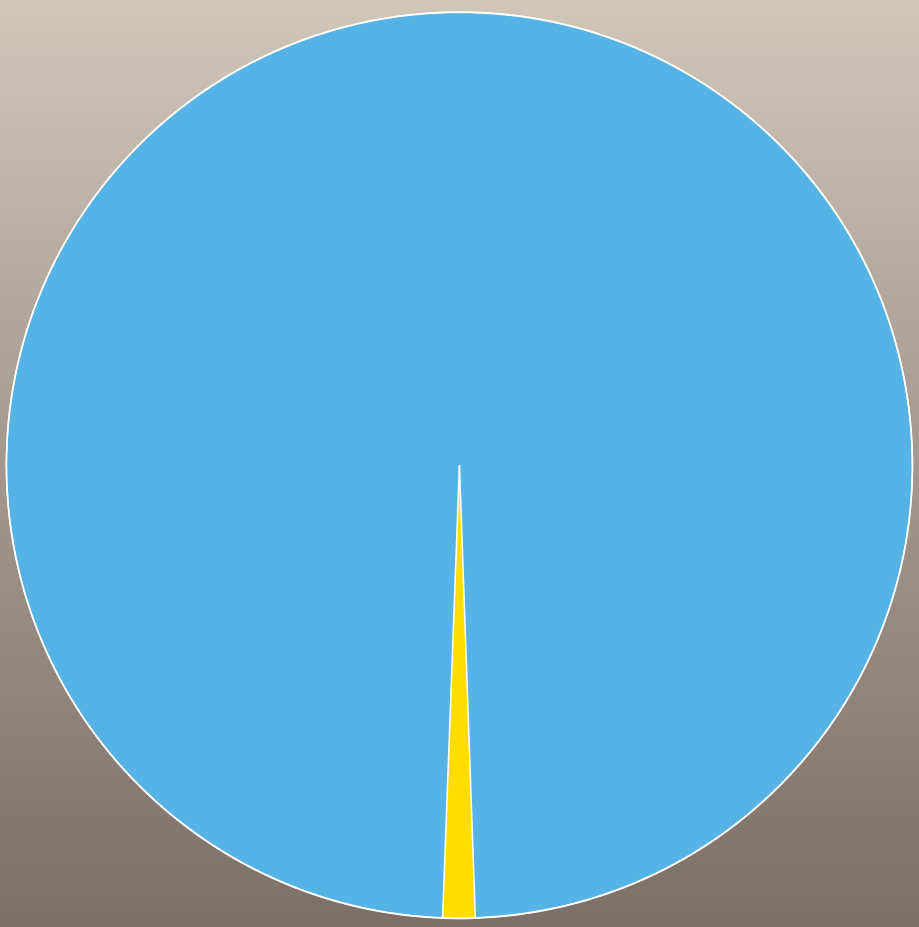
Climate change and nuclear power



An analysis of nuclear greenhouse gas emissions

Climate change and nuclear power

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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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Summary and findings

Points at issue

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.

In the official publications of the International Atomic Energy Agency (IAEA) and the nuclear industry no figures could be found regarding the present and/or envisioned future nuclear contribution to the reduction of the global emissions of greenhouse gases.

This study assesses the following questions:

- How large would the present nuclear mitigation share be, assumed that nuclear power does not emit carbon dioxide CO_2?
- How large could the reduction become in the future, starting from nuclear generating capacity scenarios published by the IAEA, and also assumed that nuclear power does not emit CO_2?
- How feasible are the projections of the nuclear industry?
- How large could the actual nuclear CO_2 emissions be, estimated on the basis of an independent life cycle analysis?
- Does nuclear power emit also other greenhouse gases?

These issues are assessed by means of a physical analysis of the complete industrial system needed to generate electricity from uranium. Economic aspects are left outside the scope of this assessment. Health hazards of nuclear power are also not addressed in this report.

Present nuclear mitigation contribution

The global greenhouse gas (GHG) emissions comprise a number of different gases and sources. Weighted by the global warming potential of the various GHGs, 30% of the emissions were caused by CO_2 from the burning of fossil fuels for energy generation. Nuclear power may be considered to displace fossil-fuelled electricity generation. In 2014 the nuclear contribution to the global usable energy supply was 1.6% and the contribution to the emission reduction of nuclear power displacing fossil fuels would be about 4.7%, provided that nuclear power is free of GHs (which it is not).

Nuclear mitigation contribution in the future

A hypothetical nuclear mitigation contribution in 2050, based on two scenarios of the IAEA and provided that nuclear power is free of GHs, comes to:

- scenario IAEA Low, constant nuclear capacity, 376 GWe in 2050: 1.3 - 2.4%
- scenario IAEA High, constant nuclear mitigation share, 964 GWe in 2050: 3.8 - 6.8%.

The high figures are valid at a growth of the global GHG emissions of 2.0%/yr, the low figures at a growth of 3.5%/yr.

Global construction pace

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 construction pace of 3-4 GWe per year is too low to keep the global nuclear capacity flat and consequently the current global nuclear capacity is declining. To keep the global nuclear capacity at the present level the construction pace would have to be doubled.

- in scenario IAEA low: 7-8 GWe per year until 2050.
- in scenario IAEA high: 27 GWe/yr until 2050.

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

Prospects of new advanced nuclear technology

The nuclear industry discusses the implementation within a few decades of advanced nuclear systems that would enable mankind to use nuclear power for hundreds to thousands of years. These concepts concern two main classes of closed-cycle reactor systems: uranium-based systems and thorium-based systems. However, the prospects seem questionable in view of the fact that, after more than 60 years of research and development in several countries (e.g. USA, UK, France, Germany, the former Soviet Union) with investments exceeding €100bn, still not one operating closed-cycle reactor system exists in the world.

Failure of the materialisation of the uranium-plutonium and thorium-uranium breeder systems can be traced back to limitations governed by fundamental laws of nature, particularly the Second Law of thermodynamics. From the above observation it follows that nuclear power in the future would have to rely exclusively on once-through thermal-neutron reactor technology based on natural uranium. As a consequence the size of the uranium resources will be a restricting factor for the future nuclear power scenarios.

Nuclear generating capacity 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?

Uranium demand and resources

The minimum uranium demand in the two IAEA scenarios can be estimated assuming no new nuclear power plants (NPPs) would be build after 2050 and consequently the NPPs operational in 2050 would be phased out by 2100.

The presently known recoverable uranium resources of the world would be adequate to sustain scenario IAEA Low, but not scenario IAEA High.

According to a common view within the nuclear industry, more exploration will yield more known resources, and at higher prices more and larger resources of uranium become economically recoverable. In this model uranium resources are virtually inexhaustable.

Energy cliff

Uranium resources as found in the earth's crust have to meet a crucial criterion if they are to be earmarked as energy sources: the extraction from the crust must require less energy than can be generated from the recovered uranium. Physical analysis of uranium recovery processes proves that the amount of energy consumed per kg recovered natural uranium rises exponentially with declining ore grades. No net energy can be generated by the nuclear system as a whole from uranium resources at grades below 200-100 ppm (0.2-0.1 g U per kg rock); this relationship is called the *energy cliff*.

Depletion of uranium-for-energy resources is a thermodynamic notion.

Apparently the IAEA and the nuclear industry are not aware of this observation. Some resources classified by the IAEA as 'recoverable' falls beyond the thermodynamic boundaries of uranium-for-energy resources.

Actual CO_2 emission of nuclear power

A nuclear power plant is not a stand-alone system, it is just the most visible component 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 from cradle to grave is called the nuclear process chain. Nuclear CO_2 emission originates from burning fossil fuels and chemical reactions in all processes of the nuclear chain, except the nuclear reactor. 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 gCO_2/kWh. Likely this emission figure will rise with time, as will be explained below.

In view of the large specific consumption of materials by the nuclear system of more than 200 g/kWh, compared with 5-6 g/kWh of an equivalent wind power system, it seems inconceivable that the nuclear system would emit less CO_2 than), as stated by the nuclear industry.

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. 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 the remaining resources have lower grades and uranium recovery becomes more energy-intensive and more CO_2-intensive, and consequently the specific CO_2 emission of nuclear power rises with time. When the average ore grade approaches 200 ppm, the specific CO_2 emission of the nuclear energy system would 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 might lose its low-carbon profile within the lifetime of new nuclear build. The nuclear mitigation share would then drop to zero.

Emission of 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.

It seems inconceivable that nuclear power does not emit other greenhouse gases. Absence of published data does not mean absence of emissions.

Krypton-85, another climate changing gas

Nuclear power stations, spent fuel storage facilities 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.

Questionable comparison of nuclear GHG emission figures with 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 GHG emissions cannot be assessed.

When the nuclear industry is speaking about its GHG emissions, only 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 emiited greenhouse gases. In this way the nuclear industry gives an unclear 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 incomplete analyses 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 not taken into account. Exactly these components of the process chain are the only contributions to the published GHG emissions of renewables. Solar power and wind power do not consume fuels or other materials for generation of electricity, as nuclear power does.

Latent entropy

Every system that generates useful energy from mineral sources, fossil fuels and uranium, releases unavoidably also a certain amount of entropy into the environment. Entropy may be interpreted as a measure of dispersal of matter, energy and directed flow. More entropy means more disorder. An increase of the entropy of the biosphere can manifest itself in many different phenomena, such as dispersal of waste heat, discharges of CO_2 and other GHGs, disturbing ecosystems, pollution of air and water with chemicals. Anthropogenic climate change is typical an entropy phenomenon.

The entropy contained in spent nuclear fuel will unavoidably be released into the biosphere if no measures are taken to prevent that. The explosions of atomic bombs and the disasters of Chernobyl and Fukushima showed the possible effects of unretained nuclear entropy. Each year an operating nuclear power plant of 1 GWe generates an amount of human-made radioactivity equivalent to 1000 exploded Hiroshima bombs.
As long as the nuclear entropy is enclosed in spent fuel elements it is called the *latent entropy* of nuclear power. The main purpose of the back-end processes of the nuclear chainshould be to keep the latent entropy under control.

E*nergy debt and delayed GHG emissions*

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 bill to keep the latent entropy under control from 60 years nuclear power has still to be paid. 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 GHGs is unknown, but likely.
Stating 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.

Contents

Acronyms and physical units

CO_2	carbon dioxide
CSP	concentrated solar power
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
LWR	light-water reactor
MOX	mixed oxide fuel (U-Pu fuel)
NPP	nuclear power station
ODS	ozon depleting substance
OMR	operation, maintenance and refurbishments
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

Introduction

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

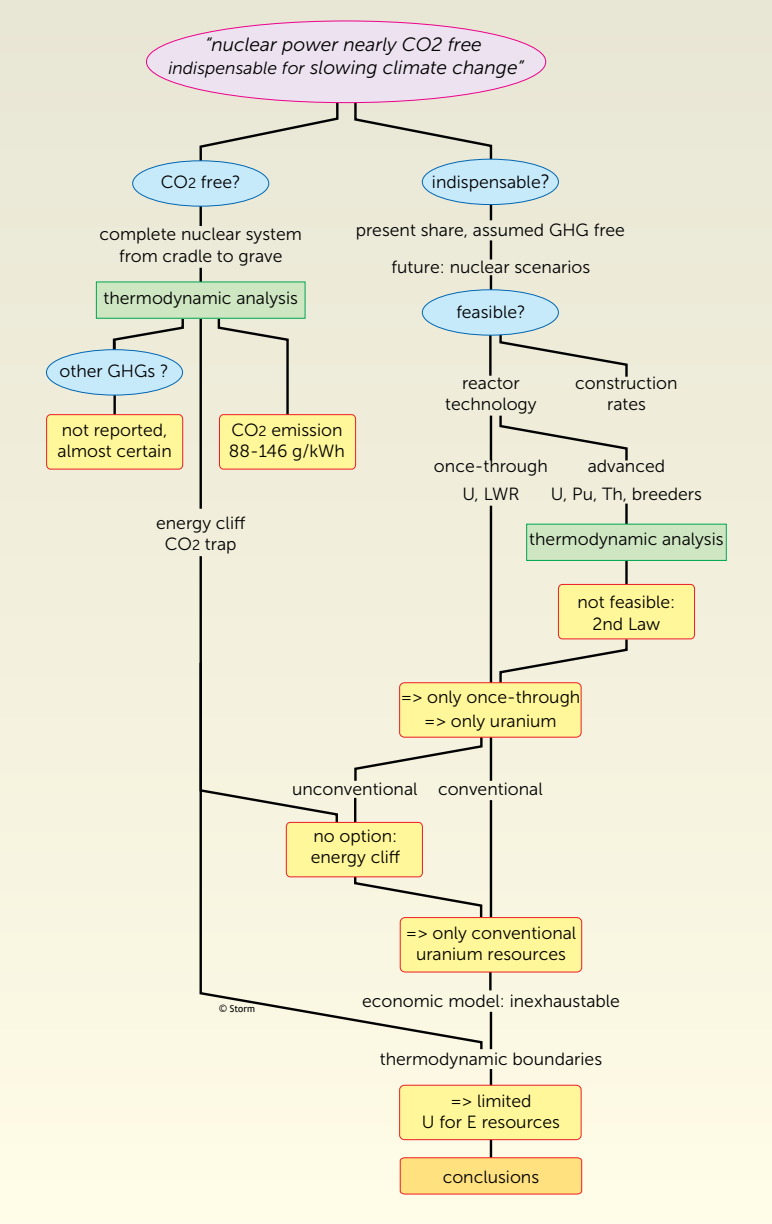


Figure 1
Outline of the assessment of this study, with two independent analysis tracks.

