lost into the environment.
- The average transmission losses of electricity are estimated at about 6%.

The final energy consumption of the world, that is the gross energy production minus above mentioned losses, amounted to about 326 EJ in 2010. Figure 5 represents the various energy flows.

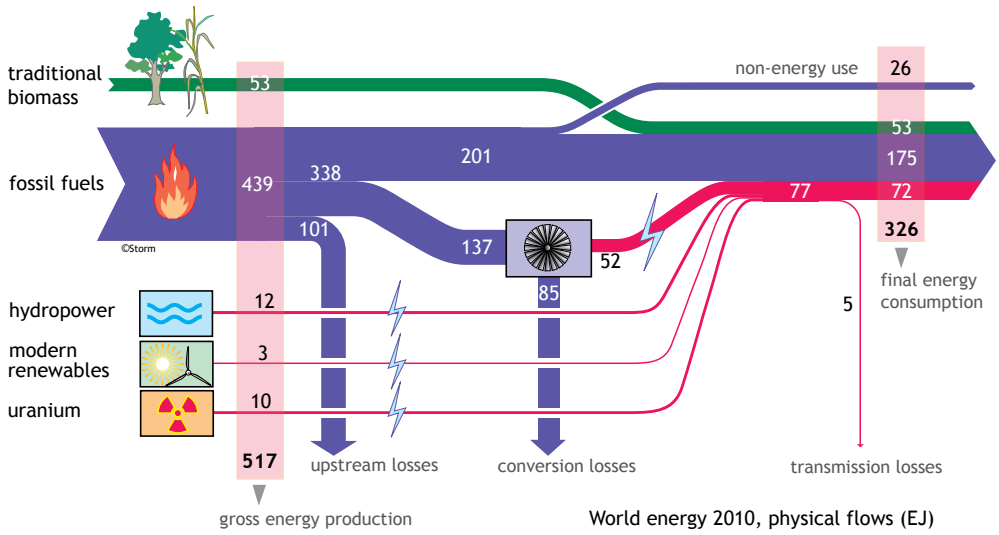


Figure 5

Physical energy flows of the world in 2010, in exajoules (EJ). Not accurately known is the amount of energy embodied in traditional biomass and the upstream losses of the fossil fuels. Therefore the world final energy consumption, here presented as 326 EJ, has a significant uncertainty range.

Biomass introduces a significant uncertainty in the energy statistics. Massive amounts of biomass are used for non-energy purposes, for example the production of paper; in 2010 394 Tg (1 Tg = 10^{12} g = 1 million tonnes) of paper was produced, of which about half was recycled. Assuming 200 Tg of paper was burned as waste in 2010 having an assumed combustion heat of 20 MJ/kg = 20 PJ/Tg then some 4 EJ of heat would need to be added to the world energy consumption in 2010. Because no clear data on this matter could be found in the above mentioned publications of BP and IEA and, moreover, exact figures would not be relevant in this matter, this study assumes 6% of the gross fossil fuel production was used for non-energy purposes in 2010, and non-energy use of biomass is left out of this calculation.

Historically some 10% of the global gross energy production consisted of 'traditional biomass' (dung, straw, wood, peat), burned for cooking and heating, but these amounts are not exactly known. For 2010 the figure of 53 EJ from IEA 2012 is used.

Nuclear contribution to GHG emission mitigation in 2010

In 2010 76% of the global warming potential was caused by CO_2: 61% by CO_2 originating from burning fossil fuels and 15% from other sources; for example cement production emitted 3% of the global GHGs (PBL 2012 [Q620]). In addition 6% of the global GHG emissions were caused by methane (CH_4) from the energy sector, so 67% of the global GHGs originate from the use of fossil fuels, see Figure 6. It is likely the mutual ratios of the various sources of GHGs did not change significantly in the years following 2010.

No data are available on the emissions of non-CO_2 GHGs by nuclear power, though emissions of fluorinated gases, powerful GHGs, are almost certain (see Chapter 7). For that reason the assessment of the potential role of nuclear power as primary energy source in mitigation of the global GHG emissions has to be limited here to the CO_2 emissions by the energy sector: 61% of the total global GHG emissions.

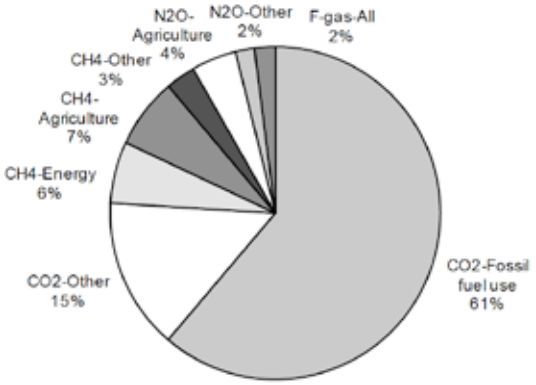


Figure 6
Global GHG emissions by gas/source in 2010. Source: PBL 2012 [Q620].

In 2010 the gross production of fossil fuels was 439 EJ and 26 EJ of this amount was used for non-energy purposes (see Figure 5), so 413 EJ of energy were generated by burning fossil fuels, producing CO_2. Considering the significant uncertainty range of the numbers in Figure 5 (see section 'Inconsistencies' above) this study conveniently simplifies the picture by taking the nuclear contribution as part of the total global gross energy production (517EJ).

In 2010 the nuclear share of the world gross energy production was 1.9%. Most energy statistics give another figure; for example BP 2011 cites a share of 5.2%. This has two reasons:

- Firstly BP lists only the traded energy (464 EJ in 2010) and ignores the non-traded energy supply by traditional biomass and waste.
- Secondly: BP uses the thermal equivalence of the world nuclear electricity production by multiplying it by a factor $f = 2.64$, as pointed out above. This method of calculation results in a number of virtual energy units. In this study no virtual energy units are used.

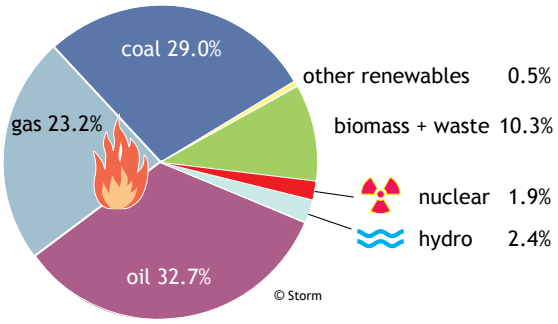


Figure 7

World primary energy production in 2010 was about 517 EJ (exajoule), of which 464 EJ traded energy.. The share of nuclear power was 1.9% in 2010 and is steadily declining. Sources: BP 2011 and IEA 2012.

In the findings above the nuclear contribution to the mitigation of the global GHG emissions in 2010 was 1.9% of 61% of the global GHG emissions, or some 1.2% of the total emissions, assuming nuclear power is CO_2-free (which it is not). By 2014 the nuclear mitigation share had declined to less than 1%.

2 Nuclear CO_2 mitigation scenario's

Present state

In 2014 the global nuclear generating capacity comprised 388 operating reactors with a joint capacity of 333 GWe (WNISR 2015) producing 2410 TWh of electricity. IAEA-sdr1 2015 [Q623] mentions higher figures of the number of reactors (438) and total generating capacity (376 GWe). To get this higher number the IAEA considers 40 reactors in long-term outage as 'in operation'; BP 2015 cites a higher figure of the nuclear electricity production in 2014 (2537 TWh); this study uses the IAEA figure of the production (2410 TWh) and the WNISR figure of the actually operating reactors (333 GWe).
The global nuclear electricity generation of 2410 TWh formed 1.6% of the world energy production in 2014. As explained in Chapter 1 this amount means that the nuclear contribution to mitigation of the global CO_2 emissions in 2014 was less than 1%, provided that nuclear power is CO_2-free, which it is not.

Scenarios

How large could the nuclear contribution to mitigation of CO_2 emissions hypothetically become in the future? At what timescale could a higher nuclear contribution be achieved?
To gain some insight into this matter this study examines seven scenario's.
IAEA-sdr1 2015 expects a growth rate of the global energy consumption of 2.0 - 3.5%/yr until 2030. Here we assume that this growth rate will continue until 2100, in order to place the scenarios of the nuclear industry in a global context after 2030-2050. Conveniently we assume also that the global GHG emissions will grow at a rate of 2.0-3.5% per year until 2100. As a consequence each scenario has two variants: one at an assumed growth of 2%/yr and the other at a 3.5%/yr growth.

Scenario 0, phase-out

In scenario 0 no new nuclear power plants would be built beyond the units under construction today. Due to the closedown of nuclear power plants after a service life of about 40 years the world nuclear capacity would approach zero by the year 2060. Scenario 0 may be regarded as the zero line of the other scenario's. In 1998 the IAEA also expected that the then operating nuclear fleet would be closed down by 2050 (Oi & Wedekind 1998). In view of the large uncertainties in regard to life extension of NPPs, the declining trend of the global nuclear capacity and the rising costs of new NPPs, this scenario 0 seems realistic. In this scenario the nuclear mitigation share will drop to zero by 2060.

Scenario 1, constant nuclear capacity, IAEA low

To keep the nuclear capacity at the present level almost the complete current fleet of nuclear power stations would have to be replaced by 2060, because the currently operable reactors would have reached the end of their operational lifetime, meaning that during the next decades each year 7.4 GWe of new NPPs have to come on line, two times the current global construction rate of 3-4 GWe/year.
If the global nuclear capacity were to remain flat at the current level, the nuclear mitigating contribution would decline to about 0.5% by 2050 if the global energy production rises at 2%/yr, and so, proportionally, would the GHG emissions. In the case of a global growth of 3.5%/yr the nuclear mitigation share would decline to 0.3% by the year 2050.The low scenario of the IAEA as published in IAEA-sdr1 2015 corresponds with this scenario 1: a nearly constant nuclear generating capacity until 2050.

Scenarios 2 and 3, constant nuclear mitigating share

Scenario 2

To keep the nuclear mitigation contribution at the current level of 1% of the global GHG emissions, provided nuclear power is GHG free, the nuclear generating capacity has to grow at 2% - 3.5% a year. If the global emissions grow at 2%/yr until 2050 the nuclear capacity has to double compared with 2015, to some 670 GWe by the year 2050, if only the actually operating NPPs are counted. This scenario 2 would imply 18 new NPPs of 1 GWe coming online each year during the next 35 years, assuming that in 2050 about 38 GWe of NPPs from before 2015 were still operational.

If the global growth rate were 3.5% a year, a nuclear capacity of 670 GWe in 2050 would correspond with a mitigation share of 0.6%.

Scenario 3

Opting for a constant nuclear mitigation share of 1.0% by 2050 at a global growth of 3.5% a year would require a nuclear capacity of 1109 GWe actually operating NPPs. At a global growth of 2.0%/yr this capacity would provide a nuclear mitigation share of 1.7%. To materialize a nuclear capacity of 1109 GWe by 2050 the construction rate would have to increase to 31 GWe new units each year, nearly 10 times the current global construction rate of 3-4 GWe/year.

Scenario 4, IAEA high

The low IAEA estimate corresponds with scenario 1 discussed above. In its high scenario IAEA-sdr1 2015 [Q623] foresees a nuclear capacity of 964 GWe by 2050, implying a construction rate of 27 new GWe reactors a year. The nuclear share of the global GHG emission mitigation then would be some 1.4%, assumed a global energy consumption growth of 2%/yr and assumed nuclear power is GHG free. The above estimate by the IAEA is significantly lower than the figure of 1092 GWe by 2050 published in 2014.

Assuming a global energy consumption growth of 3.5%/yr until 2050 the nuclear mitigation share in the high IAEA scenario would be 0.9% by 2050, about the level of 2015.

Scenarios 5 and 6, WNA scenarios

The World Nuclear Association WNA, representative of the nuclear industry, published scenarios involving drastically enlarging the global nuclear capacity. In its Nuclear Century Outlook Data (WNA-outlook 2015) WNA foresees two scenario's of global nuclear capacity:

		2030	2060	2100
5	low scenario	602 GWe	1140 GWe	2062 GWe
6	high scenario	1350 GWe	3688 GWe	11046 GWe.

The above publication, the first version of which was presumably from 2008 or 2009, is dated 2015, indicating WNA still believes these scenarios, a remarkable observation in view of the fact that each year the IAEA has lowered their projected scenarios. Scenario 5 (WNA low) looks similar to scenario 4 (IAEA high), if linearly extrapolated to 2060 and 2100, see Figure 8.

The high WNA scenario may be considered to be the highest feasible one in the view of the nuclear industry. Because various high-growth nuclear scenarios are still circulating in numerous publications, the WNA scenarios are considered as indicative and are briefly discussed here.

Assuming the global energy consumption and GHG emissions grow at an average rate of 2%/yr until 2100, the nuclear capacity would have to grow to approximately 813 GWe by 2060 and to 1793 GWe by 2100

(actually operating NPPs) in order to keep the nuclear GHG mitigation contribution at the current level of 1%, again assumed nuclear power is GHG free. At a global growth rate of 2.0%/yr the the nuclear mitigation contribution would become:

		2030	2060	2100
5	low scenario	1.4%	1.4%	1.1%
6	high scenario	3.0%	4.5%	6.2%

At a global growth rate of 3.5%/yr the mitigation shares would become:

		2030	2060	2100
5	low scenario	1.1%	0.7%	0.3%
6	high scenario	2.4%	2.4%	1.8%

The average construction rates required to materialize the WNA scenario's would vary from about 20 to 184 GWe of new NPPs per year, see also Table 2.

Overview

The seven scenarios described above are graphically represented in Figure 7. Scenario 3 (constant mitigation share at a global growth of 3.5%/yr) is approximately the samw as scenario 4 and is not represented separately.
Global nuclear construction rates required to materialize the various scenarios and the resulting nuclear shares of the mitigation of global GHG emissions are summarised in Table 2.

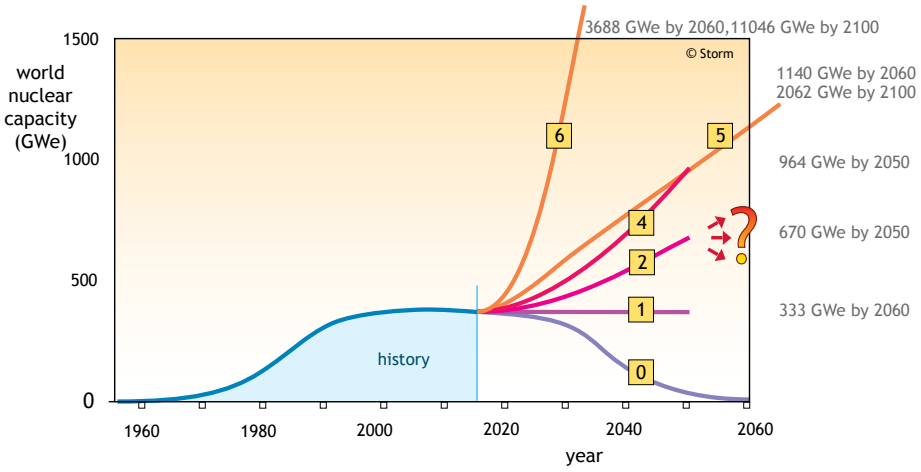


Figure 8

Scenarios of the global nuclear generating capacity. Scenario 3 is not represented, for it is similar to scenario 4. The WNA scenarios cannot be fully represented in this diagram. The query indicates the lack of clarity as to how the IAEA and nuclear industry imagine the developments after 2050: further growth, leveling off or phase-out?

Scenarios after 2050 or 2060?

Obviously the scenarios of the IAEA do not end in 2050. It is highly unlikely that the nuclear industry would build 964 GWe of new nuclear capacity by the year 2050 (scenario 4) without solid prospects of operating these units for at least 50 years after 2050. How does the nuclear industry imagine the developments after reaching their milestone in 2050? Further growth, leveling off to a constant capacity, or phase-out? Or: let tomorrow take care of itself?

Table 2

Summary of seven nuclear capacity scenarios. The construction rates are counted from the year 2015 on. The nuclear mitigation shares of the global GHG emissions are calculated assuming that nuclear power does not emit CO_2 nor other GHG gases, at two assumed global emissions growth rates: 2.0%/yr and 3.5%/yr. In practice the mitigation shares would be significantly lower, because nuclear power does emit CO_2 and other GHGs.

scenario		year	GWe	construction rate GWe/yr	mitigation share global growth 2%/yr	mitigation share global growth 3.5%/yr
0	phase-out	2060	0	0	0	0
1	constant capacity	2050	333	7-8	0.5	0.3
2	constant share (2%)	2050	670	18 *	1.0	0.6
3	constant share (3.5%)	2050	1109	31 *	1.7	1.0
4	IAEA high	2050	964	27 *	1.4	0.9
5	WNA-low	2030	602	20 **	1.4	1.1
		2060	1140	25	1.4	0.7
		2100	2062	23	1.1	0.3
6	WNA-high	2030	1350	69 **	3.0	2.4
		2060	3688	82	4.5	2.4
		2100	11046	184	6.2	1.8

* Assumed 38 GWe of existing NPPs still operating in 2050

** Assumed 313 GWe of existing NPPs still operating in 2030.

Extrapolating the course of the nuclear capacity scenarios further has profound consequences for the demand for fissile materials. In order to estimate in a realistic way the minimum amount of uranium, or other fissile material, required to sustain the various scenarios, this study assesses two variants of extending the scenarios 1 - 4 after reaching the indicated levels in 2050:

- Variant 1. No new NPPs would be built after 2050 and the then existing NPPs would be phased out, like scenario 0. This approach implies that the curves of scenarios 1 - 4 (scenario 3 is about similar to scenario 4) are modified to give them a smooth transit to the phase-out, see Figure 9.
- Variant 2. After 2050 the scenarios level off to a constant level until 2100; this variant is represented in Figure 10. The WNA scenarios, continuing until 2100, are not extended here in this way.