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

- 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.

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 for electricity generation.

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, assumed that nuclear power is free of CO_2 and other GHGs?

In the first analysis track 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 emission of CO_2 and is 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. No figures could be found on the emission of other GHGs by the nuclear energy system. A chemical analysis proves it highly unlikely that nuclear power does *not* emit other GHGs.

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 uranium resources usable as energy source turn out to be limited by boundaries determined by the thermodynamic properties of the uranium resources in situ. The thermodynamic analysis revealed also the existence of the energy cliff and CO_2 trap, important notions in the climate discussion.
Other notions to be incorporated in the assessment of mitigation of climate change by nuclear power are the latent entropy, the energy debt and the delayed CO_2 emissions.

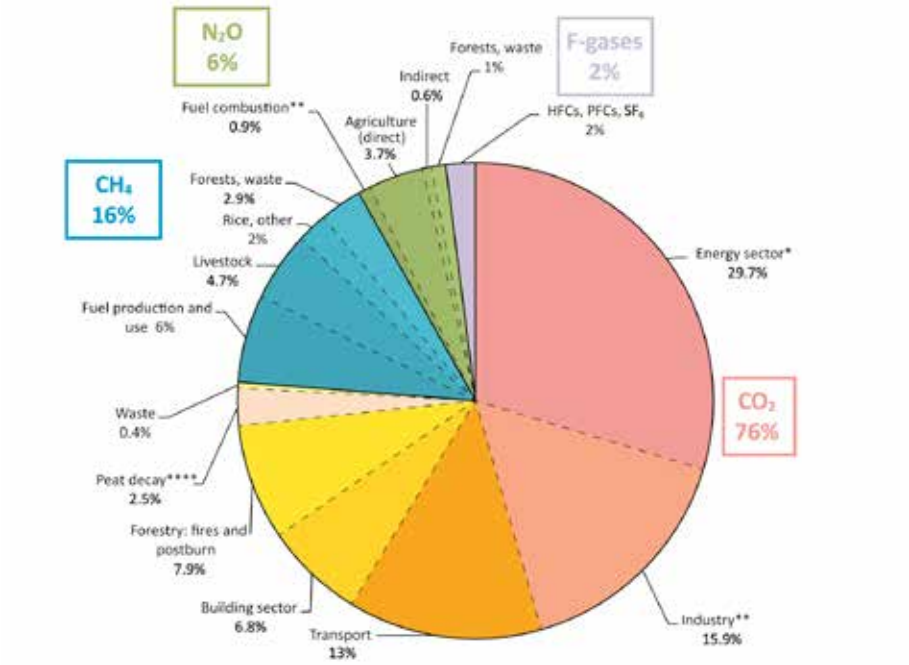
Along the second track of the analysis factors limiting the application of advanced nuclear technology are identified by means of thermodynamic analyses of advanced nuclear systems.

To make the complicated content of this report more accessible the text is presented in two layers:
The first layer comprises nine brief chapters each discussing a part of the assessment.
The second layer consists of Annexes addressing the subjects of the first chapters in more detail.

1 Greenhouse gases from energy generation

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 for the year 2010. At time of writing (2017) no diagrams of emissions in more recent years were found in literature. The global GHG emissions rise at a rate of some 2% per year. This study assumes that the partition of the various GHg emissions remained about constant through the year 2014 and will remain so in the following years; 2014 is the base year of this study, the most recent relevant data available are from that year.



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)*

Figure 2

Sources of global GHG emissions in 2010, weighted by their global warming potential (GWP). F-gases are fluorinated gases. Source of diagram: [UNEP 2012]. This study assumes that the partition of the various GHG emissions in 2014 has not changed significantly from 2010.

World energy supply in 2014

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]. 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 2. For sake of simplicity this study takes only the CO_2 emission by the energy sector into consideration.

In 2014 the nuclear share of the world gross energy production was 1.6%, as calculated in Table A1 of Annex A, based on data from [BP 2015], see also Figure 4.. Most energy statistics give another figure; for example [IEA 2016] cites a share of 4.8%. This divergence has two causes:

- Firstly BP lists only the traded energy (497 EJ in 2014) 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 $f = 2.64$, apparently the IEA uses a factor $f = 3$. This method of calculation results in a number of virtual energy units, and is thermodynamically questionable.

More details are discussed in Annex A.

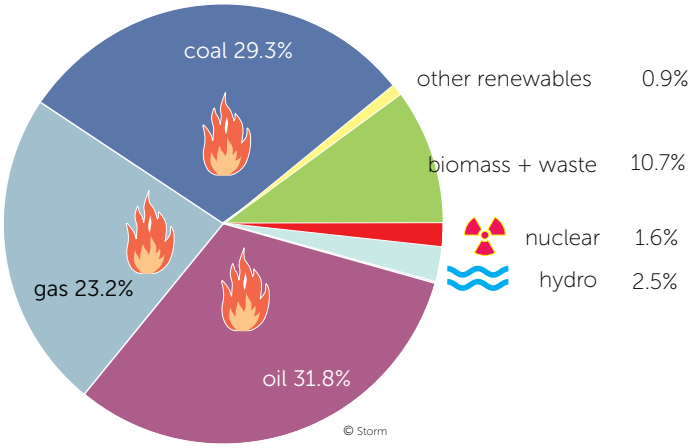


Figure 3

World primary energy production in 2014 was about 556 EJ (exajoule), of which 469 EJ traded energy. The share of nuclear power was 1.6% in 2014 and is steadily declining. This diagram is based on Table 1 and [BP 2015]; [IEA 2016] comes to slightly different figures. Mineral energy sources 85.9%: fossil fuels 84.3% + nuclear power 1.6%, traditional biomass + renewables: 14.1%, see also Figure 4.

Final energy use in 2014

A part 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. This study assumes that 6% (in2014 28 EJ) of the gross fossil fuel production is used for non-energy applications.

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 consume some 23% of the energy content of the fuels. Indirect energy use and losses due to flared and spilled fuels may not be 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 harder to refine, 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, due to liquefaction and transport.
- Conversion losses. In 2014 the average conversion efficiency of fossil fuels into electricity was about 38% [BP 2015], 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 358 EJ in 2014. Figure 4 represents the various energy flows.

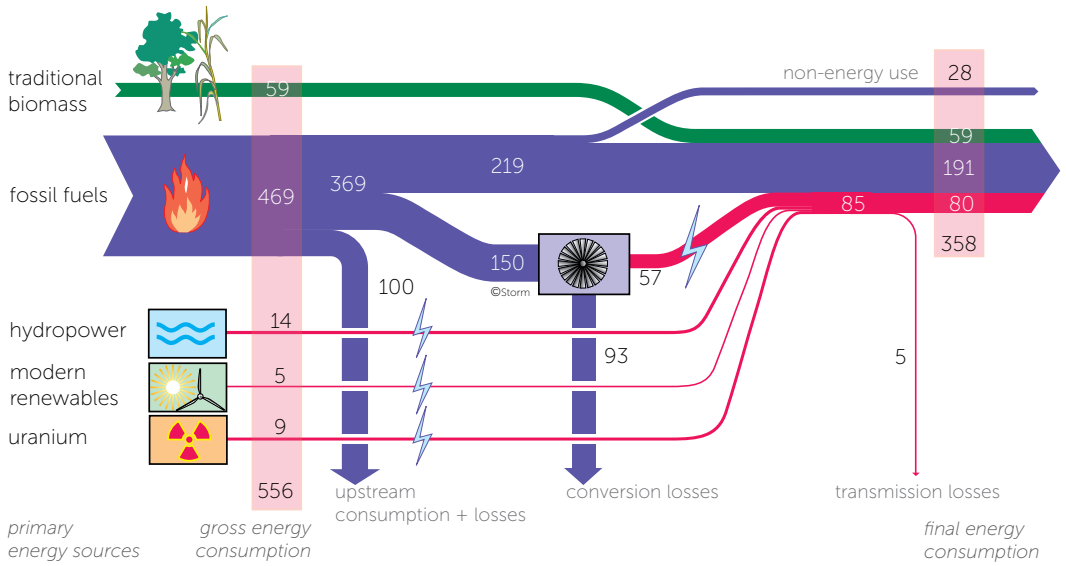


Figure 4

Outline of the physical energy flows of the world in 2014, in exajoules (EJ). Not accurately known are the amounts of energy embodied in traditional biomass and in the upstream losses of the fossil fuels. Therefore the world final energy consumption, here presented as 358 EJ, may have an uncertainty range. Sources: [BP 2015] and [IEA 2016]. Because no clear data could be found in the publications of BP and IEA regarding non-energy use, and, moreover, exact figures would not be relevant in this matter, this study assumes that 6% of the gross fossil fuel production was used for non-energy purposes in 2014; non-energy use of biomass is left out of this diagram.

2 Mitigation potential of nuclear power

Nuclear contribution to CO_2 emission reduction in 2014

As far as known the IAEA and nuclear industry did not publish figures on this subject. To get an impression of the potential contribution of nuclear power to the mitigation of global greenhouse gases emissions this study starts with the assumption that nuclear power is free of greenhouse gases (GHGs).
The current nuclear contribution can be estimated based on just two data sets:

- sources of the global GHG emissions, and
- nuclear share of the world energy supply.

Technical data on the nuclear system itself are not needed for this estimate. This chapter addresses the current nuclear mitigation contribution and the prospects by the year 2050, starting from the above assumption, in two scenarios as envisioned by the International Atomic Energy Agency (IAEA).

Nuclear power is one of energy systems providing the world economy with useful energy. 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 to the CO_2 emissions by the energy sector: 30% of the total global GHG emissions (Figure 2).

In 2014 the global nuclear generating capacity was 376 GWe producing 2410 TWh (8.7 EJ) of electricity, according to [IAEA-*sdr1* 2015]. [BP 2015] cites a higher figure of the nuclear electricity production in 2014: 2536.8 TWh or 9.1 EJ, rounded to 9 EJ. This study uses the higher BP figure of the production and the IAEA figure of the actually operating reactors (376 GWe). The global nuclear electricity generation of 9 EJ formed 1.6% of the world energy production in 2014 (see Figure 2 and Table A1 in Annex A).

Non-fossil fuelled electricity generation techniques, such as nuclear, hydro, solar, wind, biomass and geothermal power, may considered to displace fossil fuels. Estimation of the amounts of displaced fossil fuel units seems a relevant method in the discussion on mitigation of the global CO_2 emission and climate change.
Coupling Figures 2 and 4 in a simplified model this study assumes that in addition to the input of 150 EJ of fossil fuels for generation of 57 EJ of electricity a proportional part of the upstream losses, (150/369)*100 = 41 EJ (rounded), is involved. The sum, amounting to a total of 191 EJ, would correspond with 30% (rounded) of the world CO_2 emission, see Figure 2.
In 2014 nuclear power generated 9 EJ of electricity, this would displace a fraction of fossil fuels amounting to (9/57)*191 EJ = 30 EJ, corresponding with a mitigation share of the global CO_2 emission of (9/57)*30% = 4.7%, assumed nuclear power is free of emissions of CO_2 and of other GHGs. This assumption is not valid, as will be proved in the following chapter 4. Evidently this way of calculating the mitigation share of GHG emissions is also valid for hydro power and other renewables.

Future contribution: 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?
As no figures were found in the open literature, this study estimates the hypothetic contribution to the mitigation in the future based on the envisioned developments of global nuclear generating capacity.
During the past years the International Atomic Energy Agency (IAEA) 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.

To gain some insight into this matter this study assesses two recent generating capacity scenarios of the IAEA that can be considered to be typical of the views within the nuclear industry, again assumed that nuclear power is free of emissions of CO_2 and of other GHGs.

[IAEA-*sdr1* 2015] expects a growth rate of the global energy consumption of 2.0 - 3.5%/yr until 2030. In order to place the scenarios of the nuclear industry in a global context after 2030-2050, this study assumes that this growth rate will continue until 2100. Conveniently is assumed also that the global GHG emissions will grow at the same 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 (NPPs) after reaching the end of their service life 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 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 continuously escalating costs and construction periods of new NPPs, a variant of scenario 0 seems not unrealistic. In this scenario the nuclear mitigation share will approach zero by 2060.

Scenario 1, IAEA Low: constant nuclear capacity,

The low scenario of the IAEA as published in [IAEA-*rds1* 2015] and [IAEA-*ccnap* 2016] corresponds with a constant nuclear generating capacity until 2050. In this scenario 1 this study conveniently assumes that the global operating nuclear capacity would remain flat at the current level of 376 GWe and the annual electicity production would remain 9 EJ/year.
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 an average of 7.4 GWe of new NPPs have to come on line, two times the current global construction pace of 3-4 GWe/year.

Scenario 1a
In scenario 1a the world energy consumption would rise by 2%/yr and consequently would reach a level of 1137 EJ/yr by the year 2050, and the global fossil-fuelled electricity generation would reach 114 EJ/yr. The nuclear contribution would have declined then to 9/1137 = 0.8% of the world energy supply.
The nuclear mitigating contribution would decline to about (9/114)*30 = 2.4% by 2050, if both the global energy production and the CO_2 emissions would rise at 2%/yr.

Scenario 1b
In the case of a global growth of 3.5%/yr the global energy consumption would reach a level of 2068 EJ/yr by the year 2050, and the global fossil-fuelled electricity generation 208 EJ/yr.
The nuclear energy contribution would decline to 9/2068 = 0.44% of the world energy supply.
The nuclear mitigating contribution would decline to about (9/208)*30 = 1.3% by 2050, if both the global energy production and the CO_2 emissions would rise at 3.5%/yr.

Scenario 2, IAEA High, constant mitigation

In its high scenario [IAEA-*rds1* 2015] foresees a nuclear capacity of 964 GWe by 2050, a more recent figure is about 900 GWe [IAEA-*ccnap* 2016]; this study starts from the higher figure. Both estimates by the IAEA are significantly lower than the figure of 1092 GWe by 2050 published in 2014.
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 presented scenario's of higher global nuclear capacity; these scenarios are not discussed in ths study.
Assumed that the new nuclear power stations would operate at the same average load factor as the currently operating NPPs, the nuclear electricity generation would be 26 EJ/yr by 2050.
This scenario would imply an average global construction rate of 27 GWe of new reactors a year, compared with the current rate of 3-4 GWe/year. It is unclear how realistic this assumption is, in view of the current problems in the nuclear construction sector.

Scenario 2a
In scenario 2a the world energy consumption would rise by 2%/yr and consequently would reach a level of 1137 EJ/yr by the year 2050, and the global fossil-fuelled electricity generation 114 EJ/yr. The nuclear contribution would rise to 26/1137 = 2.3% of the world energy supply.
The nuclear mitigating contribution would rise to about (26/114)*30 = 6.8% by 2050, if both the global energy production and the CO_2 emissions would rise at 2%/yr.

Scenario 2b
In the case of a global growth of 3.5%/yr the global energy consumption would reach a level of 2068 EJ/yr by the year 2050, and the global fossil-fuelled electricity generation 208 EJ/yr.
The nuclear energy contribution would decline to 26/2068 = 1.3% of the world energy supply.
The nuclear mitigating contribution would decline to about (26/208)*30 = 3.8% by 2050, if both the global energy production and the CO_2 emissions would rise at 3.5%/yr.

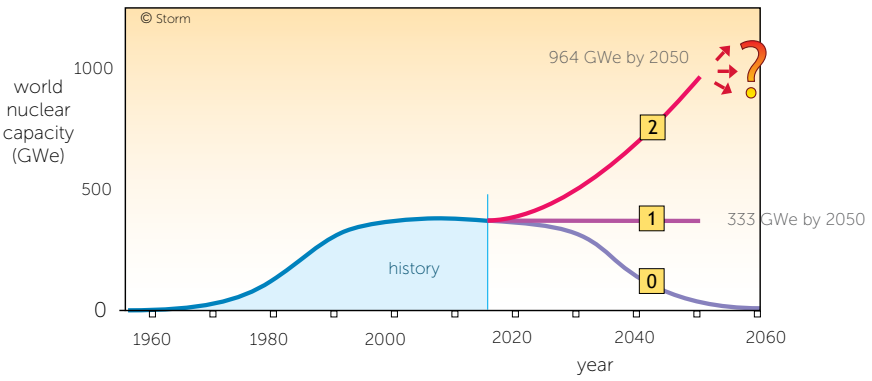


Figure 5
Three scenarios of the nuclear capacity until 2050. Scenario 0 represents phase-out of the existing nuclear capacity in the coming decades. Although the global capacity trend is declining, Scenario 0 is a hypothesis and is not discussed in the text. Scenario 1 represents the IAEA low scenario, and Scenario 2 the IAEA high scenario, discussed in the text. Both IAEA scenarios end by 2050, the IAEA did not indicate what they envision after that year. This issue is discussed in the next section.

After 2050

The future does not end at 2050. No investor will start the construction of new nuclear power plants in the year 2049 without assured uranium supply. This is one of the consequences of the extremely long-term commitments inherent to nuclear power. The plants coming on line in 2050 should have an assured uranium supply during their lifetime of, say, 40-50 years. 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?

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 scenarios, this study presents a variant of extending the scenarios 1 and 2 after reaching the indicated levels in 2050: no new NPPs would be built after 2050. All nuclear power plants then operating would be able to complete their normal operational lifetime and would be phased out, like scenario 0. This approach implies that the curves of scenarios 1 & 2 are slightly modified to give them a smooth transit to the phase-out, see Figure 6.
Obviously the nuclear contribution of the GHG mitigation after 2050 would decline to zero bij the year 2100 in the phase-out scenarios.

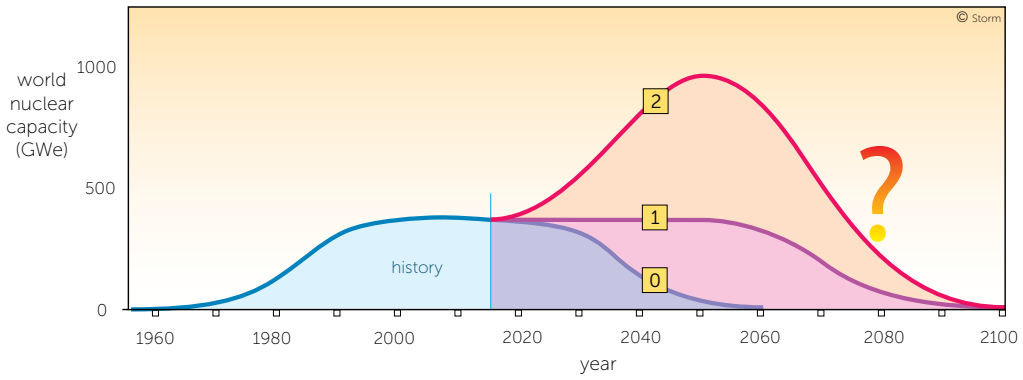


Figure 6
Scenarios 1 and 2 expanded to the year 2100, depicting the hypothetical case of phase-out after reaching the projected capacity by the year 2050. On the basis of these scenarios the minimum amount of uranium needed to materialise the scenarios 1 and 2 can be estimated.

Discussion and overview

From the mitigation figures in 2050 follows that scenario 2 may be roughly described as a 'constant contribution' scenario, and scenario 1 as a 'constant capacity' scenario.
The nuclear mitigation share in the two scenarios depends not only on the nuclear generation capacity, but also on the growth rate of the global fossil-fuelled electricity generation and the growth rate of the GHG emissions. Due to the uncertainties in the growth rates applied in the above calculations, the figures of the nuclear mitigation share are little more than indications of the order of magnitude.
Because nuclear power does emit CO_2 and most likely also significant amounts of other GHGs, as will be explained in the following chapters, the actual mitigation shares would be considerably less than the figures found based on the IAEA scenarios by 2050, summarized in Table 1. The actual mitigation share may even approach zero. The specific emission of CO_2 by the nuclear energy system is rising with time at an increasing rate as will be discussed in Chapter 4.

Table 1

Summary of the two nuclear capacity scenarios. In 2014 the virtual nuclear mitigation contribution was about 4.7%. The construction rates are counted from the year 2015 on. The nuclear mitigation contributions of the global GHG emissions are calculated assuming that nuclear power does not emit CO_2 nor other GHG gases. In practice the mitigation shares would be significantly lower, because nuclear power does emit CO_2 and other GHGs as well. For that reason the figures are called 'virtual'.

scenario		global growth rate %/year	capacity in 2050 GWe	constructi-on rate GWe/yr	nuclear E electricity in 20150 (EJ/yr)	fossil electricity in 2050 (EJ/yr)	world energy in 2050 (EJ/yr)	CO2 mitigation in 2050 (%)
1a	IAEA low	2	333	7.4	9	114	1137	2.4
1b	IAEA low	3.5	333	7.4	9	208	2068	1.3
2a	IAEA high	2	964	27	26	114	1137	6.8
2b	IAEA high	3.5	964	27	26	208	2068	3.8

In view of the current developments in the nuclear world, with a steadily declining nuclear capacity, the 'IAEA High' scenario seems not very probable. Even the 'IAEA Low' scenario seems questionable. From a practical point of view the maximum attainable mitigation share in 2050 would be 2.4% in Scenario 1a (IAEA Low), assumed nuclear power is free of GHG emissions, which it is not, as will be discussed in Chapter 4.

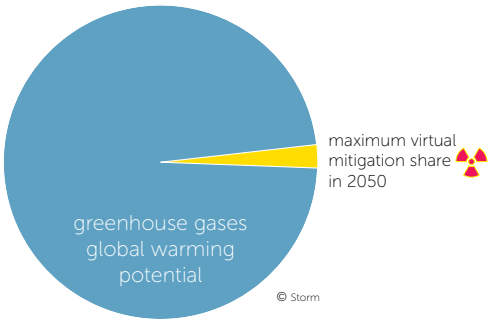


Figure 7

Maximum nuclear contribution to the mitigation of the global greenhouse gas emissions in 2050 in the IAEA Low nuclear scenario (see Table 1), provided that nuclear power is GHG free (which it is not).

Construction pace

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 1 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 the IAEA high scenario the required average construction rate in the period 2015-2050 would have to be about 27 GWe per year, 7-9 times the current rate.

In view of the massive cost overruns and construction delays of new NPPs already plaguing the nuclear industry during the last decade it is not clear how the required high construction paces could be achieved.

3 Important issues

The picture of the nuclear contribution to the reduction of CO_2 emissions, as presented in the previous chapter, is not as simple as it may seem. For judging the merits of nuclear power as means to mitigate climate change, the following issues should also be taken into account. Each of these isues are discussed briefly in the following chapters, and in more detail in the indicated Annexes. Annex A addresses the world energy consumption in 2014, the base year of this study.

1 *Actual emission of CO_2* Chapter 4, Annex B

The actual emission of CO_2 will be discussed in the next Chapter. The figures presented in this study are based on an elaborate physical analysis of the full nuclear process chain, from cradle to grave. This analysis also revealed the existence of novel notions, such as the energy cliff , CO_2 trap and delayed CO_2 emissions of nuclear power.

2 *Other GHGs* Chapter 5, Annex C

Official publications of the IAEA and nuclear industry do not mention the possibility of emission of GHGs other than CO_2 by nuclear power, neither confirmation, nor denial. A chemical assessment proves it inconceivable that nuclear power would not emit other GHGs.

3 *Figures of the IAEA* Chapter 6

The official figures of the nuclear CO_2 emissions presented by the IAEA and the nuclear industry are a fraction of the figures resulting from the physical analysis in this study. Why this divergence?

4 *Closed-cycle systems* Chapter 7, Annex F

The currenty operational power reactors cannot fission more than 0,6% of the nuclei in natural uranium. The nuclear industry states that in the future closed-cycle reactors could become available, able to fission 30% - 60% of the nuclei in natural uranium. A thermodynamic assessment reveals some insurmountable hurdles, based on the Second Law of thermodynamics, barring materialisation of the envisioned advanced nuclear generating concepts.

5 *Uranium resources* Chapter 8, Annex D

Another important point is the availability of uranium in the future: how large are the uranium quantities that would be needed to make the various scenarios possible and how large are the known resources? This issue turns out to be be less simple than comparison of the uranium demand with the known uranium resources. The size of the world uranium resources as energy source are limited by the energy cliff and the thermodynamic quality of the uranium-bearing rocks.

6 *Latent entropy* Chapter 9, Annex E

A unique feaure of nuclear power is the generation of human-made radioactivity: each year a reactor of 1 GWe produces an amount comparable with 1000 exploded Hiroshima bombs. This fact may bee seen as the generation of latent entropy, Practical consequences of the latent entropy are the energy debt and delayed emissions of CO_2 and possibly also of other GHGs.

4 Actual emission of CO_2 by nuclear power

Nuclear process chain

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. This sequence of industrial activities from cradle to grave is called the nuclear process chain.

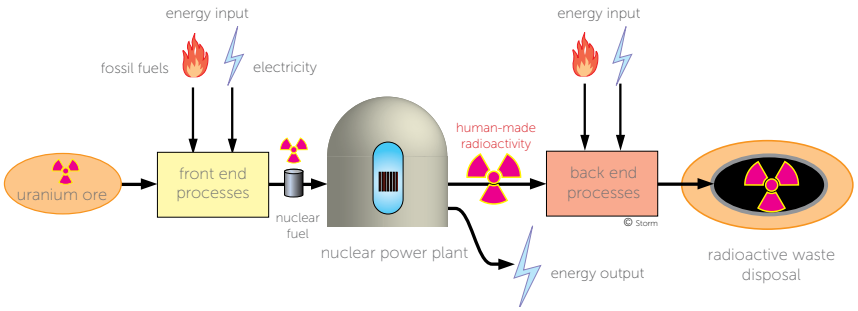


Figure 8

Simple outline of the nuclear process chain, also called the nuclear energy system, from cradle to grave. 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 disposal of all radioactive wastes).

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

- The front end of the nuclear chain comprises five processes - mining, milling, refining and conversion, enrichment, fuel fabrication - to produce nuclear fuel from uranium ore and are mature industrial processes.
- The midsection encompasses the construction of the nuclear power plant plus operating, maintainance and refurbishment it during its operational lifetime.
- The back end comprises the 12 processes needed to manage 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.

The back end comprises a larger number of industrial processes than the front end: the nuclear system has a more extensive back end than any other energy system, for more details see Annex B. The most important processes of the back end, needed to isolate the radioactive wastes permanently from the human environment, are not operational. Since the first nuclear reactor became critical in 1945 all human-made radioactivity is still awaiting final treatment and safe disposal.

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 processes does not need advanced technology, it is just a matter of getting started with investments of energy, materials and human effort.

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.