Obviously the demand for uranium or other fissile material would be far greater in the extended scenario's than in case of the scenarios as depicted in Figure 8, ending nuclear power completely in 2050.

Development of closed-cycle nuclear power systems (breeders) that would be able to fission at least 50 times more nuclei present in natural uranium, according to the promises of the nuclear industry, will take several decades (if possible at all, see Chapter 3). Even in the optimistic prognoses of the nuclear industry the first NPP based on the breeder reactor could not become operational before 2050. As a consequence NPPs based on closed-cycle systems could not contribute to the global nuclear generating capacity before 2050-2060. From this observation it follows that in all scenarios the projected nuclear generating capacity until 2050-2060 is based exclusively on the current reactor technology and natural uranium as primary energy source. In Table 3 the uranium consumption rates and total uranium usage in the various scenario's are summarised, assuming that all reactors would be light-water reactors (LWRs) in the once-through mode, without plutonium recycle or other application of the breeder technology. We return to the issue of other fissile materials in Chapter 3.

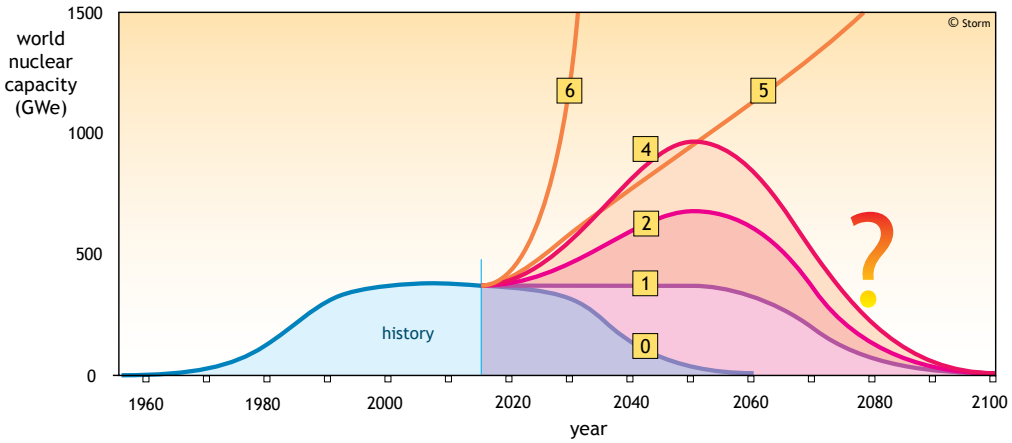


Figure 9

Scenarios 1, 2 and 4 expanded to the year 2100 in variant 1, depicting the hypothetical case of phase-out after reaching the projected capacity by the year 2050. Scenario 3 is not represented here, for it is similar to scenario 4. Neither WNA scenarios (5 or 6) are 'expanded' here. On the basis of these scenarios the minimum amount of uranium needed to materialise the scenarios 1, 2, 3 and 4 can be estimated.

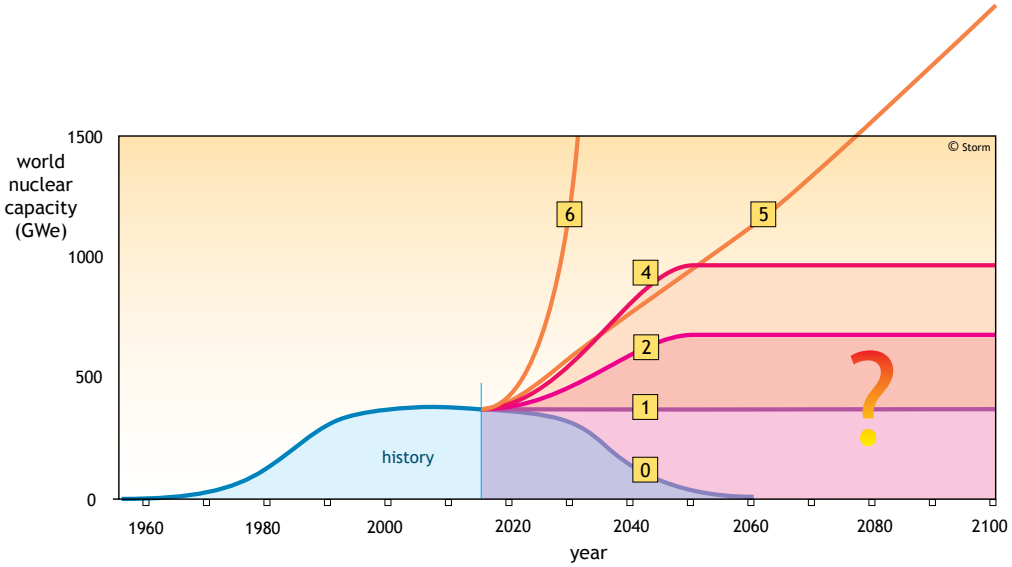


Figure 10

Scenarios 1, 2 and 4 expanded to the year 2100 in variant 2, depicting the hypothetical case of flattening out to a constant level after reaching the projected capacity by the year 2050. Scenario 3 is not represented here, for it is approximately the same as scenario 4. Both WNA scenario's (5 and 6) are not changed here.

In the scenarios of variant 1 the nuclear capacity would rely exclusively on conventional reactor technology and natural uranium as feedstock.

The uranium usage in scenarios 1-4 in variant 2 are not calculated here. Evidently those figures would be considerably higher than in variant 1. Theoretically the NPPs phased out after 2050-2060 could be replaced by advanced closed-cycle reactor systems in variant 2.

Table 3

Summary of the projected nuclear capacity, average annual uranium consumption and total uranium demand in the seven scenarios. The figures are based on the assumption that all reactors are LWRs in the once-through mode, without plutonium recycle (see also the conclusion of Chapter 3).

scenario		year	nuclear capacity GWe	peak U usage Gg/yr	average U usage Gg/yr	U demand Tg
0	phase-out	2060	0	66	33	1.5
1	constant capacity	2050	333	66	66	2.3
	phase-out	2100 *	0	-	33	1.7
	sum uranium					4.0
2	constant share (2.0%)	2050	670	132	100	3.5
	phase-out	2100 *	0	-	66	3.3
	sum uranium					6.8
3	constant share (3.5%)	2050	1109	220	143	5.0
	phase-out	2100 *	0	-	110	5.5
	sum uranium					10.5
4	IAEA high	2050	964	191	129	4.5
	phase-out	2100 *	0	-	96	4.8
	sum uranium					9.3
5	WNA-low	2030	602	119	93	1.4
		2060	1140	226	173	5.2
		2100	2062	409	318	12.7
	sum uranium					19.3
6	WNA-high	2030	1350	268	167	2.5
		2060	3688	731	500	15.0
		2100	11046	2189	1460	58.4
	sum uranium					75.9

* Phase-out parts after 2050 added by author, for explanation see text. To the WNA scenarios no phase-out parts are added after 2100.

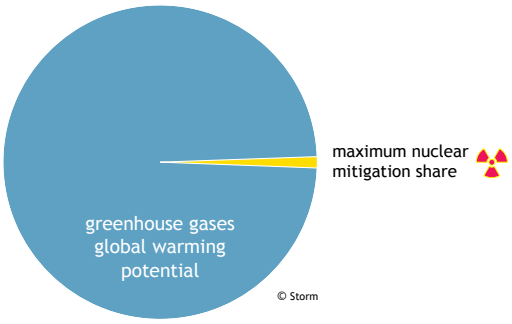


Figure 11

Maximum nuclear contribution to the mitigation of the global greenhouse gas emissions in 2050-2060 in the most optimistic IAEA nuclear growth scenario (see Table 2), provided that nuclear power is GHG free (which it is not).

Construction rates

A first obstacle to be removed in order to be able to realize the various scenarios is a drastic scaling-up of the global construction capacity of new nuclear power plants. As Table 2 shows, even to keep the global generating capacity at the present level during the next decades the average construction rate has to be increased to 7-8 GWe a year, double the current rate of 3-4 GWe/yr. In this scenario the nuclear mitigation share would decline to 0.5% or less, provided nuclear power is GHG free.
In the other scenarios the required construction rates are much higher, for example in the high IAEA scenario (scenario 4) the average construction rate in the period 2015-2050 would have to be about 27 GWe per year, 7-9 times the current rate. This scenario would lead to a nuclear mitigation share of 0.9 - 1.4% of the global GHG emissions by 2050.
In view of the massive cost overruns and construction delays of new NPPs already plaguing the nuclear industry for decades it is not clear how the required high construction rates could be achieved.

Health hazards

Increasing the world nuclear capacity inevitably will increase the health hazards posed by radioactivity for several reasons, such as:

- More reactors will mean more planned and unintential discharges of radioactive materials into the human environment.
- The chance of large nuclear accidents, comparable with Chernobyl and Fukushima, will increase due to a larger number of operating reactors and spent fuel storage facilities and larger quantities of radioactive waste in temporary storage facilities.
- More reactors require more uranium mining and milling, increasing contamination of large areas by radioactive mining waste (dust, groundwater).

These aspects will be briefly addressed in Chapter 6.

3 Thermodynamics of closed-cycle nuclear systems

Advanced nuclear technology

The nuclear industry envisions the application of other fissile materials than uranium by means of advanced closed-cycle nuclear reactors that would make possible an almost limitless expansion of nuclear power, according to the nuclear industry. Theoretically the demand for uranium could be reduced by developing substitutes, recycling and more efficient use of the uranium. According to WNA-75 2015 this could be accomplished by:

- Reprocessing of spent fuel and recycling of uranium and plutonium in light-water reactors (LWRs).
- More efficient use of uranium by implementation of 'fast reactors' (breeder reactors) that would be able to fission 50-100 times more nuclei from natural uranium than the current generation of reactors (mainly LWRs).
- Development of reactors that use thorium as fertile material to breed fissile uranium-233. Theoretically thorium could substitute uranium as input for nuclear power, according to the nuclear industry.

The only fissile nuclide found in nature is uranium-235, constituting 0,7% of the atoms in natural uranium, the remaining 99.3% consists of the non-fissile uranium-238 atoms. By means of advanced nuclear technology, involving closed-cycle nuclear power generation, it is theoretically possible to fission a much larger part of the nuclei in natural uranium: according to the nuclear industry 50-100 times more than in an LWR of the current state of technology. In its prognoses and promises the nuclear industry is usually talking only about advanced reactor technology, but reactors are only a part of the technological challenge. The pivotal component of closed-cycle concepts is reprocessing.

Reprocessing of spent fuel

Spent nuclear fuel from a light-water reactor (LWR) contains a large fraction of uranium-238, part of the original uranium-235 remaining unfissioned, fission products, plutonium and trans-plutonium actinides. Both plutonium and the higher actinides originate from uranium by neutron capture. Spent fuel is an exceedingly complex mixture of nuclides, representing almost the complete Periodic Table of the Elements, and is highly radioactive. The Zircalloy cladding of the fuel elements also becomes highly radioactive, by neutron capture.

Separation of spent fuel into fractions is possible by an intricate complex of physical and chemical separation processes, called reprocessing. Reprocessing is the pivotal process in several nuclear concepts:

1 plutonium for weapons
2 plutonium recycling in LWRs
3 breeder reactors (U-238/Pu-239 cycle)
4 thorium reactors (in fact the Th-232/U-233 breeder cycle)
5 radioactive waste volume reduction by vitrification
6 partitioning & transmutation, to convert long-lived radionuclides into short-lived ones.

Initially reprocessing was developed in the early days of the nuclear age to produce plutonium for atomic weapons. In later years commercial applications of the reprocessing technology were developed from the military applications, when the breeder concept came into the picture. The main purpose of the civil reprocessing plants, in Europe at La Hague in France and Sellafield in Great Britain, was to get the plutonium to fuel fast breeder reactors (FBR's) and to recycle unused uranium.

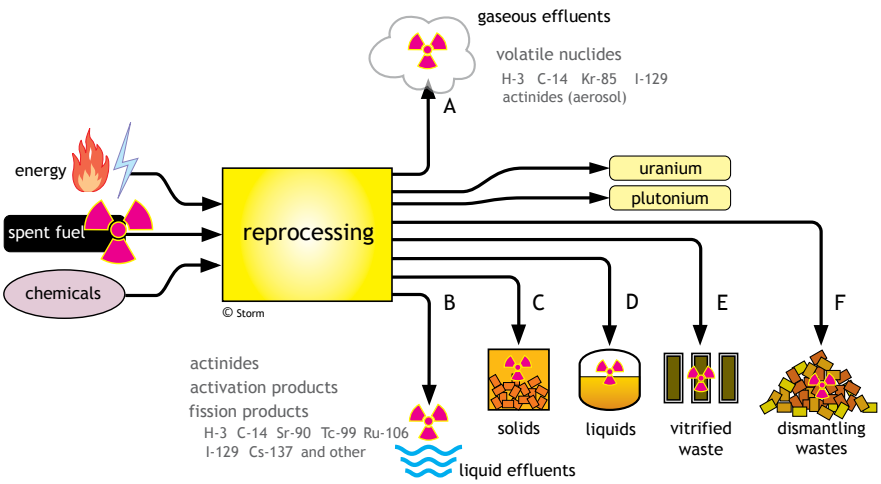


Figure 12

Outline of the radioactive mass flows of reprocessing of spent fuel. The input of a reprocessing plant consists of spent fuel, chemicals and energy (electricity and fossil fuels). Spent fuel is separated into seven fractions: unfissioned uranium, newly formed plutonium and five waste fractions A-E:

A gaseous effluents, discharged into the atmosphere, containing gaseous and volatile fission products, activation products, noble gases and some aerosols of other fission products and actinides

B liquid effluents, discharged into the sea, containing some U and Pu and other actinides, in addition to a substantial part of the highly soluble fission products

C insoluble solid waste consisting of spent fuel cladding hulls and other solids, containing small amounts of U, Pu, fission products, activation products and actinides

D liquid wastes containing fission products, activation products, uranium, plutonium and other actinides, resulting from imperfect separation and purification processes

E the fraction of fission products, activation products and actinides which can be vitrified.

An eighth radioactive waste stream, fraction F, consisting of dismantling wastes, will be released after final shutdown of the reprocessing plant, when the plant is decommissioned, cleaned up and dismantled.

Reprocessing and the Second Law

Reprocessing of spent fuel is a sequence of separation processes, involving numerous chemical equilibria and complicated by high radiation levels. Nuclear radiation causes radiolysis of the solvents and extraction liquids, which results in less effective separation and the generation of unwanted chemical species.

Separation processes are governed by the basic laws of nature. One of the consequences of these laws is that separation processes never go to completion. For that reason it is impossible to separate a mixture of *n* different chemical species into *n* 100% pure fractions without losses. Separation becomes more difficult and goes less completely as:

- more different kinds of species are present in the mixture,
- the concentration of the desired species in the mixture are lower,
- constituting species are chemically more alike
- the solution is higher in radioactivity.

Complete separation is a fiction. As a consequence a part of each desired fraction will be lost in the waste streams and each fraction will be contaminated with species from other fractions. The selectivity of separating a certain fraction from a mixture can be enhanced, at the expense of more specialized chemicals and equipment and consequently more energy, and more losses of other fractions.

Radioactive and non-radioactive isotopes of the same element cannot be separated.

Economic considerations and the human factor are left aside here. The difficulties increase with the number of compounds or elements in the mixture which are to be separated.

The amount of radioactivity in spent fuel does not change with the mechanical and chemical treatments in the reprocessing plant, it simply means a reshuffling of the radionuclides from one material to several other. Inevitably, mixing any amount of radionuclides compacted in a solid (spent fuel) with nonradioactive fluids or other substances increases the volume of the radioactive waste, complicating the waste disposal problems.

Costs of reprocessing

The costs of reprocessing are high and escalating rapidly. Large cost escalations are the norm for all advanced technologies (RAND 1979 and RAND 1981). NRC 1996 estimated the costs at 2110 $(1992)/kg HM (about 2600 $(2000)/kg HM). HM stands for heavy metal: uranium + plutonium. The cost of plant decommissioning has been neglected in this estimate.
Storm 1985 published a graph with the historical cost of reprocessing with entries from more than 20 publications. In 1983 the rapidly rising costs (escalation 50-60% per year) approached 10000 $(1982)/kg HM (about 18000 $(2000)/kg HM), including the construction of the reprocessing plant, but excluding dismantling of the facilities.