CO_2 emissions in the nuclear process chain

The emission figures of this study are based on a life cycle assessment (LCA) and energy analysis of the complete process chain from cradle to grave of a nuclear power station, representative of the newest currently operating NPPs. Assumed lifetime productivity of the reference reactor is 25 full-power years (FPY); one FPY corresponds with the electricity production during one year at 100% capacity. The world average productive lifetime of the currently operating NPPs is about 23 FPY.

The figures of the specific CO_2 emission of the full nuclear energy system found by this detailed analysis are summarised in Table 2. Assumed feedstock of the nuclear energy system is uranium ore at a grade of 0.05% U (0.5 gram uranium per kg ore), this is about the present world average grade. The ore grade dependence of the specifiec CO_2 emission is in detail addressed in Annex B and briefly discussed in the next section.
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 2
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 operational lifetime 25 FPY
1	uranium recovery (mining + milling) , (ore grade dependent)	8.4
2	other front end processes	6.2
	sum front end processes	14.6
3	construction (mean)	23.2 ± 11.6
4	operation, maintenance & refurbishments OMR	24.4
	sum mid section processes	47.6 ± 11.6
5	back end processes excluding 6 and 7	12.1
6	decommissioning & dismantling (mean)	34.8 ± 17.4
7	mine rehabilitation (ore grade dependent)	7.6
	sum back end processes	54.5 ± 17.4
	sum full nuclear energy system	117 ± 29

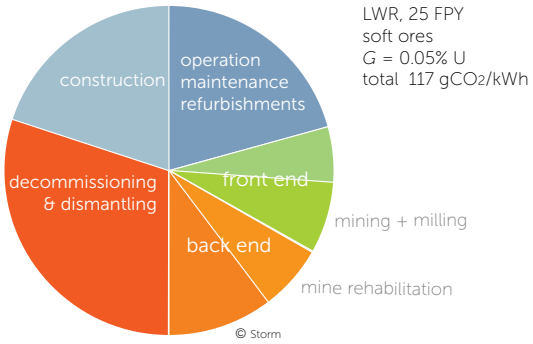


Figure 9

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 2. The contribution of mining + milling and mine rehabilitation are ore grade dependent.

In view of the large specific consumption of materials by the nuclear system of more than 200 g/kWh, compared with 5-6 g/kWh of an equivalent wind power system (see Annex B), it seems inconceivable that the nuclear system would emit less CO_2 than wind power, as stated by the nuclear industry.

CO_2 trap

The first step in the nuclear chain is the recovery of uranium from the earth's crust. The investments of energy and materials to recover 1 kg of uranium rise exponentially with decreasing grade (uranium content) of the mined ores. The richest ores known ores contain some 20% uranium and the poorest classified ores contain about 0.02% U, a difference by a factor of 1000. Higher energy investments per kg U result in a higher specific CO_2 emission of nuclear power. Below grades of around 0.02% U nuclear power surpasses the emission of fossil-fueled electricity generation. Therefore this phenomenon is called the *CO_2 trap*.

The grade distributon of the world uranium resources follows a common geologic pattern. Uranium deposits are more rare the higher the grade of the deposit, and sizes of deposits (amount of contained uranium) are larger the lower the grade of the deposits.
The world average grade of the mined ores is steadily declining with time, because the ores of highest quality are always mined first, offering the highest return on investment, so the remaining deposits are leaner in uranium. This observation is valid for all metal resources.

The average ore quality of the known uranium resources is steadily declining with time. Consequently the specific CO_2 emission by the nuclear energy system is rising over time. The rate of increase is uncertain for a number of reasons: uncertainties about operational lifetime, development of the global nuclear generating capacity, new uranium resource discoveries, etcetera.
If no new large uranium ore deposits of high thermodynamic quality (for explanation see Annex B) are discovered during the next decades, the nuclear CO_2 emission may surpass the specific CO_2 emission of gas-fired stations, and even coal-fired stations, within the lifetime of all newly constructed nuclear power plants. Figure 1 gives an impression of the CO_2 trap over time in two scenario's.

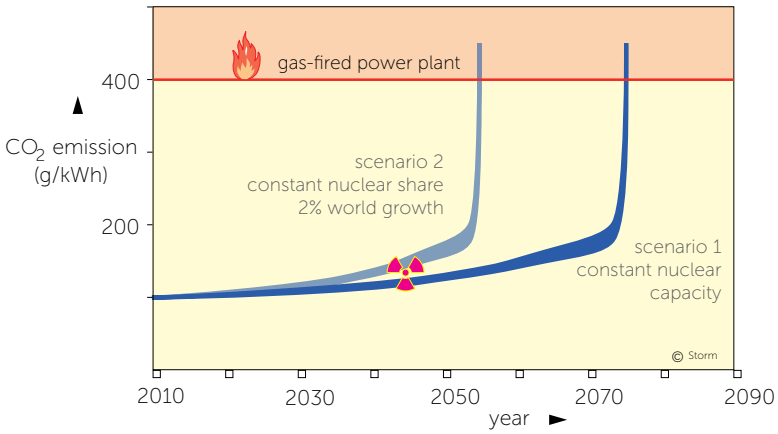


Figure 10

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.

5 Emission of other GHGs by nuclear power

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 greenhouse gases have a global warming potential (GWP) thousands of times larger than CO_2. A zero-carbon process may have a significant contribution to anthropogenic global warming if it emits high-GWP greenhouse gases.
Table C1 in Annex C shows that gaseous halocarbons and other gaseous halo-compounds may be potent greenhouse gases, up to 22200 times as strong as carbon dioxide, meaning that the emission of 1 g of such a compound has the same effect as 22.2 kg CO_2. Releases small in mass may have large effects.

Nuclear process chain

In all processes from uranium ore to nuclear fuel (front end) 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.

Annex C addresses several processes in the front end of the nuclear chain in which large amount of high-purity fluorine and chlorine are used. Doubtless significant amounts of these elements and fluoro and chloro compounds from the involved processes are released into the environment.

Nuclear emission of non-CO_2 greenhouse gases: not reported

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 no data are found in the open literature on the emissions of fluorine- and chlorine-related chemical compounds by the nuclear industry. [Vattenfall EPD 2005] noticed the absence of data on emission of greenhouse gases by processes needed to convert uranium ore into nuclear fuel.
Twenty years of searching official publications of the IAEA and the nuclear industry did not yield even one mention of other GHGs from nuclear related processes, but also never a statement was found that other GHGs could *not* be related to nuclear power.
'Not reported' does not mean 'no emissions'..

Discharges of fluoro and chloro compounds

In the front processes of the nuclear chain, comprising the processes needed to produce enriched uranium fuel elements from uranium ore, large amounts of fluorine, chlorine and chemical compounds of these elements are used. Globally about 66000 tons per year of natural uranium are processed, and the consumption of fluorine and chlorine might amount to approximately 100000 and 50000 tons per year respectively. More details are discussed in Annex C.
Unavoidably substantial amounts of fluorinated and chlorinated substances escape into the environment during these processes, in waste streams and as a result of leaks and small accidents. No chemical plant is leak-proof.
For that reason 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.

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.

6 Official CO_2 emission figures

CO_2 emission figures from the IAEA

In its most recent report concerning GHG emissions of nuclear power, *Climate Change and Nuclear Power* [IAEA-*ccnap* 2016], the International Atomic Energy Agency (IAEA) states:

> "Nuclear power is among the energy sources and technologies available today that could help meet the climate–energy challenge. GHG emissions from nuclear power plants (NPPs) are negligible, and nuclear power, together with hydropower and wind based electricity, is among the lowest GHG emitters when emissions over the entire life cycle are considered, standing at less than 15 grams CO2-equivalent (g CO2-eq) per kW·h (kilowatt-hour)."

and:

> "In order to make an adequate comparison, it is crucial to estimate and aggregate GHG emissions from all phases of the life cycle of each energy technology. Properly implemented life cycle assessments include upstream processes (extraction of construction materials, processing, manufacturing and power plant construction), operational processes (power plant operation and maintenance, fuel extraction, processing and transportation, and waste management), and downstream processes (dismantling structures, recycling reusable materials and waste disposal). The estimates for each of these phases involve some uncertainty inherent in the method used."

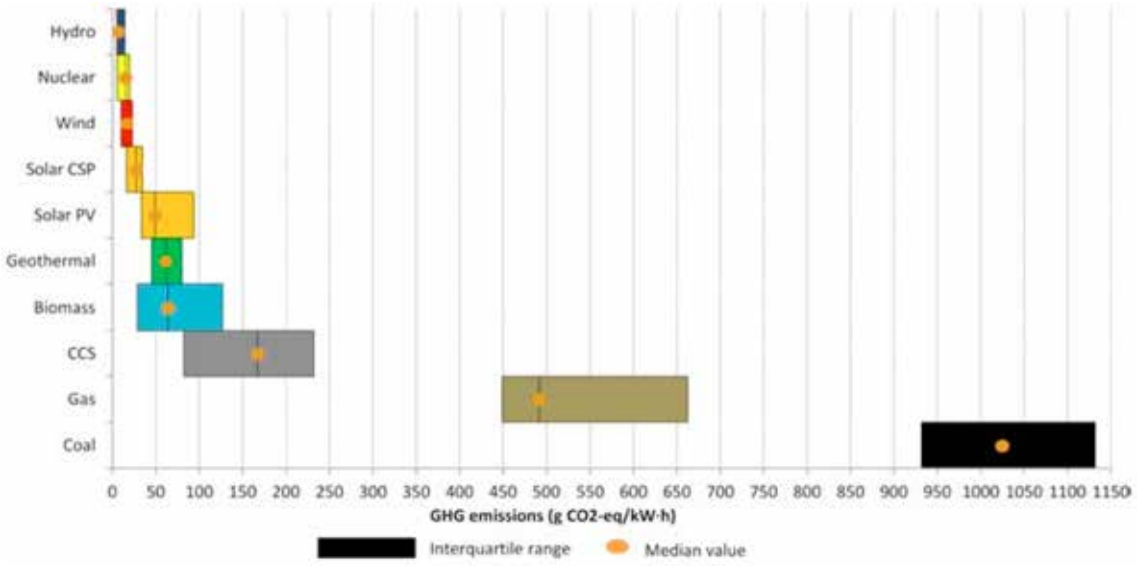


Figure 11
Life cycle GHG emissions from electricity generation. Source: [IAEA-*ccnap* 2016].

The IAEA cites a specific emission figure of less than 15 gCO_2eq/kWh, this is far lower than the figure found in this study: rounded 90-150 gCO_2/kWh. Although the IAEA in the above quote states that all phases of the life cycle of each energy technology should be taken into account, the IAEA apparently failed to implement this statement into its own assessment of nuclear CO_2 emission.

Some remarks and findings of the life cycle analysis in this study (see Annex B) are:
Just the recovery of uranium from the crust emits 8.4 gCO_2/kWh, a figure based on data from the mining companies themselves. The ore grade dependency of the nuclear CO_2 emissions found in this study is not mentioned, although this has been confirmed by [Prasser *et al.* 2008].
The total emission of the complete front end is found to be 14.6 gCO_2/kWh.

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].
Apparently the nuclear back end processes re not included in the IAEA figures.
It is unclear how the figures of the IAEA are established. Numerical results from mutually dependent studies, with undefined system boundaries and applying different assessment methodologies and system boundaries, are statistically processed as if they were stochastic measurement data on the same quantity, which they are not. Moreover many studies are not really independent, but are based on the same original studies, often dating from the early 1970s. [Sovacool 2008] compares a number of publications concerning nuclear GHG emissions.

False comparison

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 GHG emissions 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.
Emissions of greenhouse gases other than CO_2 by nuclear power 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.

Comparing de GHG emissions of wind power and solar PV energy systems with nuclear power, using the unit gCO_2**eq**/kWh, the nuclear industry compares 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. Most important is the observation that the solar PV and wind power figures concern only the construction phase of the life cycle. During operation of these energy systems no inputs of materials are needed, contrary to nuclear power and fossil fuels. Apparently the contributions of construction, operation, maintenance and refurbishments of a nuclear power plant are left out of the IAEA figures.

7 Prospects of advanced reactor systems

Advanced nuclear technology

The present global nuclear fleet is based on thermal-neutron reactors, most of them being light-water reactors (LWRs), operating in the once-through mode with natural uranium as its primary energy source. The most advanced types of the currently operating reactors cannot fission more than 0.6% of the nuclei in natural uranium.

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).
- Implementation of 'fast reactors', uranium-plutonium (U-Pu) 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 (Th-U breeders). In theory thorium could substitute uranium as input for nuclear power, according to the nuclear industry.

Development of closed-cycle nuclear power systems (breeders) that would be able to fission at least 50 times more nuclei present in natural uranium will take several decades, according to the nuclear industry. In the optimistic prognoses the first NPP based on the breeder reactor could become operational by 2050. Even this prognose seems questionable in view of the fact that, after more than 60 years of research and development in several countries (e.g. USA, UK, France, Germany, the former Soviet Union) with investments exceeding €100bn, still not one operating breeding system exists in the world.

What is called a 'breeder' is not just a reactor type or a stand-alone system. To exploit fully the promised potential of natural uranium, a complex breeder cycle system is a prerequisite, consisting of three components: a breeder reactor, a reprocessing facility and a fuel fabrication plant. Aim of the breeder cycle is the production of more fissile material than it consumes for fission and energy production. At the end of its productive lifetime a breeder system should have produced a surplus of fissile material (Pu or U-233) at least enough to fuel two reactors: one to replace the discarded reactor itself and one new reactor.
All three components of the breeder cycle must operate flawlessly, continuously and exactly tuned to the other two components, in order to let the system actually breed more fissile plutonium from non-fissile uranium-238, or uranium-233 from non-fissile thorium-232, than it consumes. If one component fails, the whole system fails. In fact, none of the three components have ever demonstrated operation as required, let alone the three components together as one integrated continuously operating system.