For the reprocessing plant at Sellafield (UK) the preliminarily cost estimates vary from GBP38bn (€45bn) (NDA 2009) to GBP50-100bn (€60-120bn) (*Nature*, 23 November 2006 p 245) and will take some 130 years. Assuming the decommissioning and dismantling of the Sellafield reprocessing plant will cost €100bn and its lifetime spent fuel throughput was 10000 Mg (metric tonne), the contribution to the reprocessing cost from decommissioning and dismantling alone would be 10000 €(2006)/kg HM. Most likely in practice these costs will rise to some multiple of this value: cost overruns are the rule in the nuclear industry.
The decommissioning and dismantling of the US West Valley reprocessing plant, which operated from 1966-1972 and reprocessed 640 tonnes of spent fuel, will cost from 2007 on at least €4bn (€(2007)) and will take another 40 years to complete. Very likely the final cost will be considerably higher. Before 2007 several billion dollars had already been spent on West Valley (UCS 2007). The above figures point to a specific dismantling cost of some 10000 €(2007) per kilogram of reprocessed heavy metal.

How viable is reprocessing from an economic point of view?
We found no indications that LWR spent fuel will be reprocessed in the future on a significant scale, once the existing contracts expire; see also MIT 2003.

U-Pu recycle in LWRs

Reprocessing of spent fuel is an exceedingly polluting process consuming massive quantities of energy and chemicals. Decommissioning and dismantling of the ageing reprocessing plants will be extremely costly, as pointed out in the previous section, and very time and energy consuming. These activities should be included in the energy balance of this option. Also the fabrication of the uranium-plutonium mixed-oxide fuel (MOX) to be used in the currently operational thermal reactors is more energy intensive than the fabrication of fresh nuclear fuel from enriched uranium. Jointly these three factors cause a strongly negative energy balance of uranium-plutonium recycling in conventional reactors.
Apart from this prohibitive condition, the contribution of U-Pu recycling in LWRs to more efficient use of uranium would be marginal: at best some 18% of the annual consumption of natural uranium, provided that all spent fuel of the world were to be reprocessed and the separated plutonium could be used to produce MOX fuel.

Risks of nuclear terrorism

MOX is the acronym of Mixed OXide fuel, nuclear fuel with plutonium instead of U-235. MOX fuel is relatively low in radioactivity and can be handled without specialized equipment. A terrorist group would have little difficulty in making a crude atomic bomb from MOX fuel. Separating uranium dioxide and plutonium dioxide from MOX fuel can be done using straightforward chemistry. Converting the plutonium dioxide into plutonium metal, and assembling the metal together with conventional explosives to produce a crude nuclear explosive does not require materials from special suppliers. The information required to carry out these operations is available in the open literature (Barnaby 2005a, Barnaby 2005b). Technology needed to make nuclear bombs from fissile material is available outside of the established nuclear-armed countries and in the open literature, as proven in 'Nth Country Experiment' (Frank 1967, Schneider 2007).
The authors of MIT 2003 considered the proliferation and safety risks of reprocessing and the use of mixed-oxide (MOX) fuel unjustified. But there are also economic reasons not to recycle in their view.
Studies by the Oxford Research Group show that MOX fuel poses a large and underrated terrorist risk (Barnaby 2005a, 2005b, Barnaby & Kemp 2007). The 6 kg of plutonium contained in the Nagasaki bomb would fit in a soft drink can.

Nuclear weapons can be made from reactor-grade plutonium, as pointed out above, although those made using weapon-grade plutonium are more effective. The USA and UK exploded devices based on reactor-grade plutonium in 1956 and in the 1960s. A good nuclear weapons designer could construct a nuclear weapon from 4-5 kg of reactor-grade plutonium. Less reliability or a less predictable explosive yield than a military weapon would not be a problem for a terrorist group planning an attack in the center of a large town. This is the reason why so many scientists all over the world are strongly opposing the reprocessing of spent fuel and the use of MOX fuel in civilian reactors.

Fast reactors

The nuclear industry uses the term 'fast reactor' in reference to the breeder system, a system that would generate (breed) more fissile nuclei from uranium than consumed in the fission process, by conversion of the non-fissile uranium-238 nuclei into fissile plutonium nuclei. During the 1980s and 1990s this type of reactor was usually called a 'breeder' or 'fast breeder reactor' (FBR) but this term has disappeared from the publications of the IAEA and the nuclear industry, presumably because of the failure to put the concept in practice. The prefix 'fast' refers to the fact that this type of reactor operates with fast neutrons, contrary to the currently operating commercial reactors, in which fission occurs by thermal (slow) neutrons. Now the breeder concept is part of the so-called Generation IV program. This program also includes other types of fast reactors without a breeding capacity that are not discussed here.

The nuclear industry promised (and is still promising) that a closed-cycle reactor system (breeder) could fission 100 times more nuclei present in natural uranium, and consequently generate 100 times more energy from 1 kg uranium, than the conventional once-through system based on light-water reactors (LWRs). France ('*tout électrique, tout nucléaire*') and the UK ('*too cheap to meter*') embarked at the time on the materialization of the breeder concept, expecting that this could make their energy supply largely independent of fossil fuels. These promises ignored the thermodynamic aspects of the breeder.

The MIT 2003 study *The Future of Nuclear Power*, does not expect breeders (in effect the breeder cycle) to come into operation before 2040-2050. 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. The IAEA (Omoto 2007) does not expect the first fast reactor or breeder of Generation IV to come on line before 2040.

What is called a 'fast reactor' (breeder, FBR) is not just a reactor but a cyclic system consisting of a fast-neutron nuclear reactor plus reprocessing plant plus fuel fabrication plant. Each of the three components of the breeding cycle would have to operate flawlessly and finely tuned to each other for decades without interruption. If one component fails in any respect, the whole system fails and breeding is out of question. Operation of the cyclic system is further complicated by the high radioactivity of the materials to be processed, increasing with each following cycle.
Decades of intensive research in several countries (e.g. USA, UK, France, Germany, the former Soviet Union) and investments of some $100bn, have proved that the breeding cycle is technically unfeasible.

The causes of this failure have nothing to do with arguments like: 'not economically attractive' (obviously a technically unfeasible system is not economically attractive) nor with protests of environmental activists. The failure of materialization of the breeder concept can be traced back to fundamental laws of nature, particularly the Second Law of thermodynamics. From this law it follows, among other consequences, that separation processes of mixtures of different substances never go to completion and consequently perfect materials are not possible. From the Second Law it also follows that the deterioration of materials by ageing processes are inevitable. Pivotal in the breeder cycle is the reprocessing of the spent fuel as soon as possible after unloading from the reactor.

Thorium

Thorium is a radioactive metal, more abundant in the Earth's crust than uranium. The concept of the thorium reactor is based on the conversion by neutron capture of non-fissile thorium-232 into uranium-233, which is as fissile as plutonium-239. In common with the uranium-plutonium breeder the thorium-uranium breeder is not just an advanced reactor, it is an intricate cyclic system of reactor, reprocessing plant and fuel element fabrication plant. Each of the three components of the cycle has to operate flawlessly for decades, finely tuned to the two other components.
The feasibility of the thorium breeder system is even more remote than that of the U-Pu breeder. After four decades of research there are still no solutions for the basic problems mentioned by ORNL-5388 1978. The fundamental obstacles that render the U-Pu breeder technically unfeasible apply also to the thorium breeder.

Another drawback of the thorium cycle is that a thorium reactor cannot sustain a fission process in combination with breeding uranium-233 from thorium-232, but will always need an external accelerator-driven neutron source, or the addition of extra fissile material, such as plutonium or uranium-235 from conventional reactors.

Conclusion

Implicitly the various breeder concepts are based on a few basic assumptions. *Conditio sine qua non* is the availability of:

- perfect materials
- fail-safe and fool-proof technical systems with perfectly predictable properties across decades
- perfect separation of strongly radioactive, complex mixtures of numerous different chemical species into 100% pure fractions.

Not one of these conditions is possible, as a consequence of the Second Law of thermodynamics, and for that reason the breeder concept is inherently unfeasible.
As a consequence the nuclear generating capacity in the future will completely rely on the conventional technology of thermal-neutron reactors in the once-through mode.

4 Uranium supply

The present global nuclear fleet operates in the once-through mode and uses natural uranium as its primary energy source.
Chapter 3 addressed these advanced nuclear power concepts and concluded, based on the Second Law of thermodynamics, that they would not work as promised: they are technically unfeasible. From this observation it follows that in all scenarios the projected nuclear generating capacity in the future has to be based exclusively on the current conventional reactor technology and natural uranium as primary energy source.

Conventional uranium resources

The mining industry usually distinguishes between conventional and unconventional uranium resources. Conventional resources are defined as resources from which uranium is recoverable as a primary product, a co-product or an important by-product. The uranium resources that are currently being mined are conventional resources and have generally higher uranium contents than the unconventional resources, that are addressed in the next section.

Table 4
Identified (conventional) uranium resources: reasonably assured resources (RAR) + inferred resources (IR) as of 1 January 2013 (rounded). Tg = teragram = 10^{12} gram = million metric tonnes. Source: Red Book, 2014.
The highest cost category includes the lower ones. On 14 September 2015 the uranium price was about USD 82/kg U (€ 73/kgU) according to www.uxc.com.

RAR + IR cost category	resources Tg
< USD 260/kg U	7.6
< USD 130/kgU	5.9
< USD 80/kgU	2.0
< USD 40/kgU	0.7

Uranium resources are classified by a scheme based on geologic certainty and costs of production. Identified resources include reasonably assured resources (RAR) and inferred resources (IR); the latter are defined with less confidence in estimates of grade and tonnage than the reasonably assured resources. Other resource categories, identified with even less confidence than inferred resources, are not included in the figures of Table 4.

How long could the currently known uranium resources feed the global nuclear fleet under the various scenarios? In 2014 the global nuclear fleet of about 333 GWe operating NPPs (376 GWe operable according to the IAEA) had an annual usage of natural uranium of 66 Gg/year, according to WNA-worldU 2015.
In scenarios 3 and 4 the currently known resources would be depleted within the operational lifetime of new nuclear builds, a situation worsening in the WNA scenarios.
Major new uranium resources must be found to make scenario 3-6 possible. We return to this issue in one of the following sections.

Table 5

Summary of the total uranium demand in the seven scenarios until the year 2100 in variant 1: phase-out of scenarios 1-4. The figures are based on the assumption that all reactors are LWRs in the once-through mode, without plutonium recycle.

scenario		required uranium Tg	mitigation share %	
			2050-2060	2100
0	phase-out	1.5	0	0
1	constant capacity, including phase-out *	4.0	0.5 - 0.3	0
2	constant mitigation share (growth 2.0%), including phase-out *	6.8	1.0 - 0.6	0
3	constant mitigation share (growth 3.5%), including phase-out *	10.5	1.7 - 1.0	0
4	IAEA high, including phase-out *	9.3	1.4 - 0.9	0
5	WNA-low	19.3	1.4 - 0.7	1.1 - 0.3
6	WNA-high	75.9	4.5 - 2.4	6.2 - 1.8

* Phase-out after 2050 in scenarios 1-4 added by author, for explanation see text and Figure 8. The WNA scenarios are not changed.

Unconventional uranium resources

Unconventional resources are resources from which uranium is only recoverable as a minor by-product, they are usually not mined. In unconventional resources uranium is associated with phosphate rocks, non-ferrous ores (e.g. ores of rare earth elements), carbonatites, black shales and lignite. Seawater is also considered a potential uranium resource.

According to Red Book 2014 the uranium content of the known global phosphate rock resources is estimated at 7.0-7.3 Tg uranium. The content of other unconventional resources (non-ferrous ores, carbonatites, black shales and lignite) combined is estimated at some 1 Tg, amounting to a total of 7.3-8.4 Tg U. Due to their low uranium content and other factors the recovery of uranium from these resources will require more useful energy than can be generated from the recovered uranium. Consequently these uranium resources are not energy resources, in Chapter 5 we return to this issue.

Black shales and lignite

The above figures include Ranstad shales (Sweden), but do not include the estimated uranium resources associated with the Chattanooga shales (USA) and Ronneburg shales (Germany) with a combined content of about 4-5 Tg U. Black shales are a huge geologic reservoir of uranium, according to Deffeyes & MacGregor, at grades typically ranging between 30-100 ppm. A few small deposits have higher grades, but are not globally significant.

The Chattanooga shales for example contain 4-5 Tg uranium at an average grade of 57 ppm U (IAEA 2001), To provide one NPP of the newest design with natural uranium for one year, 5-10 Tg shales would have to be mined and chemically processed each year. A coal-fired power station consumes about 2 Tg of coal to generate the same amount of electricity. To feed the current world nuclear fleet some 560 km² of the Chattanooga shales would have to be mined and processed annually, an area of 24x24 km.

Phosphate rocks

The largest phosphate deposits of the world are in Morocco (55% of the world's resources) and have a uranium content varying from 70-230 ppm (Bergeret 1979), with a geometric mean of 127 ppm. Nearly all

other known deposits contain less than 180 ppm uranium, most of them around 100 ppm or less (0.01% or less), although some small deposits might have a higher uranium content
The phosphate rock processing rate required to meet the current world uranium demand would be 10-20 times the rate necessary to meet the agricultural demand for phosphate. One of the deleterious effects of a fast exploitation of phosphate resources for uranium recovery is the fast degradation of the quality of the remaining phosphate resources. The richest and cleanest ores are always recovered first, so the ores with lower grades and more contaminants remain. This would result in fertilizers contaminated with more toxic and radioactive elements and a higher specific energy consumption per unit product.

Phosphate rock is the source of an essential agricultural fertilizer. There are no substitutes for phosphorus in agriculture. So the exploitation of phosphate rock should be tailored exclusively to the agricultural needs and to the demand for food production.

Seawater

Technically it is possible to extract uranium from seawater. The first stage of the extraction process is the adsorption of the complex uranium ions dissolved in seawater on solid adsorption beds. The extremely low concentration of uranium and the relatively high concentrations of a great number of other dissolved chemical species in seawater have important consequences for the technical system that would be needed to recover uranium from seawater on a scale significant for nuclear energy generation.

To provide one nuclear power plant of 1 GWe with uranium, 285 km^3 seawater per year per would have to be processed, or 9000 m^3 per second. This is about 3-4 times the outflow of the river Rhine into the North Sea. To fuel the current global nuclear fleet a volume of about 95000 km^3 seawater per year would have to be processed, or 3.0 million m^3 per second.

The mixing entropy of uranium ions in seawater is extremely high, due to the very low concentration of uranium ions and the relatively high concentrations of a large number of other dissolved species, such as sodium, magnesium, sulphate and chloride ions. To separate uranium from all other chemical species in seawater, in the exceedingly pure form needed for nuclear fuel, large quantities of work (high-quality useful energy) and processed materials are needed.
The work needed to get uranium dissolved in seawater into the purified state required for nuclear fuel has a thermodynamic minimum, that cannot be circumvented by advanced technical means. In practice the thermodynamic minimum work can only be approached but never reached. The separation work of the recovery of one kilogram of uranium from seawater will be higher than the useful energy which can be generated from the extracted kg uranium.

Conclusion

Thermodynamic assessment of the unconventional resources proves that these resources cannot be an energy source when used in reactors of current technology that operate in the once-through mode.

Economics and uranium resources

WNA and the IAEA are approaching the matter of uranium resources from an economic viewpoint in which the production costs are paramount as is evident from the quote from IAEA-ccnap 2014:

> "Including nuclear power in the energy mix can help alleviate these concerns because ample uranium resources are available from reliable sources spread all over the world and the cost of uranium is only a small fraction of the total cost of nuclear electricity."

And from WNA-75 2015:

> "The price of a mineral commodity also directly determines the amount of known resources which are economically extractable. On the basis of analogies with other metal minerals, a doubling of price from present levels could be expected to create about a tenfold increase in measured economic resources, over time, due both to increased exploration and the reclassification of resources regarding what is economically recoverable."

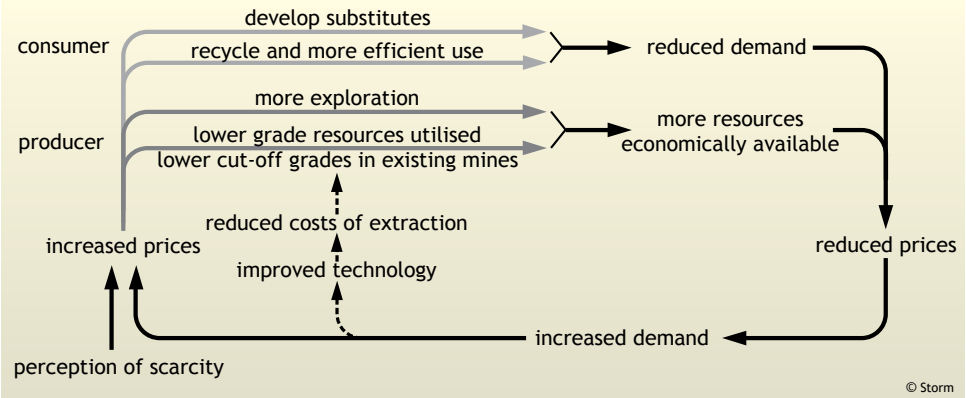


Figure 13
Economic model of the availability of mineral resources at large, according to WNA-75 2015 [Q85].