The causes of this failure have nothing to do with arguments like: 'not economically attractive' (obviously a technically infeasible 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. Pivotal in the U-Pu and Th-U breeder cycles is the flawless separation of the spent fuel into numerous pure fractions, as soon as possible after unloading from the reactor, cycle after cycle. From the Second Law it also follows that the deterioration of materials by ageing processes are inevitable.
Problems of the breeder system are discussed in more detail by, among others, [UNIPEDE/CEC 1981] and

[Lidsky & Miller 1998]. These authors concluded that the breeder system is not feasible, not only due to the technical hurdles, but also because the system cannot meet the requirements of safety, proliferation and economy.
Annex F addresses the issue of closed-cycle reactor systems in more detail.

U-Pu recycle in LWRs

Reprocessing of spent fuel is a highly polluting process consuming massive quantities of energy and chemicals. Decommissioning and dismantling of a reprocessing plants at the end of its service life might be expensive, the costs might amount to hundred of billions of euros, and very time consuming: timescales off more than 100 years are mentioned. Needless to say that the investments of energy, materials and human effort would be huge.
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 could be displaced, 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 can be 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 and 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.

8 Uranium resources

Uranium demand

From the previous chapter it follows that in all scenarios the projected nuclear generating capacity are to be based exclusively on the current technology of thermal-neutron reactors and natural uranium as primary energy source. Table 3 summarises the uranium consumption rates and total uranium usage in the discussed scenario's, assuming that all reactors would be light-water reactors (LWRs) in the once-through mode. Plutonium recycle in LWRs plays a negligible part and may come to an end in the future.

Table 3

Summary of the projected nuclear capacity, mitigation contribution and total uranium demand in the two scenarios. The figures are based on the assumption that all reactors are LWRs in the once-through mode, without plutonium recycle.

scenario		year	capacity GWe	maximum mitigation % *	total U demand Tg
1	IAEA low	2050	376	1.3 - 2.4	2.3
	phase-out	2100	0	0	4.0
2	IAEA high	2050	964	3.8 - 6.8	4.5
	phase-out	2100	0	0	9.3

* Assumed nuclear power is free of GHG emissions (which it is not).

Uranium resources

Conventional 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 currently mined uranium resources are conventional resources. 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.

Unconventional 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.

Due to their low uranium content and other factors the recovery of uranium from these resources might require more useful energy than can be generated from the recovered uranium. Consequently these resources would be just uranium resources but not energy resources.

Table 4
Identified (conventional) uranium resources: reasonably assured resources (RAR) + inferred resources (IR) as of 1 January 2015 (rounded). Tg = teragram = 10^{12} gram = million metric tonnes. Source: [Red Book, 2016].
The higher cost categories include the lower ones. On 2 October 2017 the uranium price was about USD53/kgU, or €45/kgU according to [www.uxc.com].

RAR + IR cost category	resources Tg U
< USD 260/kg U	7.64
< USD 130/kgU	5.72
< USD 80/kgU	2.12
< USD 40/kgU	0.65

Phosphate rock
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 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. For more details see Annex D.

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, as is addressed in Annex B, 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.

Economics and uranium resources

The IAEA and the World Nuclear Association (WNA) 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 [WNA-*U* 2016]:

> "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."

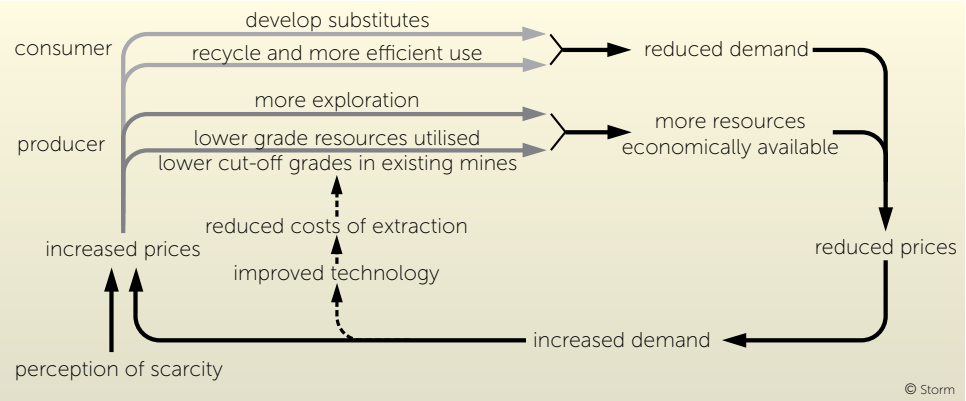


Figure 12
Economic model of the availability of mineral resources at large, according to [WNA-*U* 2016].

The production costs of the uranium are related to physical variables, such as the ore grade, ore body size and depth, mineralogy, transport distances, but non-physical factors may also contribute to the market price, e.g. economic and political factors, so the qualification 'economically recoverable' is flexible notion. 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.

9 Latent entropy, energy debt and delayed GHG emissions

Latent entropy

Every system that generates useful energy from mineral sources, fossil fuels and uranium, releases unavoidably also a certain amount of entropy into the environment. Entropy may be interpreted as a measure of dispersal of matter, energy and directed flow. More entropy means more disorder. An increase of the entropy pf the biosphere can manifest itself in many different phenomena, such as dispersal of waste heat, discharges of CO_2 and other GHGs, disturbing ecosystems, pollution of air and water with chemicals. Anthropogenic climate change is typical an entropy phenomenon.
Entropy effects from the use of mineral energy sources can partly be compensated for by investment of useful energy, such as electricity, and human effort. From the Second Law of thermodynamics follows that the generation of a given amount of useful energy from a mineral energy source is inevitably accompanied by the generation of more entropy than could theoretically be 'neutralised' by that amount of useful energy.

Uranium is a mineral energy source, so the above observation regarding entropy generation is also valid for nuclear power. In the nuclear power plant the potential energy in the uranium is converted into heat and radiation, and the heat is partially converted into electricity. During these conversions large amounts of entropy are generated. A part of the entropy becomes observable during operation of the nuclear power plant, such as: waste heat, nuclear radiation, dispersal of radioactive and non-radioactive materials. The main part of the entropy is contained in the nuclear fuel elements and the reactor, and its effects are not observable at the moment of its generation. However, the question is not *if* nuclear power generates entropy - the Second Law is relentless -, the question is: *how* can it become manifest?

The entropy contained in spent nuclear fuel will unavoidably be released into the biosphere if no measures are taken to prevent that. The disasters of Chernobyl and Fukushima showed the possible effects of unretained nuclear entropy. As long as nuclear entropy is enclosed in spent fuel elements it is called the *latent entropy* of nuclear power.

The latent entropy forms a bill for the use of nuclear power to generate electricity. Thermodynamics tells us that an entropy bill can only be paid by investments of useful energy and dedicated human effort. The energy to be invested in the future to pay the bill for the nuclear generated electricity consumed today is called the *energy debt* in this study. If the entropy bill is not paid humankind might expect nuclear disasters that would dwarf Chernobyl and Fukushima.

Energy debt

Purpose of the back-end processes of the nuclear chain would be to keep the latent entropy under control. Size and implications of the entropy bill may be greatly underrated by the nucleasr industry.
As pointed out in Chapter 4 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. No new technology is required.

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*. For more details see Annex D.

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, due to several factors:

- Increasing amount of radioactive materials generated as long as nuclear power generation is 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.
- Preotection against terroristic actions.
- 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 copper from its 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 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 with that of other energy systems. From Table 2 in Chapter 4 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, but well conceivable.

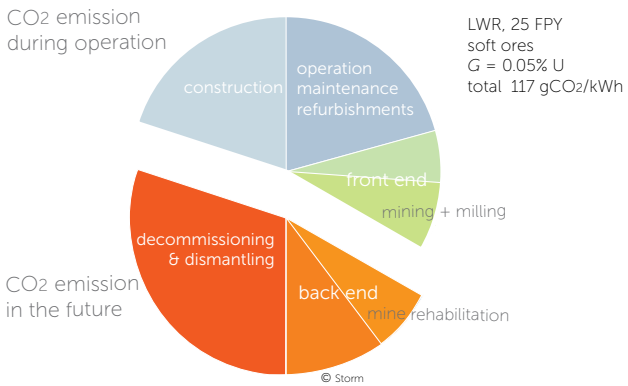


Figure 13

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.

Annex A

World energy supply

World gross energy supply

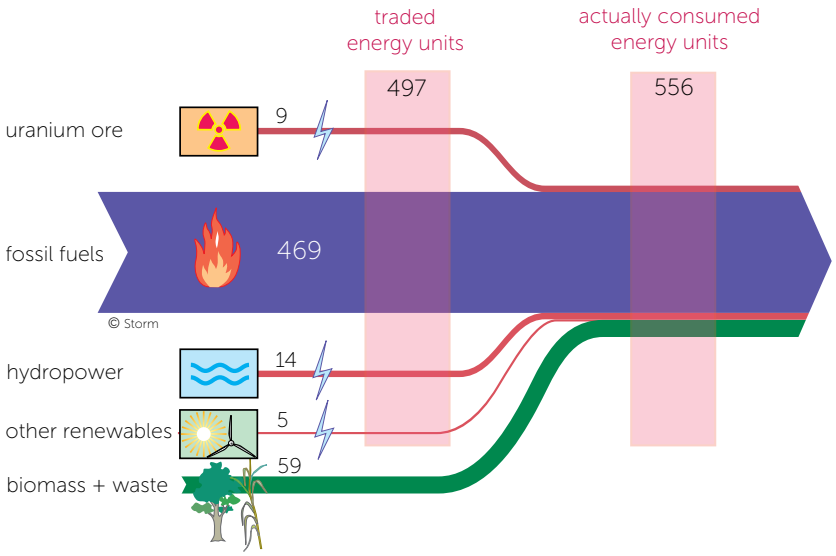
In 2014 the world gross energy consumption was about 556 EJ (exajoule, 1 EJ = 10^{18} J), that is the sum of the combustion heats of fossil fuels and biomass plus the electricity generated by hydropower, nuclear power and modern renewables. The total world energy consumption is not exactly known, for the 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 2015] 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 2016], although this publication does not make clear how it arrived at its figures.

Usually the energy flows in world energy statistics are given in million tonnes of oil equivalent (MTOE, also written as Mtoe, 1 MTOE = 0.042 EJ according to [BP 2015]). In most statistical energy reviews 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 38% (the currently operating nuclear power plants have 30-34% thermal efficiency). In its statistics before 2001 BP applied the factor $f = 3$ for nuclear and $f = 1$ for hydro and for 'modern renewables', (e.g. photovoltaics PV, wind, concentrating solar power CSP). In [IEA 2016] and probably also in other publications these conversion factors are still being used. In its last few editions of World Energy Statistics BP converts also electricity from 'modern renewables' into 'primary energy' units.
The issue of thermal equivalences will be discussed ion the next section 'thermodynamic inaccuracies'.

Table A1
Energy actually made available in 2014 to the global economic system. Sources: [BP 2015] and [IEA 2016]. 1 MTOE = 0.042 EJ, 1 TWh = 0.0036 EJ = 1 billion kWh, 1 EJ = 10^{18} joule.

	energy source	electricity TWh	fuels MTOE	real energy EJ	fraction %	traded MTOE *
1	nuclear **	2536.8		9.13	1.6	574.0 *
2	hydro	3884.6		13.98	2.5	879.0 *
3	other renewables	1400.6		5.04	0.9	316.9 *
4	oil		4211.1	176.87	31.8	4211.1
5	natural gas		3065.5	128.75	23.2	3065.5
6	coal		3881.8	163.04	29.3	3881.8
7	fossil fuels (sum 4+5+6)		11158.4	468.66		11158.4
8	traded energy (sum 1+2+3+7)			496.81		12928.3
9	biomass + waste		1411.0	59.26	10.7	–
10	world total (sum 8+9)		12569.4	556.07	100	–

* According to [BP 2015]. Conversion of electricity in TWh into 'primary' energy units MTOE is discussed in text below. These numbers are not used in this study. Electricity production in EJ is calculated from the reported production in TWh.
** Nuclear power produced in 2014 2543.2 TWh according to [BP 2016], 2410 TWh according to [IAEA-*ccnap* 2016], the reasons for these differences are not clear.



Gross world energy consumption 2014, physical flows in exajoules (EJ)

Figure A1

Actually delivered usable energy (in exajoules EJ) to the world economy in 2014. This diagram is based on Table A1. The numbers are rounded. Source of traded energy figures: [BP 2015]. The figure of traditional biomass (59 EJ) is not accurately known, source: [IEA 2016]. Other renewables comprise: solar (PV and CSP), wind, small hydro, geothermal and 'modern' biomass.

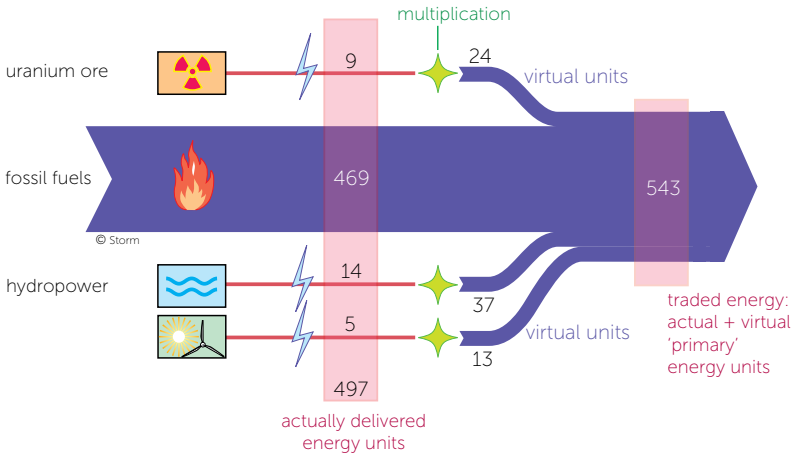
Table A2

World electricity generation in 2014. Sources: [BP 2015] and [IEA 2016].

	energy source	electricity TWh	EJ	fraction %
1	nuclear	2536.8	9.132	10.8
2	hydro	3884.6	13.985	16.5
3	solar	185.9	0.669	
4	wind	706.2	2.542	
5	geothermal + biomass	508.5	1.831	
6	sum 'modern' renewables (3+4+5)	1400.6	5.042	6.0
7	fossil	15714.5	56.572	66.8
8	world total (1+2+6+7)	23536.5	84.731	100

Thermodynamic inaccuracies

The heat from a nuclear reactor cannot be used directly, like the combustion heat of a fuel. The only form of usable energy (work) from a nuclear power plant is the electricity it delivers to the grid. A hydropower plant does not produce heat at all. Applying the statistical conversion of electricity into thermal equivalences 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 (work) units.



World traded energy production in 2014 (exajoules, EJ), commercial view

Figure A2

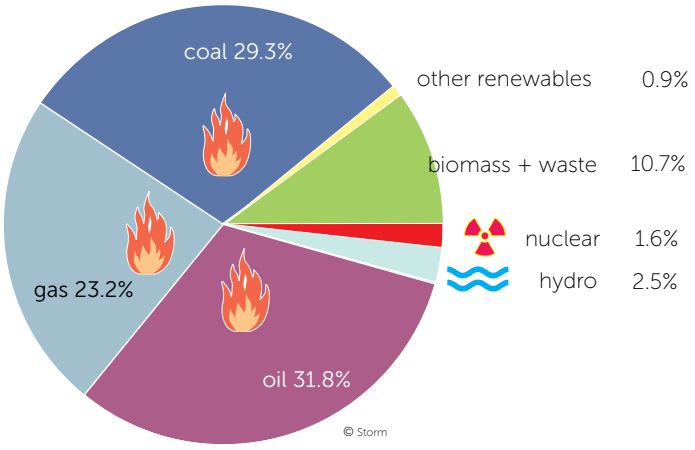
World energy production in 2014 according to [BP 2015] and the nuclear industry. The unit of energy in this diagram is the exajoule EJ, the original figures are counted in milion tons of oil equivalent (MTOE). This diagram comprises only traded energy flows. The electricity produced by nuclear power, hydro power and modern renewables is converted into virtual energy units, called 'primary energy' units. Before 2001 BP converted only nuclear energy into 'primary energy' units; in some other statistical publications this is still so. The virtual energy units are added to the actually delivered energy units. The numbers are rounded. Not included in the BP statistics is the energy in traditional biomass.

Conversion into thermal equivalence units seems to imply that 1 joule electricity from a nuclear power plant equals nearly 3 units of heat. This is in conflict with the First Law of thermodynamics: 1 joule of electricity, from whatever source, can be converted into not more than exactly 1 joule of heat.
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 quality cannot be added 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 A1, without using the notion 'thermal equivalence'. The electricity production figures of nuclear, hydro and other renewables are also listed in the actually measured unit terawatt.hour (1 TWh = 0.0036 EJ). Terawatt.hours and million tonnes oil equivalent cannot be added, so at least one of the two has to be converted. In Table A1 all figures are converted into joules, so they can be added.

In 2014 the nuclear share of the world gross energy production was 1.6%, as calculated in Table A1. Most energy statistics give another figure; for example [IEA 2016] cites a share of 4.8%. This divergence has two causes:

- Firstly BP lists only the traded energy (497 EJ in 2014) 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 $f = 2.64$, apparently the IEA uses a factor $f = 3$. This method of calculation results in a number of virtual energy units, and is thermodynamically questionable, as explained above.



world primary energy consumption in 2014: 556 EJ
traded real energy: 497 EJ, sum fossil fuels 469 EJ

Figure A3

World primary energy production in 2014 was about 556 EJ (exajoule), of which 469 EJ traded energy. The share of nuclear power was 1.6% in 2014 and is steadily declining. This diagram is based on Table 1 and [BP 2015]; [IEA 2016] comes to slightly different figures.

Mineral energy sources 85.9%: fossil fuels 84.3% + nuclear power 1.6%. Traditional biomass + renewables: 14.1%.

Final energy consumption

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 may not be 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 harder to refine, 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, due to liquefaction and transport.
- Conversion losses. In 2014 the average conversion efficiency of fossil fuels into electricity was about 38% [BP 2015], 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 358 EJ in 2014. Figure A4 represents the various energy flows.

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 2014, 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 2014 the figure of 59 EJ from [IEA 2016] is used.

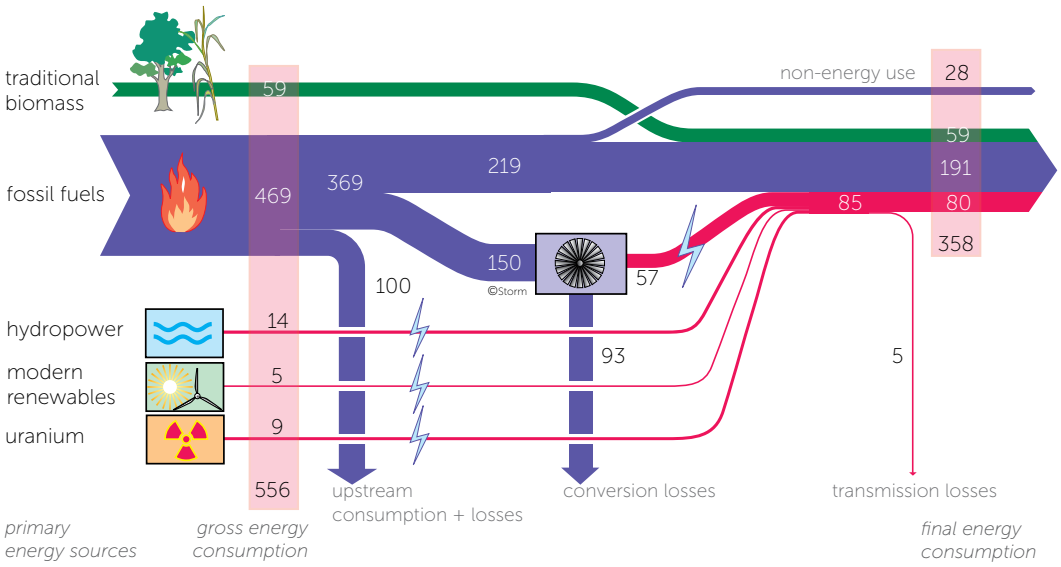


Figure A4

Outline of the physical energy flows of the world in 2014, in exajoules (EJ). Not accurately known are the amounts of energy embodied in traditional biomass and in the upstream losses of the fossil fuels. Therefore the world final energy consumption, here presented as 358 EJ, has an uncertainty range. Sources: [BP 2015] and [IEA 2016]. Because no clear data could be found in the publications of BP and IEA regarding non-energy use, 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 2014, and non-energy use of biomass is left out of this diagram.

Annex B

Actual CO_2 emissions of nuclear power

Why a thermodynamic analysis?

Arguments based on economic models may be 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, coupled to 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 may 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 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*.

Nuclear process chain

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. 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.

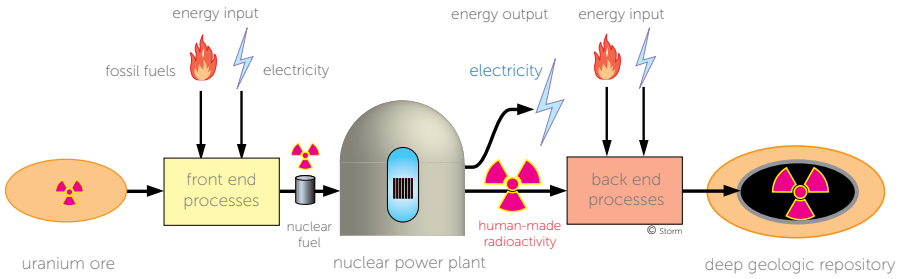


Figure B1

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).

Thwe three sections of the nuclear chain iare:

- 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 during its operational lifetime.
- 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 B2, a working out of the simple outline in Figure B1. As Figure B2 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

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.

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 products 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.
- rehabilitation of uranium mining areas after depletion of the ore deposits.

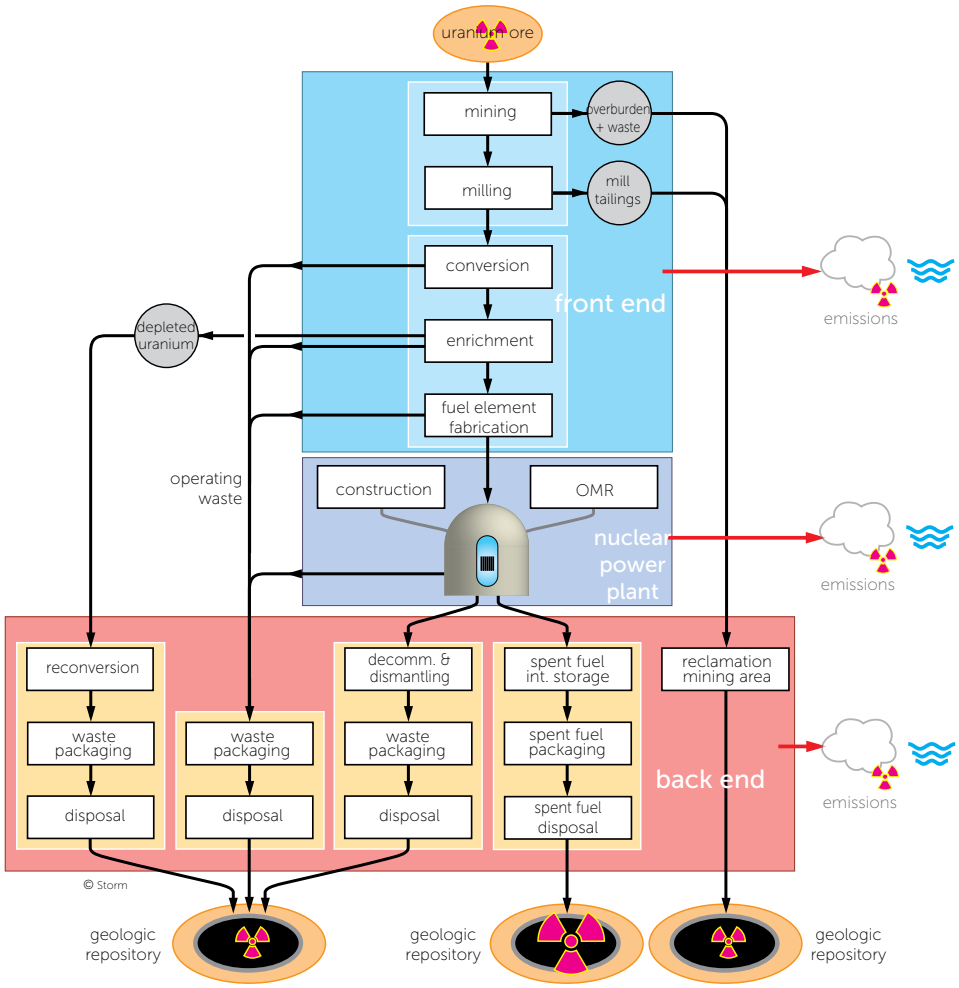


Figure B2

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 a few processes, spent fuel storage and packaging of operational waste from front end and reactor operation, are operational in the present practice. OMR = operation, maintenance and refurbishment

The above mentioned activities are included in the flowsheet in Figure B2, 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 B2 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.

Reprocessing of spent fuel is not included in the flowsheet of Figure B2, because closed-cycle systems would not play a significant part in the nuclear electricity generation in the foreseeable future.

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 result 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.

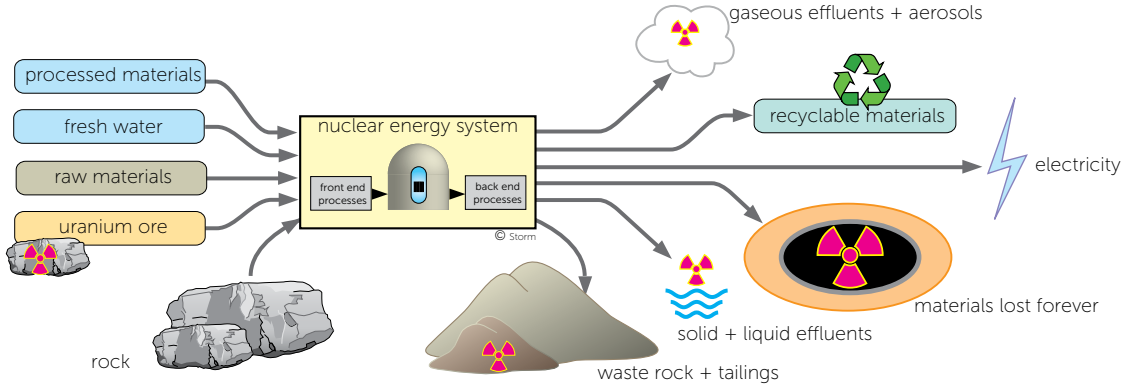


Figure B3

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 at temporary sites.