The production costs of the uranium are related to physical variables, such as the ore grade, ore body size and depth, mineralogy, transport distances (see e.g. Brinck 1975 [Q55]); non-physical factors may also contribute to the costs, such as economic and political factors.

The nuclear industry expects new large uranium resources will be discovered when exploration is intensified, see for example WNA-75 2015, Wikdahl 2004, MacDonald 2001 and MacDonald 2003. According to a common view within the mining industry more exploration will yield more known resources, and at higher prices more and larger resources of a mineral commodity become economically recoverable. In this model, as illustrated by Figure 13, mineral resources are virtually inexhaustable.

Despite more exploration during the last 2-3 decades few to no large new discoveries have been reported. The main part of the increase of known uranium resources results from reclassification of known occurrences. The only external input of the cyclic model presented in Figure 13 seems to be 'perception of scarcity'. What does that mean? Perception is a vague and subjective notion. Development of improved technology is seen as being spurred by higher demand, but may be considered also as an external input. In the case of uranium as a mineral commodity WNA has refined the model according to Figure 14.

Generally the demand of a mineral commodity can be reduced by developing substitutes, recycling and more efficient use of the mineral. In the case of uranium, as indicated in the diagram of Figure 14, WNA-75 2015 factors into their calculations, as viable options:

- Reprocessing of spent fuel and recycling of uranium and plutonium in light-water reactors (LWRs).
- More efficient use of uranium by implementation of 'fast reactors' (breeder reactors) that would be able to fission 50 times more nuclei from natural uranium than the current generation of reactors (mainly LWRs).
- Development of reactors that use thorium as fertile material to breed fissile uranium-233. Theoretically thorium could substitute for uranium as input for nuclear power, according to the nuclear industry.

These issues, and their shortcomings, have been addressed in Chapter 3.

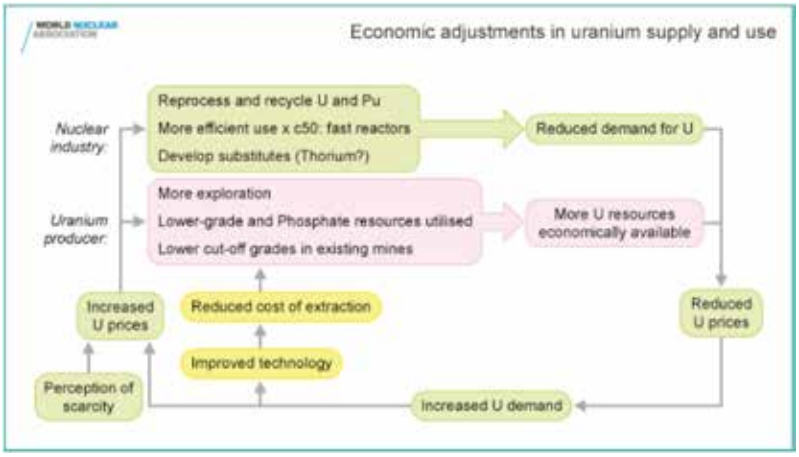


Figure 14
Refined economic model predicting the availability of uranium resources, source: WNA-75 2015.

Physical aspects

Strikingly no conserved physical quantities are included in the model. In effect the diagram is based on non-physical notions, which are not unambiguously quantifiable. Physical factors, especially the energy input and CO_2 emission per unit product, are absent from this model. Lower grades of the processed ores imply more rock has to be mined and processed resulting in a higher specific energy consumption and consequently higher CO_2 emission per kg recovered uranium.

Notable is the view of the nuclear industry concerning the report of the Club of Rome *Limits to Growth* as is evident from the following quote from WNA-75 2015:

> From time to time concerns are raised that the known resources might be insufficient when judged as a multiple of present rate of use. But this is the Limits to Growth fallacy, a major intellectual blunder recycled from the 1970s, which takes no account of the very limited nature of the knowledge we have at any time of what is actually in the Earth's crust. Our knowledge of geology is such that we can be confident that identified resources of metal minerals are a small fraction of what is there. Factors affecting the supply of resources are discussed further and illustrated in the Appendix.

Obviously the WNA does not understand the basic message of the report, but adheres to a persistent misunderstanding. *Limits to Growth* does not predict the depletion of mineral resources within a certain period, it describes the basic physical mechanisms which are active with respect to growth phenomena within a physically finite system, albeit ecosystems or the human economic system. The biosphere is a physically finite system: at one side limited by empty space, at the other end limited by the accessible part of the lithosphere containing minerals; other limiting parameters are, for example, the area of arable land and the capacity of the atmosphere and fresh water reservoirs to absorb pollutants and harmful materials. Some limits are quantitative, other qualitative, for instance the acceptable amounts of GHGs in the atmosphere. The mechanisms described in *Limits to Growth* concern phenomena like exponential growth with positive or negative feedback and overshoot and collapse of systems. These basic natural mechanisms do not depend on our knowledge of them, as WNA seems to suggest, they will be active anyway. Lack of knowledge may, however, cause surprise due to 'unexpected' and adverse consequences.

A finite system inevitably has its limits, although they may seem very remote from a purely quantitative viewpoint. The earth's crust and the oceans contain almost limitless amounts of minerals, including uranium. However, there are other limits, set by the fundamental laws of nature, especially the Second Law of thermodynamics.

Thermodynamic boundaries

There is one crucial difference between mineral resources at large and uranium resources in particular: uranium is almost exclusively used as an energy source, contrary to all other mined metals. A simple conclusion from this observation is that a given uranium occurrence in the Earth's crust can only be considered as an energy source if the extraction of one mass unit of uranium from that occurrence consumes considerably less useful energy than can be generated from that same mass unit of uranium by means of the complete nuclear energy system.

The above criterion, which can be quantified by an energy analysis of the complete nuclear energy system, sets clear thermodynamic boundaries to the uranium resources that fit the uranium-for-energy conditions. By application of more advanced technology it may be possible to approach the thermodynamic minimum a bit more closely, and so enlarge somewhat the size of the uranium resources that can be considered energy sources, but the thermodynamic limit can never been surpassed.
The same reasoning holds true for fossil fuels. If, for instance, the extraction of oil from a given tar sand deposit, plus its transport and refining takes as much or more energy than can by generated by burning the oil, the tar sand occurrence in question is not an energy source anymore, but an energy sink.
In the economic models no system boundaries are defined.

The feasibility of the nuclear scenarios described in Chapter 2 depends on the quantity of uranium resources at a quality higher than a certain thermodynamic minimum. We return to this issue in Chapter 5.

5 Nuclear power and thermodynamics

Why a thermodynamic analysis?

Arguments based on the free-market paradigm are not well suited to assess the implications of nuclear power in a global perspective with a long time horizon. Only a method based on unambiguously defined quantities, which do not depend on political and economic viewpoints, is appropriate.
Answers to questions regarding nuclear security, energy security, public health safety and climate security (CO_2 emissions) of nuclear power can be found only by means of a complete life-cycle assessment (LCA), covering the full cradle-to-grave period, and a thermodynamic analyis of the complete nuclear process chain. It is essential that all material and energy flows involved in applied nuclear technology are analyzed and accounted for in energy balances. Materials and construction required in the process chain must be represented in the energy balance based on the amount of energy consumed by their production from raw materials as found in nature. In this way it will be possible to express the material and energy inputs and outputs of a technical system in one unit of one unambiguous quantity: energy unit joule (J).
These balances should include the investments in future processes that are directly coupled to the present-day operation of nuclear power plants. Energy is a conserved quantity, so unambiguous comparison of the benefits and drawbacks of different energy technologies is only possible by means of energy analyses of the involved energy systems, each spanning their full cradle to grave period. Balances in monetary units depend on economic notions involving a number of assumptions that vary with time and location.

Energy costs energy

What we call 'energy' in everyday life is energy that can be used at will to perform energy services, such as transport, lighting, chemical syntheses, etcetera. Examples of useful energy are electricity, mechanical energy and process heat. Generation of useful energy from mineral energy resources (fossil fuels, uranium) involves the conversion of the potental energy embodied in these mineral resources into a usable form. This conversion is the only possible by means of a chain of industrial processes, e.g. extraction from the earth's crust, transport, refining and conversion. Each of these processes require investments of energy, in practice fossil fuels and electricity, and processed materials, such as chemicals, construction materials and machines. This holds true also for generation of useful energy from renewable energy sources, e.g. solar power, wind and hydropower. So *energy costs energy*.

Procedures are also usually needed to reduce adverse effects to the environment in the use of a mineral energy resource. The complete chain of processes of sound utilization of a mineral energy source has three main parts, comparable with an every-day household chain of activities:

collecting ingredients + cooking a meal —› enjoying the meal —› washing the dishes + clearing the mess

Conversion of the potential energy in uranium into electricity requires an intricate system of industrial processes, actually the most complex energy system ever designed. Assessment of the CO_2 emission of nuclear power must include the complete system of processes needed to generate electricity from uranium and safely manage the radioactive wastes, not just the nuclear reactor. The figures of the nuclear specific CO_2 emission presented in this study are the result of an assessment of the complete nuclear process chain, from cradle to grave, from recovery of the first kg of uranium from the Earth's crust through final storage in a geologic repository of the last kg of radioactive waste. Estimates of the nuclear cradle-to-grave period vary from 100-150 years.

Nuclear process chain

As stated above a nuclear power plant is not a stand-alone system, it is just the most visible component, the midpoint of a sequence of industrial processes which are indispensable to keep the nuclear power plant operating and to manage the waste in a safe way, processes that are exclusively related to nuclear power. This sequence of industrial activities is here called the 'nuclear process chain' for it includes also industrial activities not directly related to the processing of nuclear fuel. The term 'nuclear fuel chain' may suggest that only activities directly related to the processing of nuclear fuel are included in the observed system.
The nuclear process chain as a whole includes important activities such as construction of the nuclear power plant, decommissioning and dismantling of the NPP and sequestration of all radioactive wastes into a geologic repository

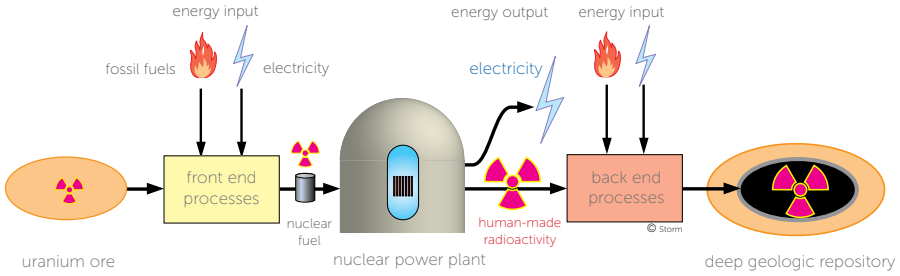


Figure 15
Simple outline of the nuclear process chain, also called the nuclear energy system, as it ought to be. The three main parts are the front end processes (from ore to nuclear fuel), the powerplant itself (construction, operation, maintenance & refurbishments during its operational lifetime) and the back end processes (safe and definitive sequestration of all radioactive wastes).

Like any industrial production system the nuclear chain is comprised of three sections: the front end processes, the production process itself and the back end processes.

- The front end of the nuclear chain includes the processes to produce nuclear fuel from uranium ore and are mature industrial processes.
- The midsection encompasses the construction of the nuclear power plant plus operating, maintaining and refurbishing it.
- The back end comprises the processes needed to handle the radioactive waste, including dismantling of the radioactive parts of the power plant after final shutdown, and to isolate the radioactive waste permanently from the human environment.

A flowsheet of the full nuclear process chain as it ought to be is presented in Figure 16, a working out of the simple outline in Figure 15. As Figure 16 shows, the back end comprises a larger number of industrial processes than the front end. In fact the nuclear system has a much more extensive back end than any other energy system.

Back end of the nuclear process chain as it ought to be carried out

Contrary to the front end processes, which involve mature technology and are fully operational, most back end processes still exist only on paper, despite reassuring publications of the nuclear industry. This study starts from the idea that all radioactive wastes generated by nuclear power would have to be isolated from the human environment forever. In Chapter 6 we return to this issue.

Notably the following activities of the back end of the nuclear process chain will be demanding tasks:

- dismantling and site cleanup of nuclear power plants
- dismantling and site cleanup of reprocessing plants
- durable packaging of spent fuel
- rendering the inventories of plutonium, uranium-233, neptunium and americium unusable for nuclear explosives and packaging the resulting chemically stable product in durable containers for final disposal in a geologic repository
- cleanup of temporary waste storage facilities, including spent fuel cooling pools and spent fuel dry storage
- reconversion of all depleted uranium, presently stored as UF_6 in leaking vessels, into uranium oxide for permanent disposal
- durable packaging of all radioactive wastes, including depleted uranium, reprocessing waste and dismantling waste; spent fuel would be packaged separately, after decades of cooling
- construction of the required geologic repositories, sequestration of spent fuel canisters will require separately designed and constructed repositories
- definitive storage of all radioactive waste in geologic repositories and filling the remaining volumes of the galleries and access tunnels of the repositories with a bentonite-sand mixture.
- remediation of uranium mining areas after depletion of the ore deposits.

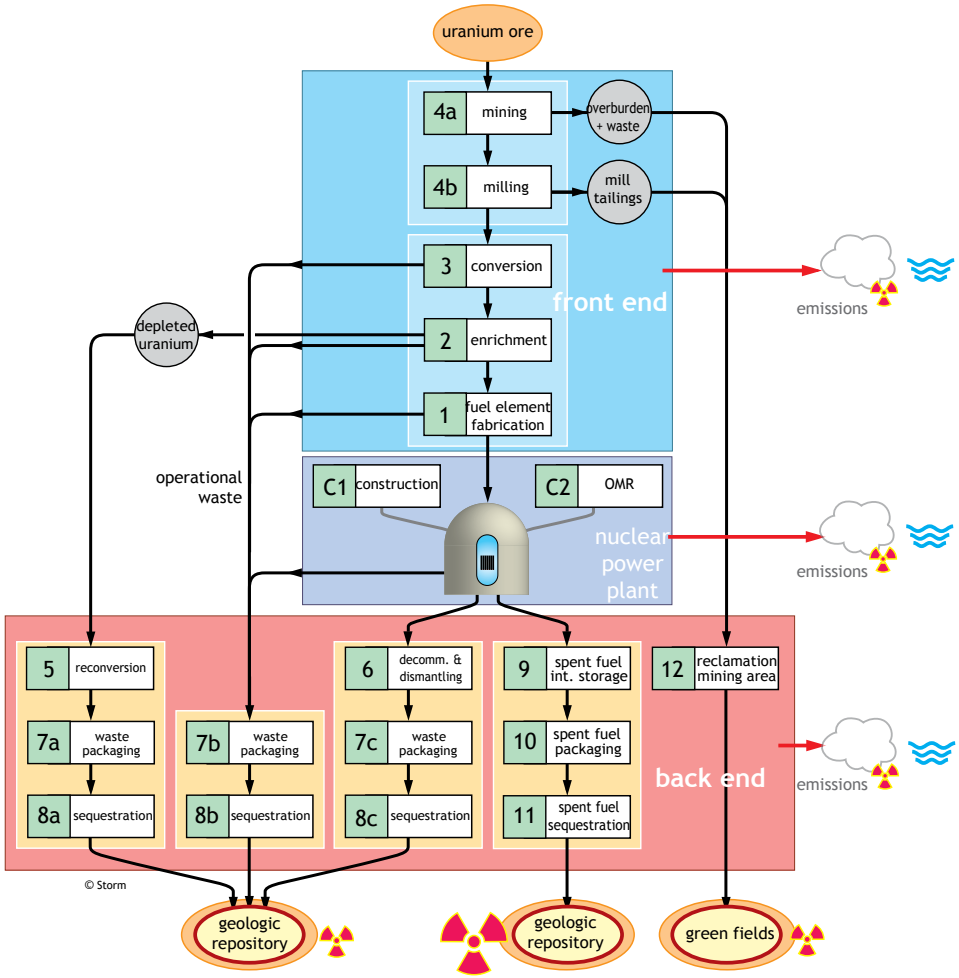


Figure 16

Full process chain of a light-water reactor (LWR) nuclear power plant in the once-through mode from cradle to grave. The black arrows represent flows of radioactive materials. Calculations in this study are based on this full chain. In the back end of the nuclear chain only processes 7b and 9 are operational in the present practice.

The above mentioned activities are included in the flowsheet in Figure 16, except dismantling of reprocessing plants, because reprocessing is not part of the reference nuclear system of this study. Only a few processes of the back end are operational. In the thermodymanic analysis of this study all processes indicated in Figure 16 are included as if they were operational. Each of the industrial processes of the nuclear process chain consumes useful energy (fossil fuels and electricity) and materials. The input of construction materials and chemicals represents an indirect energy input: the embodied energy is the energy needed to produce the materials from raw materials.

Materials consumed by the nuclear energy system

All materials entering the nuclear energy system are extracted from the environment and all materials leaving the nuclear system will end up in that same environment sooner or later. During operation the nuclear system generates tremendous amounts of radioactivity: a billionfold the radioactivity of the fresh nuclear fuel which is placed into the reactor. The human-made radioactivity is mainly contained in the spent fuel elements, but a part of it leaves the nuclear system dispersed over large volumes of construction materials as a consequence of neutron irradiation and contamination with radionuclides. In addition to the generation of human-made radioactivity the nuclear system mobilises vast amounts of natural radionuclides from the uranium ore. During operation and thereafter the nuclear system discharges radioactive and non-radioactive wastes into the environment.

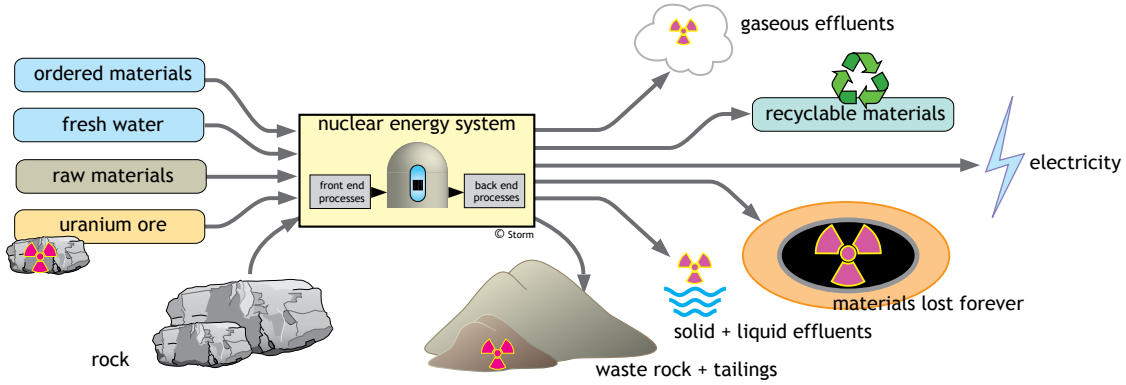


Figure 17

Outline of the flows of materials of the complete nuclear energy system as it should be, from cradle to grave. All radioactive materials are assumed to be sequestered definitively in geologic repositories, except the intentional discharges (including the complete fresh water input) and unintentional discharges (leaks, accidents) into the environment. In the current practice all radioactive waste is still present in mobile condition within the human environment.

The material flows leaving the nuclear system and entering the human environment can be divided into the following categories:

- recyclable construction materials
- discharges of radioactive and non-radioactive materials into the human environment, intentionally and unintentionally
- water, most of it contaminated with toxic chemicals, radioactive and non-radioactive
- materials lost forever, due to radioactivity
- waste rock

The recovery of raw materials and the production of processed materials (chemicals, construction materials) consume useful energy, fossil fuels and electricity, and consequently are accompanied by CO_2 emissions.

Figure 18 below represents the material balances of nuclear power and wind power. Not included in both material balances are:

- materials required for mining and processing of the construction materials
- materials for the distribution grid
- materials for maintenance and refurbishments of the systems.

Comparison of nuclear power with renewable and fossil power is only scientifically sound if all systems are assessed from cradle to grave.

Looking at the large amounts of materials passing through the nuclear system it is inconceivable that the nuclear system would emit less CO_2 than wind power and no other greenhouse gases, as asserted by the nuclear industry.

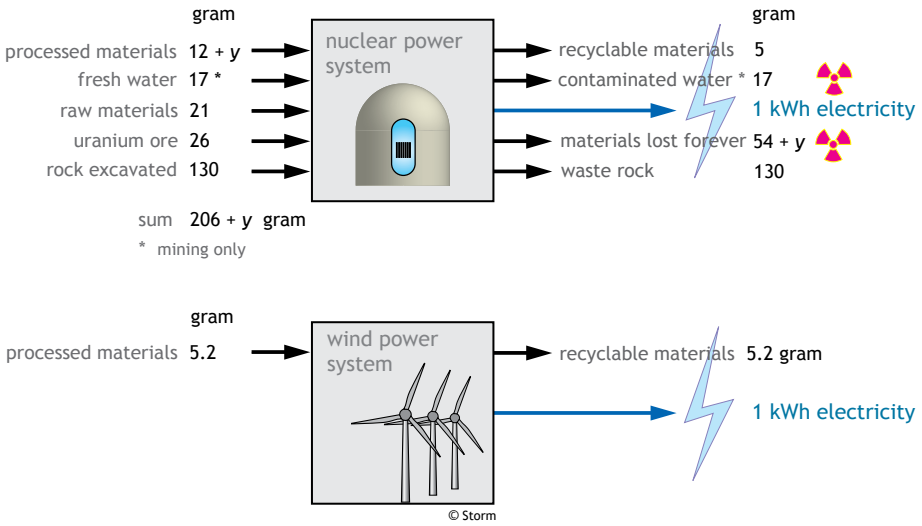


Figure 18

Material balances of a generic nuclear energy system and an offshore wind farm of current operational technology. Both systems are assessed from cradle to grave. The uranium ore has an assumed grade of 0.1% U. The input of processed materials of the nuclear system is indicated by 12 + *y* gram/kWh, because the input is larger than 12 with an unknown amount *y*.

Origin of the nuclear CO_2 emission

Each process of the nuclear chain consumes thermal energy, provided by fossil fuels, and electricity: the direct energy input. In addition all processes consume materials, the production of which also consumed thermal energy and electricity: the embodied (indirect) energy input. By means of an energy analysis the direct and indirect energy inputs of the full nuclear system from cradle to grave can be quantified.
Though operational data on the back end processes are rarely available, because most of them exist only on paper, energy inputs, material consumption and CO_2 emission of the non-operational processes can be reliably estimated by analogy with existing conventional industrial processes. Completion of the back end does not need advanced technology, it is just a matter of getting started, the necessary technology is waiting on the shelf.

The CO_2 emission of the nuclear system originates from burning fossil fuels to provide the direct and indirect thermal energy inputs of the system, and from chemical reactions (e.g. the production of cement and steel). In this study the electrical energy inputs of the nuclear system are assumed to be provided by the nuclear system itself. By this convention the results of the energy analysis become independent of place, time,

local conditions such as fuel mix of fossil-fueled electricity generation. In practice this convention would imply a steady state, in which the number of NPPs coming online would equal the number of NPPs being decommissioned. The operating plants would provide the electrical energy inputs needed for construction of new plants and for decommissioning of the closed-down plants. It should be emphasized that this steady-state model is hypothetical, because no commercial NPP has ever been dismantled completely.
By this convention the energy analysis of this study deviates from analyses of other energy systems, such as wind power and solar photovoltaics, in which the CO_2 emission associated with the generation from fossil fuels of the electricity consumed for construction is included in the total specific GHG emissions.

Energy analysis

Future nuclear generating capacity will completely rely on the present technology of thermal-neutron reactors in the once-through mode, because advanced nuclear systems, closed-cycle or semi-closed cycle, are not feasible, as explained in Chapter 3.

An important indicator of the effectiveness of a nuclear power plant is its lifetime electricity production. This analysis measures the operational lifetime of a NPP in full-power years. A full-power year (FPY) is the period in which a nuclear power plant generates an amount of electricity equal to the production during one year of operation at full power with no interruptions. Expressing the operational lifetime in the unit FPY avoids discussion about load factors and lifetimes in calender years. In case of the reference reactor with a nominal power of 1 GWe 1 FPY corresponds with 1 GW•year, or 31.54 PJ (petajoule).

The analysis has been done for three operational lifetimes: 25, 30 and 34 FPY. The reference reactor is a pressurised light water reactor (PWR) with a capacity of 1 GWe and corresponds to the newest currently operating LWRs. The average operational lifetime of the global nuclear fleet in 2014 was about 22 FPY, a figure that has barely increased during the past years, so the baseline scenario of 25 FPY is slightly optimistic. The higher figures promised by the nuclear industry seem unlikely in view of the evidenceof the past. Some individual NPPs may achieve operational lifetimes higher than 25 FPY, but others are, and will be, closed down after much lower performances. Climate change and CO_2 emissions are a global issue, so figures averaged from world-wide production should be used. For that reason only the baseline case is presented here.

This energy analysis quantifies all direct and indirect inputs of materials and energy (electricity and thermal energy by fossil fuels) to make the functioning of all indispensable processes of the nuclear chain possible. The contributions to the total energy input and consequently the CO_2 emission of the nuclear process chain can be divided into three groups:

- Lifetime fixed inputs. The input of materials and energy for construction of the NPP has a fixed value and does not depend on the lifetime of the plant. The input for decommissioning and dismantling of the NPP probably increases slightly with its lifetime, due to increasing radioactivity of the reactor, associated installations and surrounding constructions, but is assumed to have a fixed value after a few years of operation of the NPP. The contribution to the specific energy input and CO_2 emission per kilowatt-hour delivered electricity depends on the operational lifetime (number of FPYs) of the nuclear system.
- Constant inputs. Most processes of the nuclear chain have constant inputs of materials and energy per full-power year, so their contributions to the specific energy input and CO_2 emission per kilowatt-hour delivered electricity do not depend on the operational lifetime of the nuclear system.
- Ore-dependent inputs. The specific energy inputs and CO_2 emission of uranium recovery (mining and milling) and rehabilitation of the uranium mine after depletion depend on the thermodynamic quality of the uranium ore. This notion will be explained in the next section.

Results

The energy analysis of the reference nuclear power station, representative of the newest currently operating NPPs, from cradle to grave with a lifetime productivity of 25 FPY makes it possible to estimate the specific CO_2 emission of the nuclear energy system; the results are summarised in Table 6 in case of uranium ore at a grade of 0.05% U (0.5 gram uranium per kg ore).
The figures for construction and dismantling have an uncertainty spread of ±50%, causing the uncertainty range of the total figure to be: 88-146 gCO_2/kWh.

Table 6
Specific CO_2 emission of the reference nuclear energy system in the baseline scenario. Uranium from soft ores at a grade of 0.05% U, about the current global average.

	main components of the nuclear process chain	specific emission g CO_2/kWh baseline operational lifetime
1	uranium recovery (mining + milling) , (ore grade dependent)	8.41
2	other front end processes	6.23
3	construction (mean)	23.2
4	operation, maintenance & refurbishments OMR	24.4
5	constant back end processes	12.08
6	decommissioning & dismantling (mean)	34.8
7	mine rehabilitation (ore grade dependent)	7.57
	sum (mean)	117

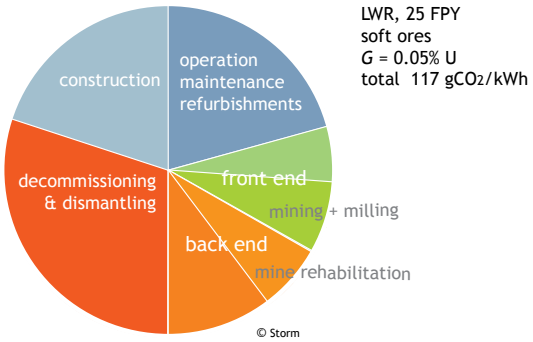


Figure 19
Contributions to the cradle-to-grave (c2g) CO_2 emission of the nuclear energy system based on the reference LWR in baseline case (operational lifetime 25 FPY), using soft uranium ores at an ore grade of 0.05% U (about the present world average). The seven main components are represented as in Table 6. The contribution of mining + milling and mine rehabilitation are ore grade dependent.

Figure 19 illustrates the contributions of the seven main components of the nuclear system from cradle to grave CO_2 emission, at an assumed uranium ore grade of 0.05% U and soft ores, about the present global average. Notable features of this diagram, based on Table 6, are for example:

- The back end of the chain including decommissioning and dismantling of the reactor generate nearly as much CO_2 as all the previous components added together. As the back end and decommissioning of all reactors have been passed on to the future up until now, the emissions of these activities have yet to happen and actually are a kind of CO_2 debt.

- The front end processes, excluding uranium recovery, generate only about 10% of the CO_2 emitted by the nuclear system during its operation. Enrichment, usually presented by the nuclear industry as the main energy consumer and CO_2 emitter of the nuclear process chain, turns out to be of minor importance
- The emission contributions of construction and decommissioning are half of the total specific CO_2 emission. The nuclear industry usually omits decommissioning and dismantling from its estimates of costs, energy consumption and specific CO_2 emission, or uses unrealistically low figures.

Thermodynamic quality of uranium resources

Here we define the thermodynamic quality of a uranium resource as the amount of useful energy (direct + indirect energy inputs) to be expended per mass unit pure uranium from that resource. The thermodynamic quality of uranium resources depends on a number of variables, such as:

- ore grade
- size of deposit
- depth of the ore body below the surface
- mineralogy of the uranium occurrence, refractoriness of uranium minerals and host rock
- location of the uranium occurrence: availability of fresh water, climate, transport distances for chemicals, auxiliary materials, equipment and products.

Of these variables the ore grade is usually the most important one and moreover the most easily quantifiable. For this reason this study quantifies the thermodynamic quality of uranium resources as function of the ore grade. A distinction is made between soft ores, from which uranium is relatively easily extractable, and hard ores, with more refractory mineralogy requiring more energy investments per mass unit recovered uranium. The grade dependency is determined by two variables: the dilution factor and the extraction yield.

Dilution factor

The ore grade is defined as the uranium content of the uranium-bearing rock, usually given as mass-% U, or in grams uranium per kg rock. The minimum amount of rock to be mined and milled to obtain 1 kg uranium is inversely proportional to the ore grade. The *dilution factor* is a simple mathematical relationship between ore grade and mass of rock to be processed per recovered mass unit of uranium, and does not depend on recovery technology nor on ore type.

Extraction yield

The *extraction yield*, also called the *recovery factor* or *recovery yield*, is the ratio of the mass of uranium actually extracted and the mass of the uranium present in the processed amount of rock. The recovery yield decreases exponentially with decreasing uranium content; this follows from the Second Law of thermodynamics. The mixing entropy of uranium in a given mixture of other chemical species strongly increases with:

- decreasing concentration of the uranium in the mother matrix, and
- increasing number of other species in the matrix, and
- increasing concentrations of the other species in the matrix.

The higher the mixing entropy of a species the more energy and specialized effort is needed to extract that species from the mixture. Extraction processes are governed by basic physical and chemical laws, which cannot be circumvented by technology. Perfect extraction is impossible: separation processes never go to completion, as follows from the Second Law of thermodynamics.

At ore grades below 0.02% U the extraction yield rapidly declines to very low values, making uranium extraction by means of the current technology practically unfeasible. The yield at low grades can be improved by application of more selective separation processes, however at the expense of higher specific energy requirements and higher CO_2 emission per mass unit recovered uranium.

Mine rehabilitation

Uranium mining is a polluting activity: radioactive dust is blown over vast distances from the immense heaps of mining waste (mill tailings) and large volumes of water contaminated with chemicals and dissolved radioactive materials are discharged into the environment. This study assumes that the mining area will be rehabilitated as well as possible. The energy input and consequently also the specific CO_2 emission depend on the ore grade in accordance with the dilution factor.

Conclusion

The combination of the exponentially rising dilution factor and the exponentially decreasing extraction yield explain why the energy input per kg recovered uranium exponentially rises with decreasing grade of the ore it is extracted from, and in consequence why the specific CO_2 emission of the uranium recovery rises.
Figure 20 represents the specific CO_2 emission of the nuclear system as function of the ore grade. The specific energy input of the system has similar curves.