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 B4 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.

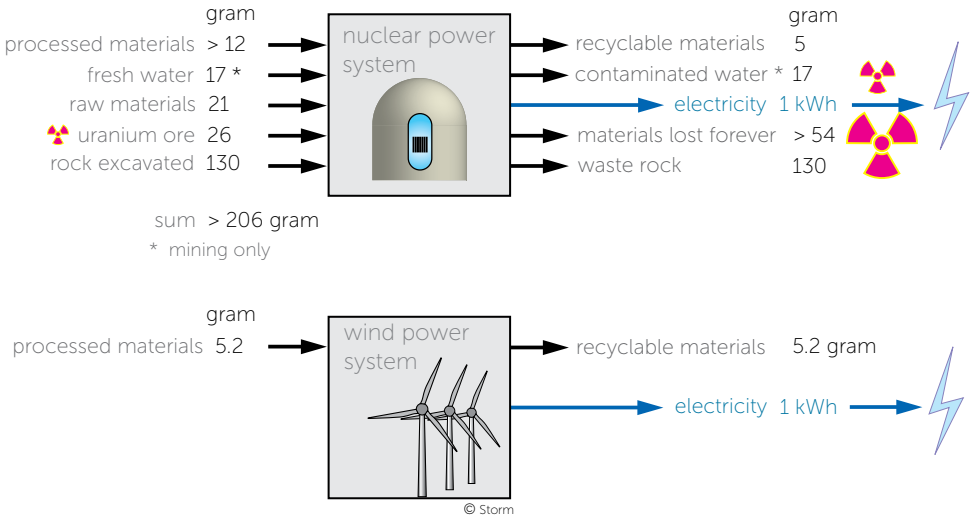


Figure B4

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 few operational data on the back end processes are 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 with investments of energy, materials and human effort.

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.

Energy analysis of the nuclear energy system

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 7 and in more detail in Annex F.

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 an operational lifetime of 25 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 23 FPY, a figure that has barely increased during the past years, so the baseline scenario of 25 FPY is slightly optimistic. 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.

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 per FPY 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 grade of the used uranium ore. These inputs per FPY are growing as will be explained in the next sections.

Results of the energy analysis

The energy analysis of the reference nuclear power station 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 B1 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.

Figure B5 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 B1, 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.

Table B1

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

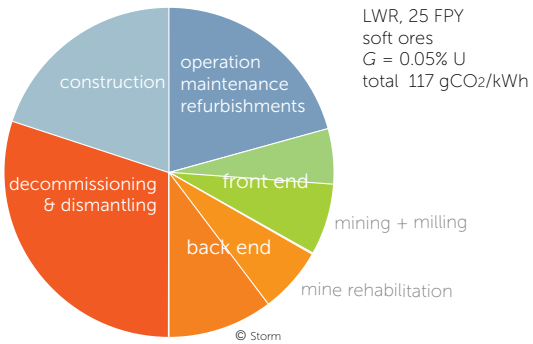


Figure B5

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 B1. The contribution of mining + milling and mine rehabilitation are ore grade dependent.

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.

Mine rehabilitation is not included in the figures from the nuclear industry.

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 B6 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.

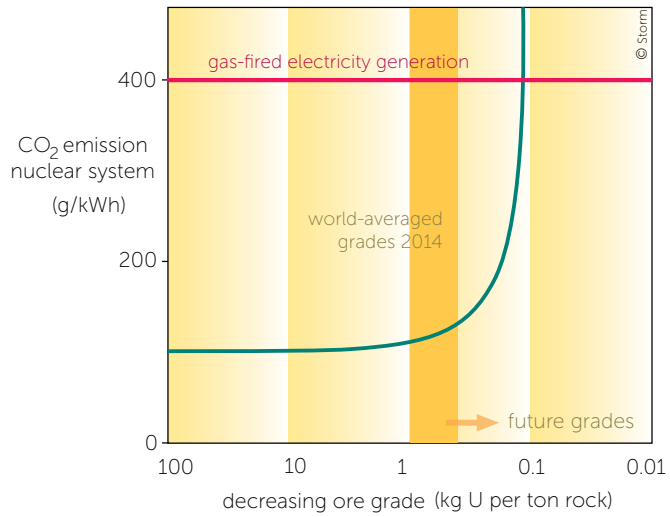


Figure B6
Specific CO_2 emission of the nuclear system (baseline case) as function of the uranium ore grade. At present the world-averaged ore grade is 0.1-0.05% U. This diagram is called the 'CO_2 trap'. The curve is similar to the curve of the thermal energy inputs of uranium mining and milling + mine rehabilitation as function of the ore grade.

The diagram of Figure B6 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

The amount of useful energy extractable from 1 kg natural uranium by means of the available reactor technology 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 declining 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 approaches 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 B7 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.

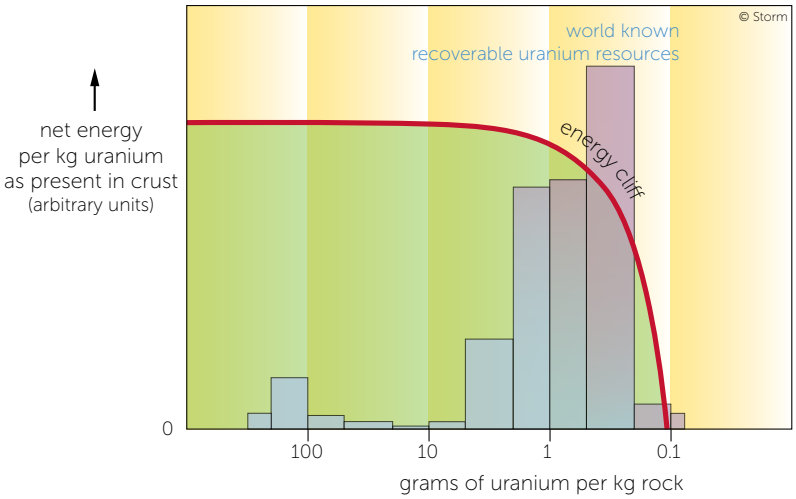


Figure B7
The energy cliff of the nuclear system in relation to the currently known recoverable uranium resources. The ore grade distribution of the known resources in 2014 does not differ significantly from the distribution in 2008, which forms the basis of the bar diagram.

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.

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 typical for uranium ores, but applies to all mineral resources, see for example [Mudd 2009], [Mudd 2011].

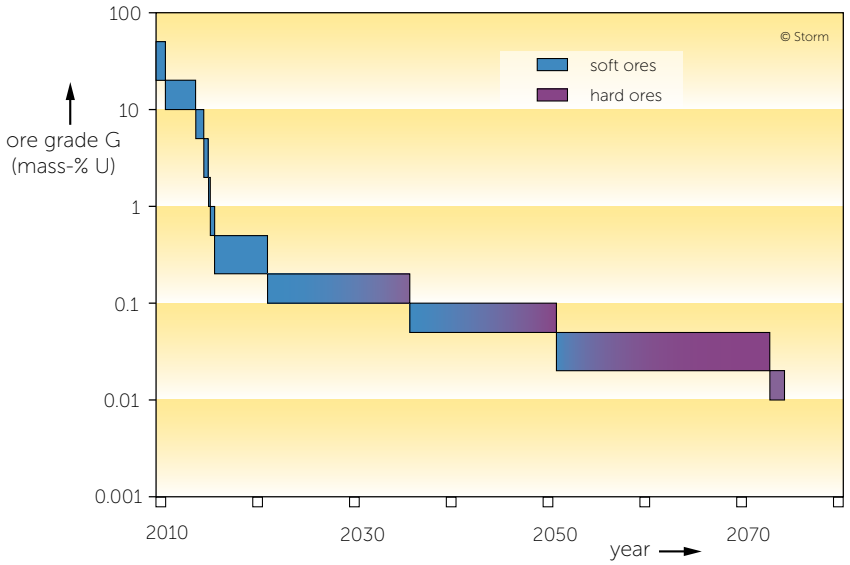


Figure B8

Depletion of the currently known recoverable uranium resources, at an assumed constant annual uranium consumption of 66 Gg/a in scenario IAEA Low. This diagram is based on the assumptions that no major new resources are discovered during the next 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 B7).

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 B6. 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 new nuclear builds.
Figure B9 gives a rough 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.
During the past three decades no major new uranium resources have been discovered.

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.

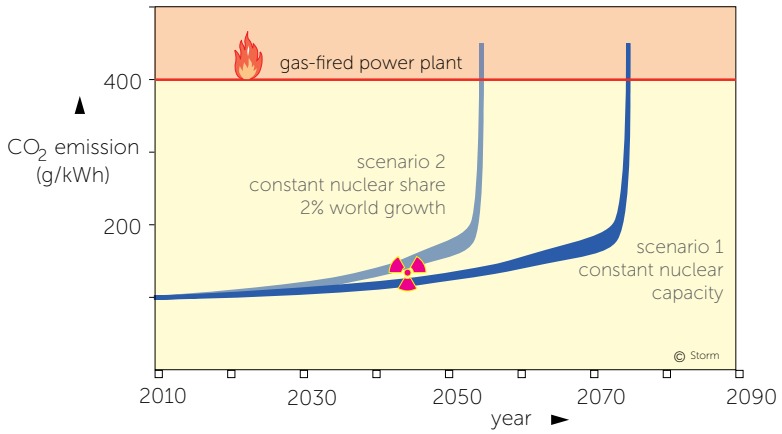


Figure B9

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.

Annex C

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 C1
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. Reuse of depleted uranium in MOX fuel is not a viable option, as explained in Chapter 7 and Annex F.

World wide some 66000 Mg natural uranium is fluorinated each year, consuming a stoichiometric minimum of about 32000 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: not reported

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. [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.

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, in addition `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.

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].

Annex D

Latent entropy, energy debt and delayed GHG emissions

Latent entropy

Every system that generates useful energy from mineral sources, fossil fuels and uranium, releases unavoidably also a certain amount of entropy into the environment. Entropy may be interpreted as a measure of dispersal of matter, energy and directed flow. More entropy means more disorder. An increase of entropy can manifest itself in many different phenomena, such as dispersal of waste heat, discharges of CO_2 and other GHGs, disturbing ecosystems, pollution of air and water with chemicals. Anthropogenic climate change is typical an entropy phenomenon.
Entropy effects from the use of mineral energy sources can partly be compensated for by investment of useful energy, such as electricity. From the Second Law of thermodynamics follows that the generation of a given amount of useful energy from a mineral energy source is inevitably accompanied by the generation of more entropy than could theoretically be 'neutralised' by that amount of useful energy.

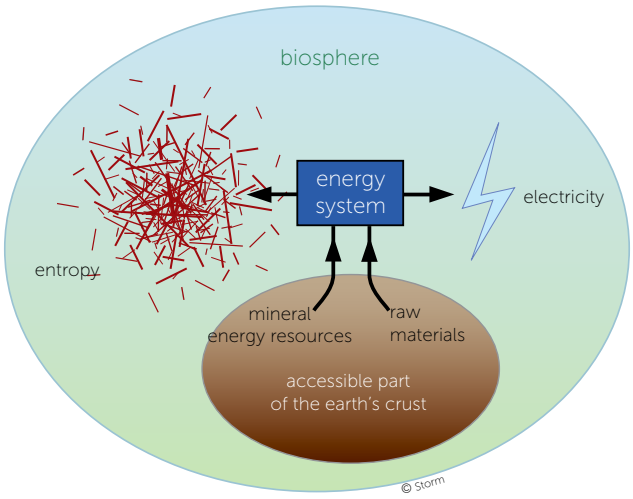


Figure D1
Generation of electricity from mineral energe sources within the biosphere. Inevitably the conversion generates entropy in the biosphere, with always deleterious effects.

Uranium is a mineral energy source, so the above observation regarding entropy generation is also valid for nuclear power. In the nuclear power plant the potential energy in the uranium is converted into heat and radiation, and the heat is partially converted into electricity. During these conversions large amounts of entropy are generated. A part of the entropy becomes observable during operation of the nuclear power plant, such as: waste heat, nuclear radiation, dispersal of radioactive and non-radioactive materials. The main part of the entropy is contained in the nuclear fuel elements and the reactor, and its effects are not observable at the moment of its generation. However, the question is not *if* nuclear power generates entropy – the Second Law is relentless –, the question is: *how* can it become manifest?

The entropy contained in spent nuclear fuel will unavoidably be released into the biosphere if no measures are taken to prevent that. The disasters of Chernobyl and Fukushima showed the possible effects of unretained nuclear entropy. As long as the nuclear entropy is enclosed in spent fuel elements it is called the *latent entropy* of nuclear power.

The latent entropy forms a bill for the use of nuclear power to generate electricity. Thermodynamics tells us that an entropy bill can only be paid by investments of useful energy and dedicated effort. The energy to be invested in the future to pay the bill for the nuclear generated electricity consumed today is called the *energy debt* in this study. If the entropy bill is not paid humankind may expect nuclear disasters that would dwarf Chernobyl and Fukushima.

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 D2 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*.