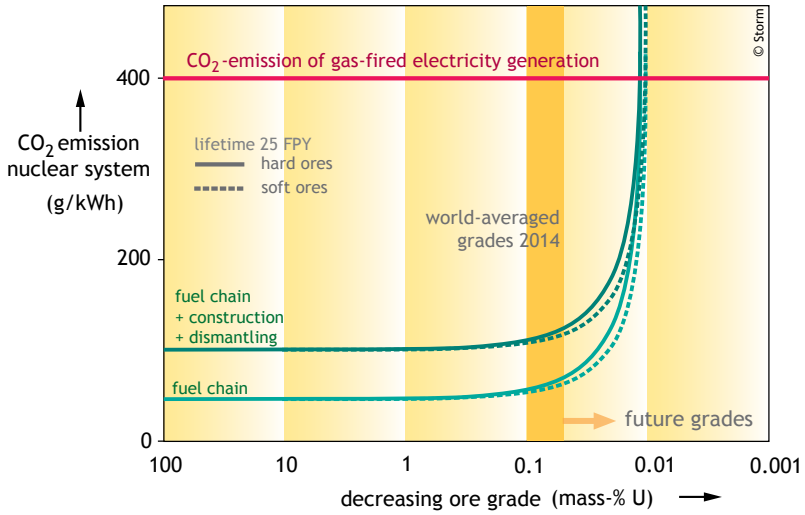


Figure 20

Specific CO_2 emission of the nuclear system (baseline case) as function of the uranium ore grade. At present the world-averaged ore grade is 0.1-0.05% U. The lower curves 'fuel chain' refer to the emission of all processes of the nuclear chain except construction and dismantling (contributions 1, 2, 4, 5 and 7 of Table 6). The higher curves include construction and dismantling. This diagram is called the 'CO_2 trap'. The curves are similar to the curves of the thermal energy inputs of uranium mining and milling + mine rehabilitation as function of the ore grade.

The diagram of Figure 20 shows that the grade at which the nuclear system emits as much CO_2 as fossil fueled generation does not depend appreciably on the choice of the system boundaries of the analysis, including or excluding the emissions of constructing and dismantling, nor on the ore quality (soft or hard ores). At ore grades of 0.02-0.01 mass % U the CO_2 intensity of nuclear power surpasses the CO_2 intensity of fossil-fueled power, eliminating the low-carbon profile of nuclear power.

Coal equivalence

At an ore grade of 0.02% U the annual mass of uranium ore to be mined and processed to fuel one nuclear power plant equals the mass of coal burned in a coal-fired power station to generate the same amount of electricity: the *coal equivalence*.

Energy cliff

Future nuclear generating capacity will rely on the present reactor technology, as explained in Chapter 3. Based on this reactor technology the amount of useful energy extractable from 1 kg natural uranium has a fixed value: roughly 500 GJ/kg natural uranium thermal energy, from which about 170 GJ/kg U electricity can be generated; minor variariations are possible due to different reactor types. The reference reactor of this study, a pressurized water reactor (PWR) corresponding with the newest types of light water reactors (LWRs) in operation, cannot fission more than 0.6% of the nuclei in natural uranium; a higher figure in the future is unlikely.
The energy input of the nuclear system increases exponentially with decreasing thermodynamic quality of the uranium ore. For that reason the net energy delivered by the nuclear system to the economy as a whole decreases with falling ore grades. At a certain grade the energy input of the system equals the energy content of natural uranium as present in the resource being exploited. The use of ores at that critical grade results in a zero net energy production by the nuclear system: the *energy cliff*.

Energy analysis proves that the energy cliff, the ore grade at which the net energy production of the nuclear system falls to zero, only marginally depends on the energy requirements for construction and dismantling. Distinction between soft and hard ores is also hardly relevant, because leaner ores tend to be harder, so the energy cliff is effectively determined by hard ores.
In Figure 21 the energy cliff has been superimposed onto the world known uranium resources graph, as function of the ore grade. This diagram suggests that exploration for new uranium deposits may look worthwhile only at grades higher than 0.03% U, from an energy point of view. Deposits at grades of 0.02 – 0.01%, such as Valencia and Trekkopje in Namibia, have a thermodynamic quality approaching zero.

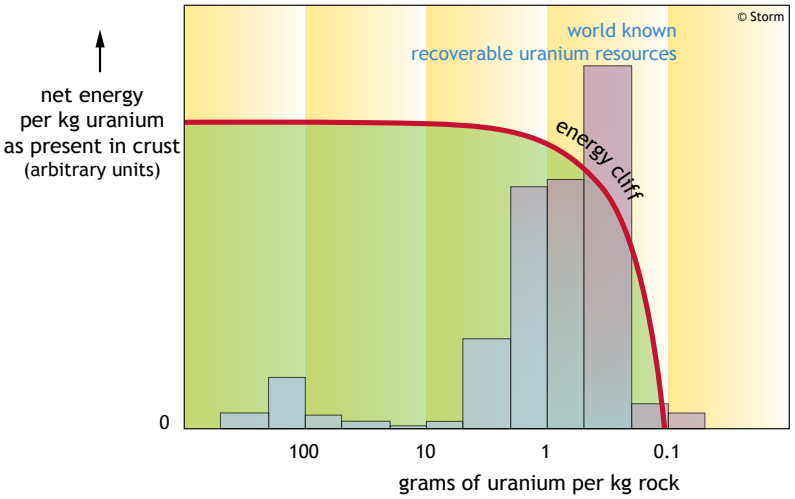


Figure 21
The energy cliff of the nuclear system in relation to the currently known recoverable uranium resources. The ore grade distribution of the known resources in 2014 does not differ significantly from the distribution in 2008, which forms the basis of the bar diagram.

Depletion of uranium resources: a thermodynamic notion

The earth's crust contains enormous amounts of uranium, dispersed in widely different rock types with grades ranging from more than 100 grams of uranium per kilogram rock to less than 1 milligram of uranium per kilogram rock. At grades lower than 0.2-0.1 grams of uranium per kilogram rock no net energy can be generated from a uranium deposit, as pointed out above. Obviously uranium can be extracted from rocks

below the energy cliff, perhaps even economically justifiable under certain conditions, but extraction from those rocks generates an energy sink, not an energy source.
From a quantative viewpoint the uranium occurrences of the world are practically inexhaustable. Actually the depletion of uranium resources as a source of useful energy is a thermodynamic notion.

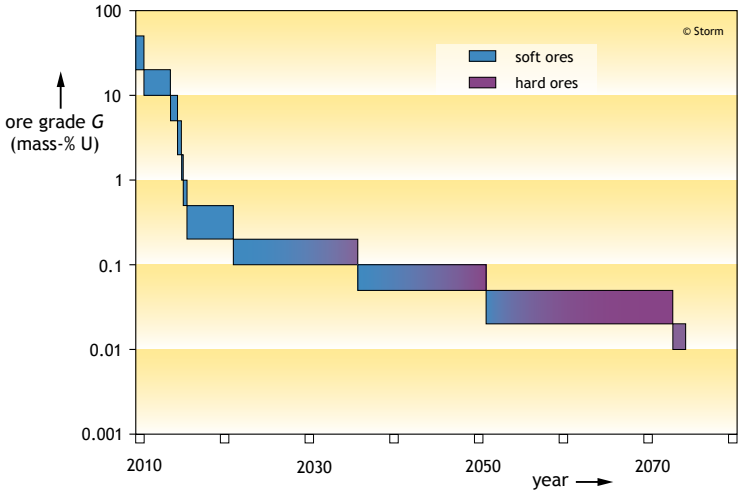


Figure 22

Depletion of the currently known recoverable uranium resources, at an assumed constant annual uranium consumption of 66 Gg/a. This scenario is based on the assumption that no major new resources will be discovered during the next decades, as has been the case during the past three decades, and that the richest available resources are exploited first. This figure is based on the ore grade distribution of the known uranium resources (see Figure 21).

Usually the richest and most easily discoverable and exploitable uranium resources become depleted first, because these offer the highest return on investments for the mining companies. Low-hanging fruit is harvested first. As the most easily available uranium resources are exploited first, the world-averaged ore quality of the remaining resources decreases with time. This phenomenon is not only typical for uranium ores, but applies to all mineral resources, see for example Mudd 2009, Mudd 2011.

CO_2 trap

The increase of the CO_2 intensity of nuclear power with decreasing ore grade in relation to the known recoverable uranium resources is illustrated by Figure 20. Below grades of around 0.02% U nuclear power surpasses the emission of gas-fired generation of electricity and effectively that of all fossil-fueled power generation. Therefore this diagram is called the *CO_2 trap*.

The world average grade of the mined ores is steadily declining with time. If no new large uranium ore deposits of high thermodynamic quality are discovered during the next decades, the nuclear CO_2 emission will surpass the specific CO_2 emission of gas-fired stations, and even coal-fired stations, within the lifetime of all new nuclear builds.
Figure 23 gives a rough impression of the CO_2 trap over time. Very likely the average uranium ore quality will decline in the future and consequently the specific CO_2 emission by the nuclear energy system will rise over time. The rate of increase is uncertain for a number of reasons: uncertainties about operational lifetime, fixed energy investments, development of the global nuclear generating capacity, new uranium resource discoveries, etcetera.
Thermodynamic analysis proves that *year of depletion*, when the curve starts rising nearly vertically and the

specific nuclear CO_2 emission surpasses that of fossil fuels, is not affected by variables such as operational lifetime and CO_2 emission of construction + dismantling, but is determined by the amount of new discoveries of high-quality uranium resources. Sooner or later the nuclear energy system will run aground in the CO_2 trap.

Figure 23 gives an impression of the CO_2 trap over time in two scenario's. The curves are an indication of what may happen if no new large uranium resources of sufficiently high thermodynamic quality are discovered during the next decades.

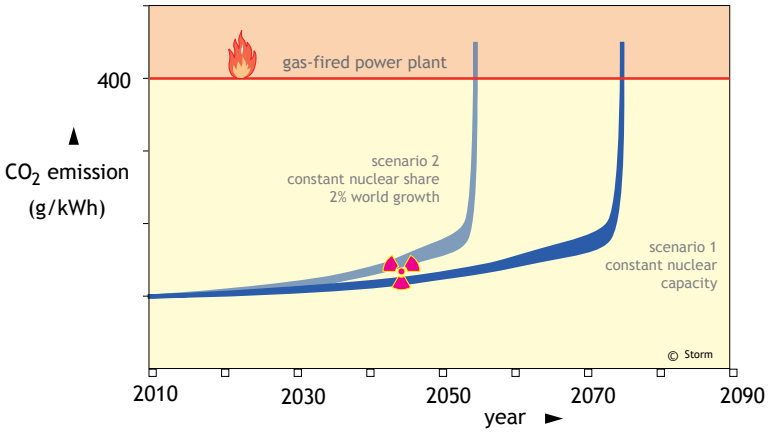


Figure 23

The CO_2 trap: the nuclear CO_2 emission over time. The specific CO_2 emission of nuclear power rises with time due to decreasing thermodynamic quality of the uranium ores. Within the lifetime of new nuclear build the specific CO_2 emission may surpass that of fossil-fuelled electricity generation if no new large high-quality uranium resources will be discovered during the next decades. The colored bands represent the uncertainty ranges regarding ore quality, mainly the difference between soft ores and hard ores.

CO_2 emission figures from the nuclear industry

In its most recent report concerning GHG emissions of nuclear power *Climate Change and Nuclear Power 2014* (IAEA-ccnap 2014) the International Atomic Energy Agency (IAEA) states:

> "Climate change is the foremost global environmental issue today."
>
> "Nuclear power plants produce virtually no greenhouse gas emissions or air pollutants during their operation and only very low emissions over their entire life cycle."
>
> "GHG emissions from nuclear powerplants (NPPs) are negligible, and nuclear power, together with hydropower and wind based electricity, is among the lowest CO_2 emitters when emissions over the entire life cycle are considered (less than 15 grams CO2-equivalent (g CO_2-eq) per kW.h (kilowatt hour), median value of 60 reviewed sources)."

The IAEA cites specific emission figures far lower than this study: 5.6-19.7 gCO_2eq/kWh with a median value of 14.9 gCO_2eq/kWh. Notably the specific CO_2 emission of just the construction of the Sizewell B NPP in the UK amounted to 11-15 gCO_2/kWh, according to ExternE-UK 1998. It is unclear how the figures of the IAEA are established. See also the publication of Sovacool 2008 in which a number of publications concerning nuclear GHG emissions are compared.

As only the CO_2 emission of nuclear power is reported in the open scientific literature, the unit gCO_2eq/kWh (gramCO_2-*equivalent* per kilowatt-hour) is misleading, because use of it implies that other GHGs are included. Comparing the nuclear CO_2 emission with the total GHG emissions of other technologies is incorrect; the specific emission of solar PV for example includes the emissions of fluorinated compounds.

A sound scientific comparison of the figures from the publication of the IAEA with the LCA of this study is not possible for several reasons:

- the original studies from which the used data were taken remain undisclosed
- no life cycle assessment (LCA) is included
- no system boundaries are defined
- no time horizon of the study is defined
- not given which CO_2 sources of the nuclear system were accounted for.

In addition the chapters on the nuclear CO_2 emission contain inconsistencies, thermodynamic inaccuracies and scientifically flawed methods. Numerical results from mutually dependent studies, with undefined system boundaries and applying different assessment methodologies, are statistically processed as if they were stochastic measurement data.
The IAEA refers in its report to ISO standards, apparently to suggest the scientific soundness of the derivation of the numerical results. ISO standards are in no way a guarantee of sound scientific quality; moreover, most known LCA studies (see Sovacool 2008) are older than the cited ISO standards. The text of the report is not transparent and is difficult to read, even to an experienced scientist.

The World Nuclear Association (WNA) comes in its assessment of the nuclear CO_2 emissions to about the same figures as the IAEA: 9-21 CO_2-eq/kWh in WNA-CO_2 2015 and 10-26 g CO_2-eq/kWh in WNA-11 2015. Although WNA gives more details on the LCAs on which the figures are based than the IAEA in its report, it remains completely unclear how the CO_2 emission figures are derived by WNA or in the publications cited by WNA.

Noticeably absent from the publications of the IAEA and WNA are statements regarding the possibilty of the emissions of other greenhouse gases and regarding the ore grade dependency of the nuclear CO_2 emissions, although this has been confirmed by Prasser et al. 2008.

Air pollutants

Striking is the section in the report stating the virtual absence of air pollutants released by nuclear power. The IAEA does not define what they call ‘air pollutants’ and does not prove that the nuclear energy system does not emit ‘air pollutants’. Without naming a scientific reference the IAEA asserts that nuclear power prevented 1.8 million air polution related deaths between 1971 and 2009. Discharges of radioactive gases and dust, resulting from normal operation of reactors, reprocessing plants and uranium mining, and from nuclear disasters, are apparently not air pollution in the view of the IAEA.

6 Energy debt and delayed CO_2 emissions

Dynamic energy balance of nuclear power

As pointed out in the previous chapter only a minor fraction of the back end processes of the nuclear chain are operational, after more than 60 years of civil nuclear power. From this observation it follows also that the back end of the nuclear power plants that have been closed-down permanently up until now and of the currently operating NPPs are still unfinished.

The fulfillment of the back end processes involve large-scale industrial activities, requiring massive amounts of energy and high-grade materials. The energy investments of the yet-to-be fulfilled activities can be estimated by a physical analysis of the processes needed to safely handle the radioactive materials generated during the operational lifetime of the nuclear power plant.

The energy investments for construction of the nuclear power plant and those for running the front end processes are offset against the electricity production during the operational lifetime. Figure 24 represents the dynamic energy balance of the full nuclear process chain, from cradle to grave. The future energy investments required to finish the back end are called the *energy debt*.

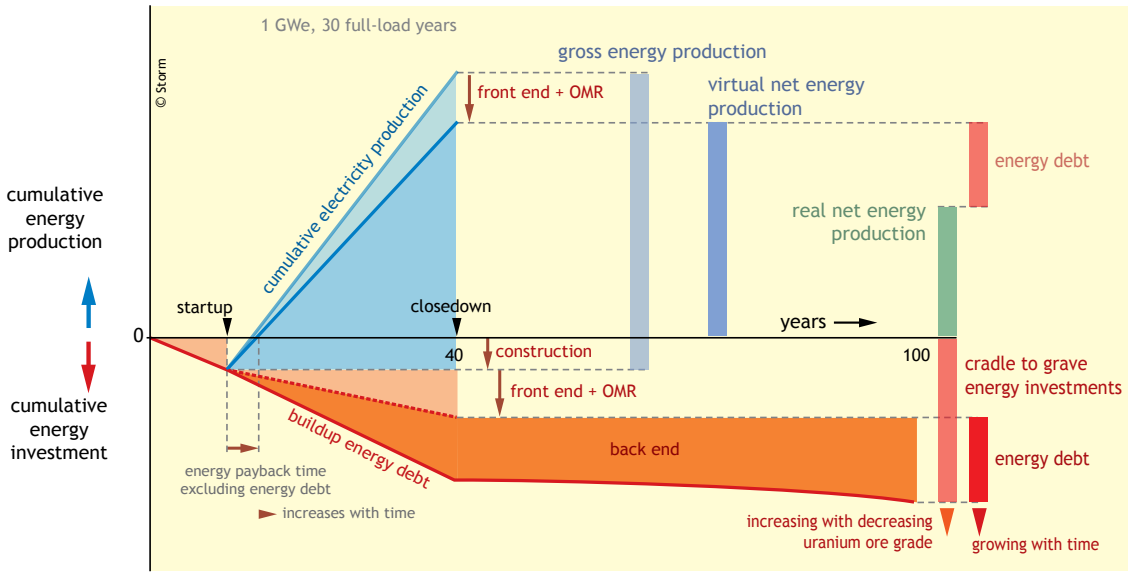


Figure 24

Dynamic energy balance of the nuclear energy system. The vertical scale has energy units, the horizontal scale is a timescale. The reactor is assumed to operate continuously at full power for 30 years (average load factor 100%). No reactor in the world ever reached this production level, the current world average is about 22 full-load years. OMR stands for operation, maintenance and refurbishments. The graph is roughly at scale. The cradle to grave period is taken at 100 years, in practice this might be an optimistic assumption. The uranium ore grade is assumed to be 0.1 mass% uranium. The virtual net energy production, here defined as the gross energy production minus the energy investements of construction and the front end processes, will decrease with time, because of the increasing energy input of the front end part due to the decreasing quality of uranium ores. The energy debt increases with time due to spontaneous degrading processes (ageing) of the materials of the temporary storage facilities. As a result the real net energy production, here defined as the gross energy production minus all cradle-to-grave energy investments, will decrease over time; this effect comes on top of the decrease caused by the degrading uranium ore quality over time.

Energy debt

The size of the nuclear energy debt is unprecedented in history. Each nuclear power plant leaves behind an energy debt as large as approximately one third of its lifetime energy production. During the next decades this debt fraction will rise considerably, due to several factors:

- Increasing amount of radioactive materials generated as long as nuclear power generation is being continued, and an increasing number of temporary storage sites.
- Inevitable deterioration and ageing of materials, and construction of the temporary storage facilities for radioactive waste. The lower the quality of those facilities, the more energy and materials are required to upgrade them to a safe standard.
- Increasing efforts needed for maintenance and safeguarding of the temporary storage facilities, a consequence of the two points above.
- Increasing energy intensity of the required materials, as a result of decreasing ore grades and greater depths of the mineral deposits. For example: with time more energy has to be invested to obtain one kilogram of steel from iron ore deposits in the earth's crust.
- Increasing energy intensity in extraction of the mineral energy sources (chiefly fossil fuels): more energy is needed to recover a unit of useful energy from the earth's crust, due to the ongoing depletion of easy oil, gas and coal resources and exploitation of increasingly harder recoverable resources. This effect comes on top of the preceding effects.

Delayed CO_2 emissions

Nearly all processes of the back end, including dismantling of the NPP, are systematically being defered to the future. The CO_2 emissions coupled to those processes have to be added to emissions generated during the construction and operation of the NPP if the CO_2 intensity of nuclear power is to be compared to that of other energy systems. From Table 6 follows that contributions 5, 6 and 7 jointly would amount to some 54 g CO_2/kWh; effectively this is the delayed CO_2 emission of nuclear power. Whether the back end processes would emit also other greenhouse gases is unknown.

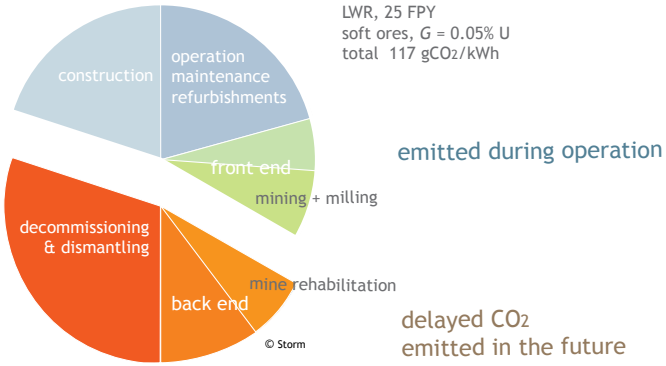


Figure 25

Delayed CO_2 emissions. Contributions to the cradle-to-grave CO_2 emission of the nuclear energy system by activities in the future, directly connected to a nuclear power plant operating today.

Claiming that nuclear power is a low-carbon energy system, even lower than renewables such as wind power and solar photovoltaics, seems strange in view of the fact that the CO_2 debt built up during the past six decades of nuclear power is still to be paid off.

Misconception

The view that the solution to the radioactive waste problem is a matter of advanced technology is a misconception, for the immobilization of radioactive materialsrequires a coming to terms with the Second Law of thermodynamics. Dispersion of radioactive materials into the human environment will irrevocably happen if it is allowed run its course. It is not possible by use of advanced, yet to be developed, technology to prevent the dispersion of radioactivity into the environment with less effort than it would require at this moment. Dispersion can only be limited by dedicated human efforts, using mature conventional technology, involving massive amounts of useful energy and materials. As useful energy and materials are becoming increasingly scarce, the chances of solving the radioactive waste problem in the least dangerous way can only decline with time, and so will nuclear security.

Financial debt

Obviously the energy debt will translate into a financial debt, for there is a strong connection between the cost of an activity in monetary units on one hand and the consumption of energy, materials and human effort of that activity on the other.
The financial debt ensuing from the energy debt and material debt has a character fundamentally different from the monetary debts economists are used to. Present economic concepts may be incapable of handling the problems and risks posed by the nuclear legacy, in view of the following characteristics:

- Energy is a conserved quantity and for that reason the energy debt and consequently the corresponding financial debt are not discountable and cannot be written off as uncollectable. The energy debt is not subject to monetary-like depreciation, on the contrary, it will increase with time, as explained above.
- The timescale of over a 100 years (see Figure 24) is unprecedented in history.
- The massive investments of energy, materials, human resources and economic means do not contribute to the improvement of the economic infrastructure and must be considered to be pure losses. As the investments are used to isolate the radioactive wastes including their safe storage away from the human environment, the profits of the investments are apt to vanish from the economic system forever.
- Increasing energy intensity of materials will translate into a higher cost per unit product. The longer the definitive and safe disposal of radioactive waste is postponed, the higher the cost per unit waste will have in order to achieve a given level of security.
- In addition to the unavoidable growth over time of the energy debt, measured in physical energy units, energy from fossil fuels will become more expensive with time, due to reasons explained above.

All growth effects come on top of each other, they accumulate, and cause a steep exponential growth of the cost of maintaining our security standards. If the world economy stagnates or declines, it will become even more difficult to allocate economic resources to manage the radioactive wastes in the proper fashion. These observations point to an increasing risk of making less than optimal choices on how to isolate the radioactive legacy of nuclear power from the human environment. Consequently the security and health risks of nuclear power will rise over time.
The back end processes do not generate profits for the nuclear industry and their fulfilment will require immense financial investments (trillions of euros) over a long timeframe (more than a century).

View of the nuclear industry

The World Nuclear Association (WNA) asserts (WNA 2012a and 2012b):

> Nuclear power is the only energy industry which takes full responsibility for all its wastes, and costs this into the product.

This WNA statement is, if not a lie, in sharp conflict with the evidence of the energy debt and empirical facts encountered in this study and also with the observations such as:

- In the USA the federal government is responsible for the final storage of the spent fuel in a geological repository. Because of this, by definition the American taxpayer bears financial liability for the decommissioning and dismantling of the nuclear power plants.
- In the UK the shut down nuclear power plants are sold for a symbolic amount to the government, which then takes on the responsibility of the cleanup, decommissioning and dismantling of the discarded radioactive facilities. In this case it's likely the British taxpayer also has to pay for the construction of a geologic repository plus the packaging and definitive sequestration of the nuclear waste.
- In France a different situation exists. Nuclear activities in France are managed by two state-owned companies: Areva and Electricité de France (EdF). Who pays the bill?
- In the Netherlands the State has the full financial responsibility for the management of radioactive waste (OECD-NEA 2005).

What is the situation in other countries, for example Russia, China, India, South Korea, Japan?

Questionable assumptions

Radioactive wastes from dismantling nuclear power plants and reprocessing plants are missing from the waste management scenarios published by the nuclear industry, despite the tremendous volumes to be expected, counted in hundreds of thousands of cubic meters, the astronomical costs and the imperfectly known radioisotopic composition of this waste.
The nuclear industry sharply distinguishes spent fuel and high-level waste from other radioactive wastes, suggesting that those other wastes are not dangerous. Although the specific activities of 'low level' waste are orders of magnitude lower than of spent fuel and other high-level wastes, the volumes are many orders of magnitude larger and are dispersed over more storage facilities. Consequently the chances for individuals to contract a hazardous dose by exposure to lower level radioactive materials are accordingly greater, the more so because the safeguards of the 'not-to-worry-about' wastes are substantially less stringent than of spent fuel and other high-level wastes, in some cases nonexistent.
'Low level' waste can contain extremely hazardous radionuclides, such as actinides, albeit at relatively low concentrations. An added complication is that the distincion between low and high level generally is made by measuring the gamma radiation at the outside of the waste container. Dangerous radionuclides emitting no or weak gamma radiation are not detected by the detectors. If a container should leak the dangerous, invisible radionuclides get dispersed into the human environment.

The distinction between 'low level' and 'high level' obviously has economic roots, for the final disposal options as envisioned by the nuclear industry for the 'not-to-worry-about' wastes, shallow burial and/or above-ground storage for 'only' four to ten centuries, are much cheaper than a deep geologic repository. How sure can we be of the integrity of a human construction after 400-1000 years, looking back in history to the years 1600 or 1000?

Apparently the nuclear industry bases its proposed solutions of radioactive waste management issues – they emphatically deny there is a waste *problem* – on questionable assumptions, among others:

- The assumption that future generations will keep the knowledge of the exact locations and properties of the stored 'not-to-worry-about' radioactive wastes generated centuries ago and will have the expertise and economic means to maintain the storage facilities in a proper state and to safely handle the wastes in case of unexpected events, such as earthquakes, floods and wars.
- The assumption that future generations will have the political drive and sufficient economic means and skilled workforces at their disposal to perform the demanding tasks our generation could not handle.

Après nous le déluge

Any country with an appreciable number of nuclear power plants, such as France, Great Britain and the United States, should reckon on economic efforts of Apollo project size, many hundreds of billions of euros, to keep their territory (and that of neighboring countries) habitable. Would the decision makers foster such efforts, or does the world need another Chernobyl/Fukushima disaster? That may happen in Europe or in the USA. The current way of economic thinking, pursuing only short-term profit, is not reassuring in this respect. With respect to radioactive waste problems and health risks the nuclear world seems to foster a culture of downplaying and concealing risks combined with an unrealistic belief in unproved and unfeasible technical concepts. This paradigm is exacerbated by a chronic habit of living on credit that may be best described as an *après nous le déluge* attitude, which seems to be based on questionable arguments and fallacies, such as:

> Technology advances with time and future generations will be richer than our generation, so they will have more economic means and better technological possibilities at their disposal to handle the waste problem.

Or, as John Broome put it (Broome 2008):

> How should we – all of us living today – evaluate the well-being of future generations, given that they are likely to have more material goods than we do?

A nuclear disaster cannot be prevented by denial.

Hazards

The amount of man-made radioactivity generated by a reactor is a billion times the radioactivity of the fresh uranium entering the reactor. One reactor of 1 GWe generates as much radioactivity as 1000 exploded nuclear bombs of about 15 kilotonnes, the yield of the Hiroshima bomb, each year. The radioactivity is in physically and chemically mobile form present in the nuclear chain and consequently in the human environment. Roughly 90% of the radioactivity is contained in spent fuel (if not reprocessed), the other 10% is dispersed over massive volumes of materials, such as construction materials and chemicals.

What is known about chronic exposure to 'low' doses of radionuclides entering the body via inhalation of gases and aerosols and ingestion via drinking water and food? Exposure to radioactive materials implies more than exposure to radiation. Radiological models are based on radiation and do not include the biochemical behaviour of radionuclides inside the human body, such as accumulation in specific organs. Weak radiation emitters, for example tritium, might be very dangerous in unshielded living cells in the body. The effects could be exacerbated in the case of chronic exposure of people living in contaminated areas.
Nothing is known about exposure to a mix of different radionuclides. The published reports on childhood cancers in the vicinity of nuclear power plants (see for example KiKK 2007 and Geocap 2012) and on the consequences of the Chernobyl and Fukushima disasters (IPPNW 2011) are far from reassuring with respect to health hazards posed by radioactive materials.

Realization of the nuclear scenarios combined with the currently prevailing après nous le déluge culture of the nuclear industry would greatly enhance health hazards and risks of accidents and terrorism. We can expect increased dispersion of radioactive materials into the environment due to the unavoidable and progressive deterioration of the materials enclosing the radioactive wastes of the nuclear chain, combined with increasing amounts of radioactive waste, stored at an increasing number of temporary storage facilities. Other risks are posed by the ever increasing number of easte transports of radioactive materials.
The risks of severe accidents like Chernobyl and Fukushima will increase due to the increasing number of nuclear power plants and spent fuel cooling pools, this in combination with the progressive ageing of nuclear power plants and reprocessing plants.

If the reprocessing of spent fuel were to be continued in the future the risks of nuclear terrorism would grow day by day, because an increasing amount of plutonium and other fissile materials would be transported and stored at different places.
As a result of the living-on-credit paradigm prevailing in the nuclear industry, all human-made radioactivity ever generated is still stored in makeshift facilities, if not already dumped into the sea, lakes, rivers or landfills. Not one uranium mine in the world has been properly remediated after depletion of the ore deposit. Isolation from the biosphere of all radioactive materials in the least risky way is a *conditio sine qua non* to secure our children, grandchildren and future generations against the insidious hazards of the tremendous quantities of human-made radioactivity.
Based on the above observations this study started from the viewpoint that all radioactive wastes from nuclear power have to be definitively isolated from the biosphere as securely and as soon as possible after generation of the radioactive waste, to minimize discharges of radioactivity into the human environment and to minimize the risks of accidents and large disasters. Prevention of radioactive contamination and accompanying health hazards is not possible, just a minimalization of the hazards.

Economic preferences and nuclear security

Economic preferences and commercial choices can greatly increase nuclear security risks. There is the relaxation of the official standards for operational routine discharges of radionuclides into the environment by nuclear power plants and reprocessing plants. Due to ageing the frequency of leaks and spills will rise at an accelerating rate and so will the costs to repair the leaks and to prevent their occurrence. Raising allowable radioactive discharge limits for the nuclear operators keeps their costs down, while resulting in higher exposure standards for the general public, often by large factors, without scientific justification. Similar relaxation of exposure standards may be expected in the case of future nuclear accidents, as occurred after the Fukushima disaster.Another example is the relaxation of standards for clearance of radioactive construction materials for unrestricted use in the public domain. This will become a hot issue when heavily contaminated nuclear installations are dismantled; safe guardianship and disposal of the massive amounts of radioactive debris and scrap will be very expensive.
Economic reasons can push the trend of lifetime extension for nuclear power stations beyond the designed lifetime of 40 years. It is not clear how the owners of the plants and the supervisory institutes incorporate the unavoidable ageing and the bathtub function in their security assessments, or how independent or how thorough the inspections are.
The risks for catastrophic breakdown of technical devices, including nuclear reactors, change as the devices age, much like the risks for death by accident and illness change as people get older. There are three distinct stages in the lifetime of a technical system or living organism:

- the break-in phase, also called the burn-in phase or the infant mortality phase,
- the middle life phase, also called the useful life,
- the wear-out phase.

The risk profile, the failure rate as a function of time, is called the bathtub hazard curve for it curves like a bathtub. The bathtub curve is drawn from statistical data about lifetimes of both living and nonliving things, such as cars, cats or nuclear reactors (Sheldon 2009, Stancliff et al. 2006).

Another cause for concern is illegal trade and smuggling of nuclear materials, often high-grade and expensive, only a small step from nuclear criminality and terrorism. Transports of hazardous materials are difficult to detect, if detection is possible at all. This problem increases with time due to increasing amounts of radioactive materials and declining inspections. One of the consequences is the uncontrolled release of radioactive materials into the public domain and insidious exposure of a growing number of people to radionuclides. Serious accidents and terroristic actions cannot be ruled out. Political instability, for whatever reason, exaggerates the risks of illicit nuclear transports with malicious intent.

Downplaying and denial of health effects

Information from the nuclear industry to the general public on health hazards of exposure to radiation and radioactive materials originating from nuclear power stations and associated nuclear installations is controlled by the International Atomic Energy Agency (IAEA). Two other international nuclear-related institutes, the International Commission on Radiological Protection (ICRP) and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) have strong connections with the IAEA. Even the World Health Organization (WHO) cannot operate independently of the IAEA with respect to nuclear issues. From the reports of the International Atomic Energy Agency (IAEA), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and World Health Organization (WHO) on the subject of health effects, especially concerning the disasters of Chernobyl and Fukushima, a picture emerges of the nuclear world marked by *downplaying* and even *denial of health effects* caused by exposure to radiation and radioactive materials.
Non-cancerous diseases are not recognized as radiation-induced health effects, attention is paid only to acute radiation syndrome (ARS, radiation sickness).

The IAEA and the nuclear industry place full reliance on models from the 1940s and 1950s for estimation exposure to radiation (that is not the same as exposure to radionuclides) and the dosis-effect relation. In addition the models have a very limited scope and empirical evidence of the past several decades is not included in the models. The evidence presented in the KiKK, GeoCap and IPPNW studies mentioned above cannot be explained by the radiological models; as a matter of fact these studies are not even mentioned in the official publications of the IAEA and nuclear industry.
Biochemical behaviour of radionuclides inside human body are not included. Chronic exposure to a mix of different radionuclides inside the body, via ingestion (food and water) and inhalation (gases, dust) are also not covered. The radiological models applied by the IAEA and nuclear industry turn out to be easily adaptable to economic and financial considerations at a given moment, as became evident after the Fukushima disaster.

Reliable investigations of the health effects of the Chernobyl and Fukushima disasters are hampered by several factors, such as:

- poor detectability of many dangerous radionuclides
- long latency period of health effects from exposure to radioactivity, coupled with a short time horizon of the investigations
- limited measurements of radioactive contamination
- limited scope of the IAEA and WHO investigations
- absence of solid statistical databases and absence of adequate epidemiological studies
- secrecy of medical data.

There no reasons to expect that this would be better during the next disaster.

Conspicuous in the IAEA reports is the downplaying and even denial of health effects caused by radioactivity using unscientific methods, committing elementary scientific flaws.

7 Other greenhouse gases

Global warming potential

Carbon dioxide is not the only greenhouse gas, although it is the most important one due to the vast amounts being emitted. This is not to say that for any industrial process CO_2 is the most important greenhouse gas produced. Many other greenhouse gases have a global warming potential (GWP) thousands of times larger than CO_2, so even tiny emissions of such gases may have a large effect. A zero-carbon process may have a significant contribution to anthropogenic global warming if it emits high-GWP greenhouse gases.
Table 7 shows that gaseous halocarbons and other gaseous halo-compounds, in particular, may be potent greenhouse gases, as well as ozone depletion substances.

Table 7
Greenhouse gases. The unit of the Global Warming Potential GWP is kg gas per kg carbon dioxide. ODS = ozone depleting substance. Time horizon 100 years. Some gases are classified as ODS, but are also potent greenhouse gases. Sources: EPA 2002, EIA-G 2001, Blasing & Smith 2006 and Blasing & Jones 2003.

gas	formula	ODS ?	GWP
carbon dioxide	CO_2		1
methane	CH_4		23
nitrous oxide	N_2O		296
chlorofluorocarbons, CFCs	e.g. $ClCF_2CClF_2$	+	4600 - 10600
hydrochlorofluorocarbons, HCFCs	e.g. $CHClF_2$	+	120 - 2400
hydrofluorocarbons, HFCs	e.g. CHF_3		12 - 12000
perfluorocarbons, PFCs	e.g. C_2F_6		5700 - 11900
halons	e.g. CF_2ClBr	+	1300 - 6900
carbon tetrachloride	CCl_4	+	1800
sulfur hexafluoride	SF_6		22200
trifluoromethyl sulfur pentafluoride	SF_5CF_3		› 17500
nitrogen trifluoride	NF_3		10800
ethers and halogenated ethers	e.g. $F_3C\text{-}O\text{-}CHF_2$		1 - 14900

In all processes from uranium ore to nuclear fuel substantial 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.
Unknown are the amounts of fluoro and chloro compounds used in other processes of the nuclear process chain. In a nuclear power plant, for example, considerable quantities of numerous different high-grade materials are incorporated; what emissions are coupled to the production of those materials?

As with all chemical plants, significant amounts of gaseous and liquid compounds from the processes will be lost into the environment, due to unavoidable process losses, leaks and accidents. No chemical plant is leakproof. From a chemical point of view, it is likely that in several processes potent GHG's arise or are used, or that GHGs are formed when they react with materials in the environment after release. Notably halocarbons have GWPs many thousands of times stronger than carbon dioxide.

Fluorine consumption in the nuclear process chain

In the processes of uranium ore milling through fuel element fabrication fluorine and its compounds are involved, often in combination with organic solvents.
Yellow cake from the uranium mill, containing $Na_2U_2O_7$ and/or $(NH_4)_2U_2O_7$, contaminated with chemical species from the ore and the extraction process, is converted into uranium hexafluoride UF_6, using fluorine and/or its compounds, for instance hydrogen fluoride HF and elemental fluorine (F_2).
The stoichiometric mass ratio implies that for conversion of each gram uranium, a minimum of 0.48 gram fluorine is needed. In practice the ratio will be significantly higher than the stoichiometric minimum, due to unavoidable losses and secondary reactions. Because the uranium hexafluoride UF_6 has to be extremely pure, the fluorine and its compounds used in the process have to be extremely pure too. The required purification processes of the product are unavoidably coupled to significant losses. Likely the conversion process of yellow cake into UF_6 generates substantial waste streams containing compounds of fluorine, some of which may be potent greenhouse gases.

The reference reactor in our study consumes 20.3 Mg fresh enriched uranium during each reload period (in practice about each year). To prepare 20.3 Mg enriched uranium 162.35 Mg natural uranium has to be mined. For conversion of 162.35 Mg natural uranium into UF_6, a stoichiometric minimum of 77.9 Mg fluorine is required; in practice substantially higher amounts than the stoichiometric minimum are needed.

In the enrichment facility the total amount of UF_6, is separated into two fractions: one fraction is depleted in U-235 and one is enriched in U-235. In practice the enriched fraction, containing 20.3 Mg uranium, is converted into UO_2 for use in nuclear fuel. In this case 9.74 Mg fluorine is set free. It is unknown in which form it is disposed of, likely as calciumfluoride CaF_2, also in this conversion process losses are inevitable.
Depleted uranium is stored generally as UF_6 in special vessels, often in storage facilities in the open air. UF_6 is very reactive, so when it leaks into the environment, various fluorine compounds arise. Of course this method of storage cannot be a permanent one, in view of deteriorating and leaking vessels and increasing chances for accidents or terroristic actions. For that reason this study assumes that all depleted UF_6 is reconverted into a stable compound, such as U_3O_8, for permanent sequestering in a geologic repository.

World wide some 68000 Mg natural uranium is fluorinated each year, consuming a stoichiometric minimum of 32600 Mg fluorine. The actual amount certainly will be much larger, may be some 100 000 Mg. Purification of fluorine and its compounds to high specifications generates unavoidably large waste streams containing fluorine and its compounds. Separation processes never go to completion, as follows from the Second Law of thermodynamics.

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 small percentage 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 can be purified by chlorination of the metal and destillation of the resulting chlorides, to remove all traces of hafnium. The stoichiometric mass ratio chlorine/zirconium in the compound zirconium tetrachloride $ZrCl_4$ is 1.56. So a minimum of 1.56 grams of chlorine is consumed per gram of Zr to produce $ZrCl_4$.
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 of exceedingly pure chlorine (in any chemical form) is needed. In practice the amount of chlorine may be much larger to obtain an extremely pure product, and large waste streams are unavoidable.

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

About 80% of the world zirconium production is consumed by the nuclear industry. This is a one-way production flow, because Zircalloy cannot be recycled, due to the high radioactivity of the material after use in a nuclear reactor.

Nuclear emission of non-CO_2 greenhouse gases: a well-kept secret

In 2001 the US enrichment plants alone had a specific GHG (greenhouse gas) emission of 5 grams CO_2-equivalents per kilowatt-hour of freon 114 (CFC-114, $ClCF_2CClF_2$), as follows from data from EIA-DOE 2005. Apart from these we found no data in the open literature on the emissions of fluorine- and chlorine-related chemical compounds by the nuclear industry. The Vattenfall EPD 2005 noticed the absence of data on emission of greenhouse gases by processes needed to convert uranium ore into nuclear fuel.

Unknown are the GHG emissions of the front end processes, the conversion of uranium ore into ready-to-use nuclear fuel.
Unknown are the GHG emissions of the construction of a nuclear power plant, with its large mass of high-quality and often exotic materials.
Unknown are the GHG emissions of the operation, maintenance and refurbishment of nuclear power plants and the production of the materials used in these activities.
Unknown are the GHG emissions of the back end of the nuclear process chain: the handling and storage of spent fuel and other radioactive waste.

As pointed out above it is inconceivable that the nuclear process chain does not emit a gamut of fluoro and chloro compounds and it is also inconceivable that no greenhouse gases are among them.

'Not reported' does not mean 'no emissions'..

False comparison

Emissions of greenhouse gases other than CO_2 are not quantified in this study, due to the absence of data. For that reason this study explicitely uses the unit gCO_2/kWh and avoids the unit gCO_2eq/kWh (gram CO_2-*equivalent* per kilowatt-hour). The latter would imply that other greenhouse gases also are included in the emission figures.
Comparing, for instance, solar PV energy systems with nuclear power, using the unit gCO_2**eq**/kWh, the nuclear industry gives a false and misleading impression of things, comparing apples with oranges. The greenhouse gas emission of solar PV are partly due to the losses of fluorinated gases during the production of the silicon cells.
The nuclear industry mentions only the emission of CO_2 by nuclear power, albeit at an unrealisticcally low rate, but never mentions emissions of other GHGs. Nevertheless the nuclear industry incorrectly uses the unit gCO_2eq/kWh. Moreover, even the CO_2 emissions of the back end of the chain are not included in the official figures of the nuclear industry, simply because the most significant back-end processes are still not operational.

Krypton-85, another nuclear climate changer

Krypton-85 (symbols ^{85}Kr or Kr-85) is a radioactive isotope of the noble gas krypton. Although krypton is not a greenhouse gas in itself the presence of krypton-85 in the atmosphere gives rise to unforeseeable effects for weather and climate. Kr-85 is a beta emitter and is capable of ionizing the atmosphere, leading to the formation of ozone in the troposphere. Tropospheric ozone is a greenhouse gas, it damages plants, it causes smog and health problems.

According to WMO 2000:

> "The present background concentrations of ^{85}Kr in the atmosphere are about 1 Bq/m^3 and are doubling every 20 years. At this level, ^{85}Kr is not dangerous for human beings, but the air ionization caused by ^{85}Kr decay will affect atmospheric electric properties. If ^{85}Kr continues to increase, changes in such atmospheric processes and properties as atmospheric electric conductivity, ion current, the Earth's magnetic field, formation of cloud condensation nuclei and aerosols, and frequency of lightning may result and thus disturb the Earth's heat balance and precipitation patterns."

By nature krypton-85 is present in minute quantities in the atmosphere due to natural processes. In nuclear reactors massive amounts of krypton-85 are produced, as one of the major fission products. A small portion of it escapes into the atmosphere at the reactor site during operation, more will escape during storage of spent fuel in cooling pools and dry casks, for the number of leaking fuel elements increases with time due to unavoidable ageing processes. When spent fuel is reprocessed all Kr-85 is discharged from the spent fuel into the atmosphere. As a result of human nuclear activities the inventory of Kr-85 in the atmosphere has risen by a factor of 10 million and this quantity shows a rising trend (Ahlswede et al. 2012), see also Seneca 2015.
Materialization of the scenarios of the nuclear industry would lead to increased emissions of Kr-85, greatly increasing its atmospheric inventory. The Kr-85 discharges may be seen as another argument against reprocessing of spent fuel. Mitigation of CO_2 emissions would be exchanged for enhanced Kr-85 emissions.

Health hazards of krypton-85

Being chemically inert, krypton and the other noble gases are not usually involved in biological processes. They are, however, absorbed into the tissues of the body via inhalation and dissolution in body fluids and tissues. Xenon has been shown to combine with specific sites in the body with certain protein molecules. Krypton is characterized by low blood solubility, high lipid solubility and rapid diffusion in tissue.
Exceptions to the the biologically inert characterization of inert gases have been noted by numerous studies. A comparatively high uptake of krypton by the adrenal gland has been reported. These phenomena are not understood (NCRP-44 1975).

On a global scale the genetic and overall carcinogenic effects from Kr-85 are calculated to be small as compared with other possible sources of deleterious effects.
The possible interaction of radiation from krypton-85 and solar ultraviolet (UV) should be mentioned. In order to better understand the implications of long-term ^{85}Kr releases to the atmosphere, epidemiological and laboratory studies should be undertaken to define the nature and degree of interaction, if any, of UV radiation with ionizing radiation in the induction of skin cancer (NCRP-44 1975).

Acronyms and physical units

CO_2	carbon dioxide
CSP	concentrated solar power
LWR	light-water reactor
FBR	fast breeder reactor
FPY	full-power year
GWe	gigawatt electric
GWP	global warming potential
HM	heavy metal (uranium, plutonium and higher actinides)
IAEA	International Atomic Energy Agency
LCA	Life cycle assessment or life cycle analysis
LNG	liquid natural gas
MOX	mixed oxide fuel (U-Pu fuel)
NPP	nuclear power station
ODS	ozon depleting substance
Pu	plutonium
Th	thorium
U	uranium
WNA	World Nuclear Association

ppm	1 ppm = 1 part per million = 1 gram U per Mg rock
kWh	kilowatt•hour = 3.6 MJ
Mtoe	million tonnes oil equivalence = MTOE = 42 PJ
MJ	megajoule = 10^6 joule
GJ	gigajoule = 10^9 joule
PJ	petajoule = 10^{15} joule
EJ	exajoule = 10^{18} joule
Mg	megagram = 10^6 gram = 1 metric tonne
Gg	gigagram = 10^9 gram = 1000 metric tonnes
Tg	teragram = 10^{12} gram = 1 million metric tonnes

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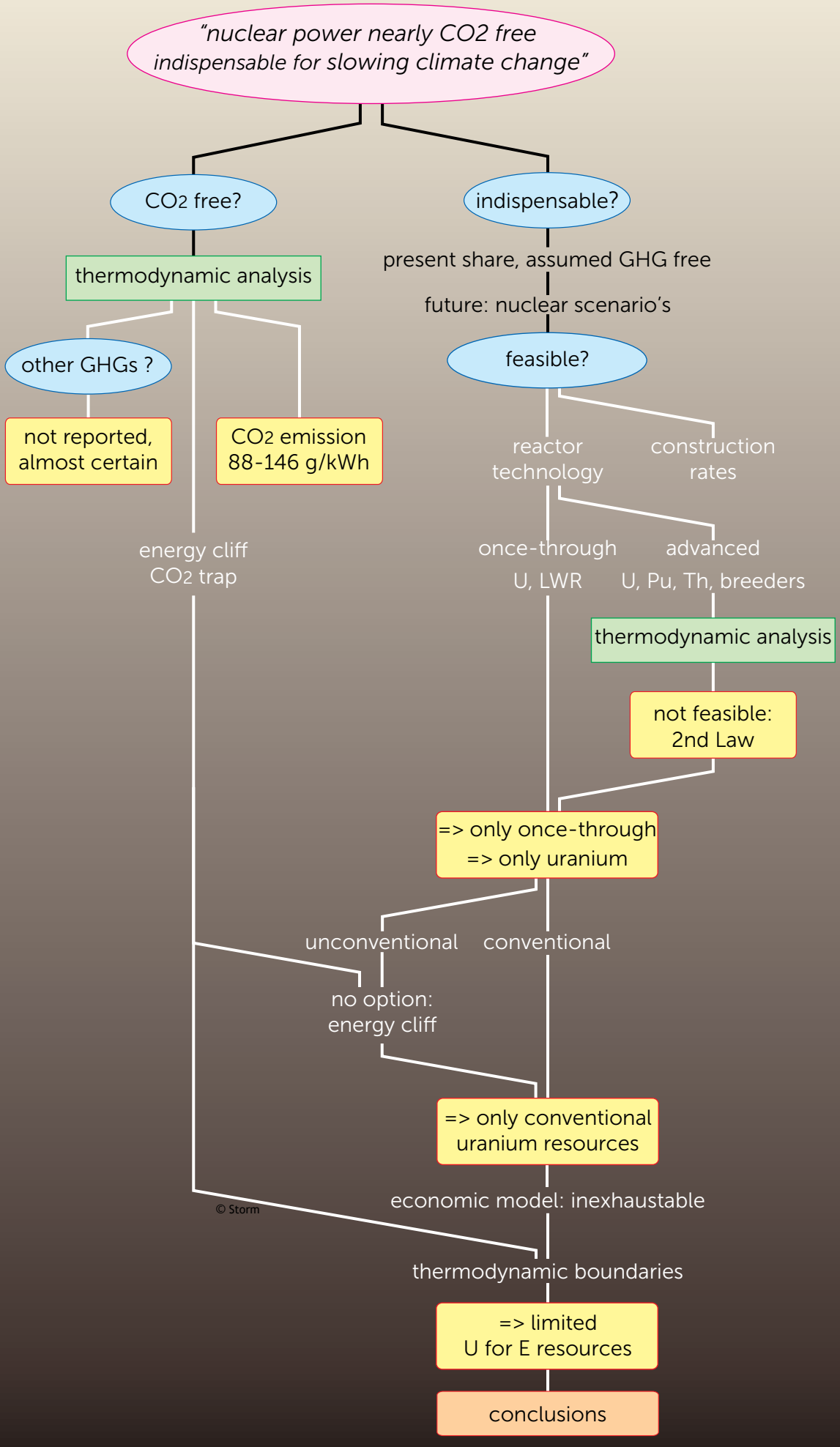
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advanced
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