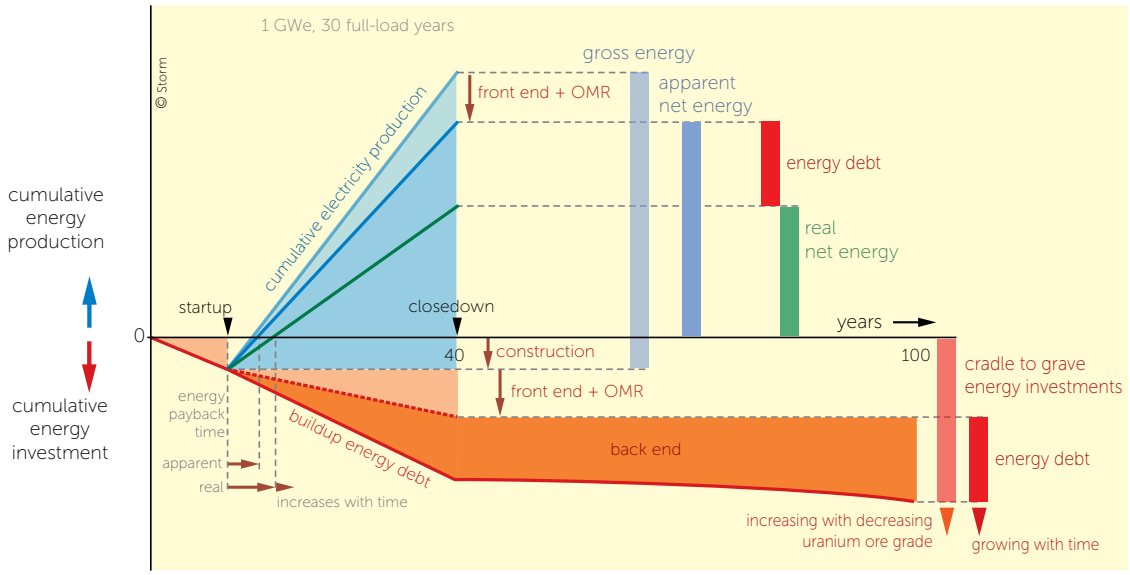


Figure D2

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 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.
- Protecting against terroristic actions.
- 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 copper from its 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 B1 in Annex B 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.

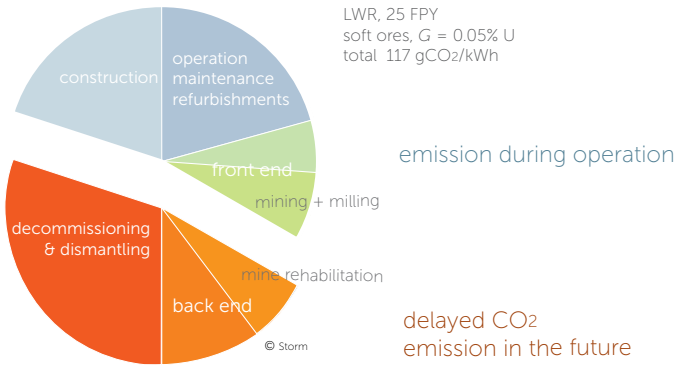


Figure D3

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 materials requires 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 D2) 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) states [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, may be millions 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 or lethal 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, UK and the USA, 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 other Chernobyl/Fukushima disasters? 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, 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 90-95% of the radioactivity is contained in spent fuel (if not reprocessed), the other 5-10% 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 waste 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 culture 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 rehabilitated 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, the latent entropy.
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 might become a hot issue when heavily contaminated nuclear installations would be dismantled; safe guardianship and disposal of the massive amounts of radioactive debris and scrap might 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, increase 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 any 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, conflict of interests

Communication between the nuclear industry and the national governments is dominated by the IAEA. The IAEA has two mandates: one as watchdog to prevent malicious use of nuclear technology – a role primarily restricted to guarding against illegal nuclear weapons production and proliferation risk –, the other as *promotor* of nuclear power. Moreover, official publications of the IAEA have to be approved by all member states of the IAEA. For these reasons the IAEA cannot be regarded as an independent scientific institute. No agency can be a true watchdog for an industry it is tasked with promoting. Political and economic interests may play a role in the decision processes concerning nuclear issues.
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.

The World Health Organization (WHO) also reports on the health aspects of nuclear power, especially in case of large accidents (Chernobyl, Fukushima). Although the WHO is an independent UN organization, its reports on nuclear matters are subject to IAEA's approval. According to an agreement between the International Atomic Energy Agency and the World Health Organization [UN Res. WHA12-40, 28 May 1959] the WHO cannot operate independently of the IAEA on nuclear matters, see also [Tickell 2009], [WHO 2009], [Sinaï 2013] and the preface of [WHO 2013a]. The IAEA ranks higher in the UN hierarchy than the WHO.
Concerning health effects of radioactivity the IAEA, ICRP, UNSCEAR and WHO speak with one voice.

From the reports of the IAEA, UNSCEAR and WHO on the subject of health effects, especially concerning the disasters of Chernobyl and Fukushima, emerges a picture 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 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 is 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 with handheld radiation counters
- 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.

The IAEA reports are committing elementary scientific flaws in downplaying and even denial of health effects caused by exposure to radioactivity and radioactive materials, externally and inside the body. Examples of questionable methods are:

- Presentation of 'definitive answers' on the consequences of the Chernobyl disaster [WHO 2005]
- Ignoring studies with diverging results, see e.g. IPPNW 2011].
- Missing proofs, see e.g. IPPNW 2011]
- Models prevailing over empirical evidence, [WHO 2005], [Chernobyl Forum 2006]
- Absence of a scientific discourse, absence of a dialogue, for example concerning the studies [KiKK 2007], [GeoCap 2012], [Mousseau et al. 2013]
- Downplaying critiques to 'ignorance' and 'fear of the unknown'

A downplaying trend becomes clear in the IAEA/UNSCEAR/WHO reports concerning the disasters of Chernobyl and Fukushima, see for instance the following studies and reports:
[UNSCEAR 2013b], [UNSCEAR 2011], TORCH 2006], [Greenpeace 2006], [Yablokov *et al*. 2009], [UCS 2011], [Yablokov 2011], [Chernobyl Forum 2006], [IPPNW 2011], [IPPNW 2013], [WNA-*chern* 2016], [Paulitz 2012], [Rosen 2012b], [WHO 2011a], [WHO 2012], [WHO 2013b],
This issue is not further addressed in this report.

Annex E

Uranium resources

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 E1

Identified (conventional) uranium resources: reasonably assured resources (RAR) + inferred resources (IR) as of 1 January 2015 (rounded). Tg = teragram = 10^{12} gram = million metric tonnes. Source: [Red Book 2016].
The higher cost categories include the lower ones. On 2 October 2017 the uranium price was about USD53/kgU, or €45/kgU according to [www.uxc.com].

RAR + IR cost category	resources Tg
< USD 260/kg U	7.64
< USD 130/kgU	5.72
< USD 80/kgU	2.12
< USD 40/kgU	0.65

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 E1.
How long could the currently known uranium resources feed the global nuclear fleet under the various scenarios? In 2014 the global nuclear fleet of 376 GWe of operableNPPs, according to the IAEA, had an annual usage of natural uranium of 66 Gg/year, according to [WNA-worldU 2015].

Table E2

Summary of the projected nuclear capacity, mitigation contribution and total uranium demand in the two scenarios. The figures are based on the assumption that all reactors are LWRs in the once-through mode, without plutonium recycle.

scenario		year	capacity GWe	maximum mitigation % *	total U demand Tg
1	IAEA low	2050	376	1.3 - 2.4	2.3
	phase-out	2100	0	0	4.0
2	IAEA high	2050	964	3.8 - 6.8	4.5
	phase-out	2100	0	0	9.3

* Assumed nuclear power is free of GHG emissions (which it is not).

From Tables E1 and E2 it follows that only scenario 2 with phase out is questionable, in view of the currently known recoverable uranium resources. Likely the energy cliff and CO_2 trap could prevent materialisation of that scenario.

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.

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 1980], 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 km^2 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. Even closed-cycle technology would not offer a solution, due to the negative energy balance of these technologies, if feasable at all.

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-*U* 2016]:

> "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."

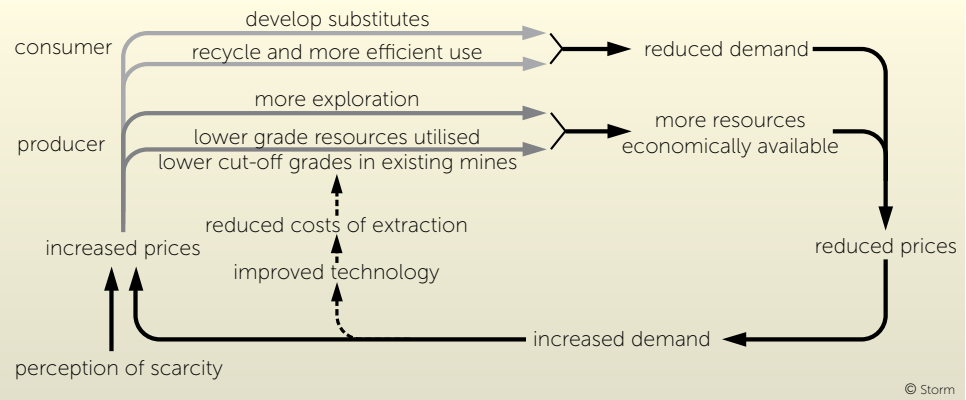


Figure E1

Economic model of the availability of mineral resources at large, according to [WNA-*U* 2016].

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]; 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-*U* 2016], [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 E1, 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 E1 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.

Generally the demand of a mineral commodity could be reduced by developing substitutes, recycling and more efficient use of the mineral. In the case of uranium [WNA-*U* 2016] proposes 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, are addressed in Chapter 7 and Annex F..

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-*U* 2016]:

> 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.

Annex F

Feasibility 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-*U* 2016] 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 50x 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.

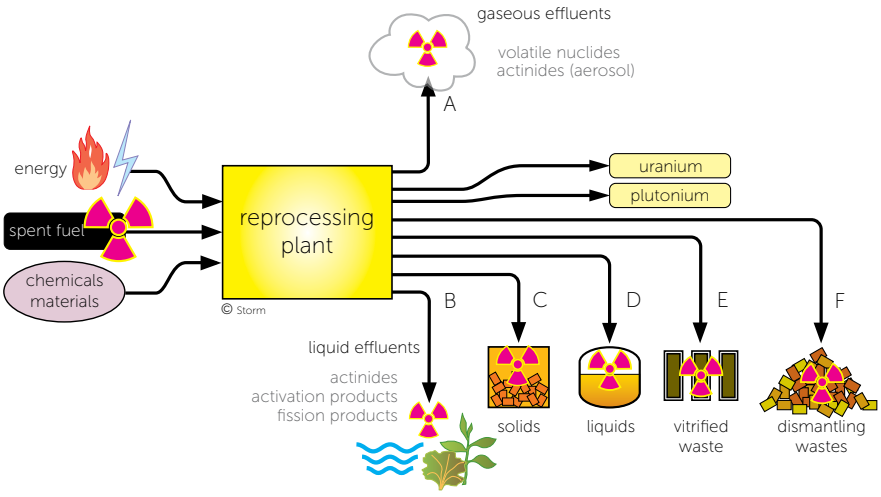


Figure F1

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 of a complex mixture of nuclides into pure fractions 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 and with the radiation level.
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 of dismantling 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 about 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.

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 might 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 processes – reprocessing of spent fuel, fuel fabrication and decommissioning + dismantling of the reprocessing plant –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 states that a closed-cycle reactor system (breeder) could fission 50 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.
Six d,ecades 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.

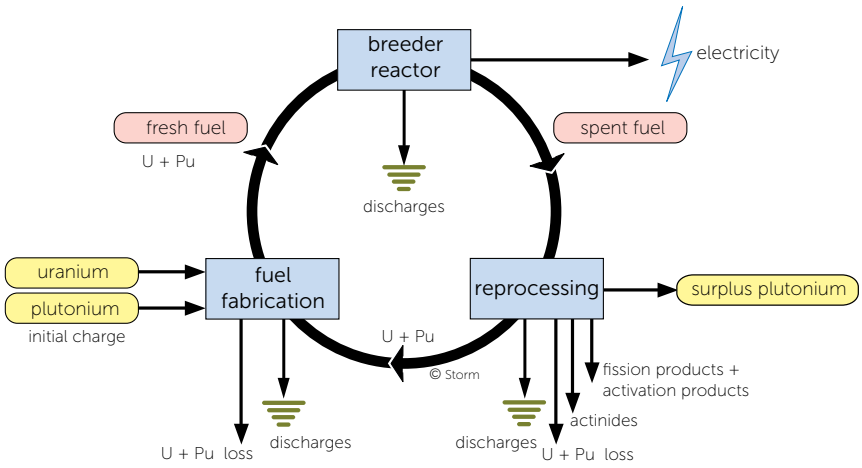


Figure F2
Outline of the breeder system concept in steady state. By repeatedly recycling spent fuel, it would be theoretically possible to fission the main part of natural uranium. If all would work as advertised, the cycle produces during its operational life a plutonium gain, large enough to start up two or more new breeders: one to replace the closed down unit, and one or more additional breeders. The cycle represents the mass flows of uranium and the nuclides originating from the nuclear processes in the reactor (fission, activation and decay). The initial plutonium charge to start up the breeder reactor is about 3 Mg Pu for a 1 GW(e) FBR.

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 and 100% pure 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.
- Absence of Second Law phenomena, such as ageing of materials

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 has to rely completely on the conventional technology of thermal-neutron reactors in the once-through mode.

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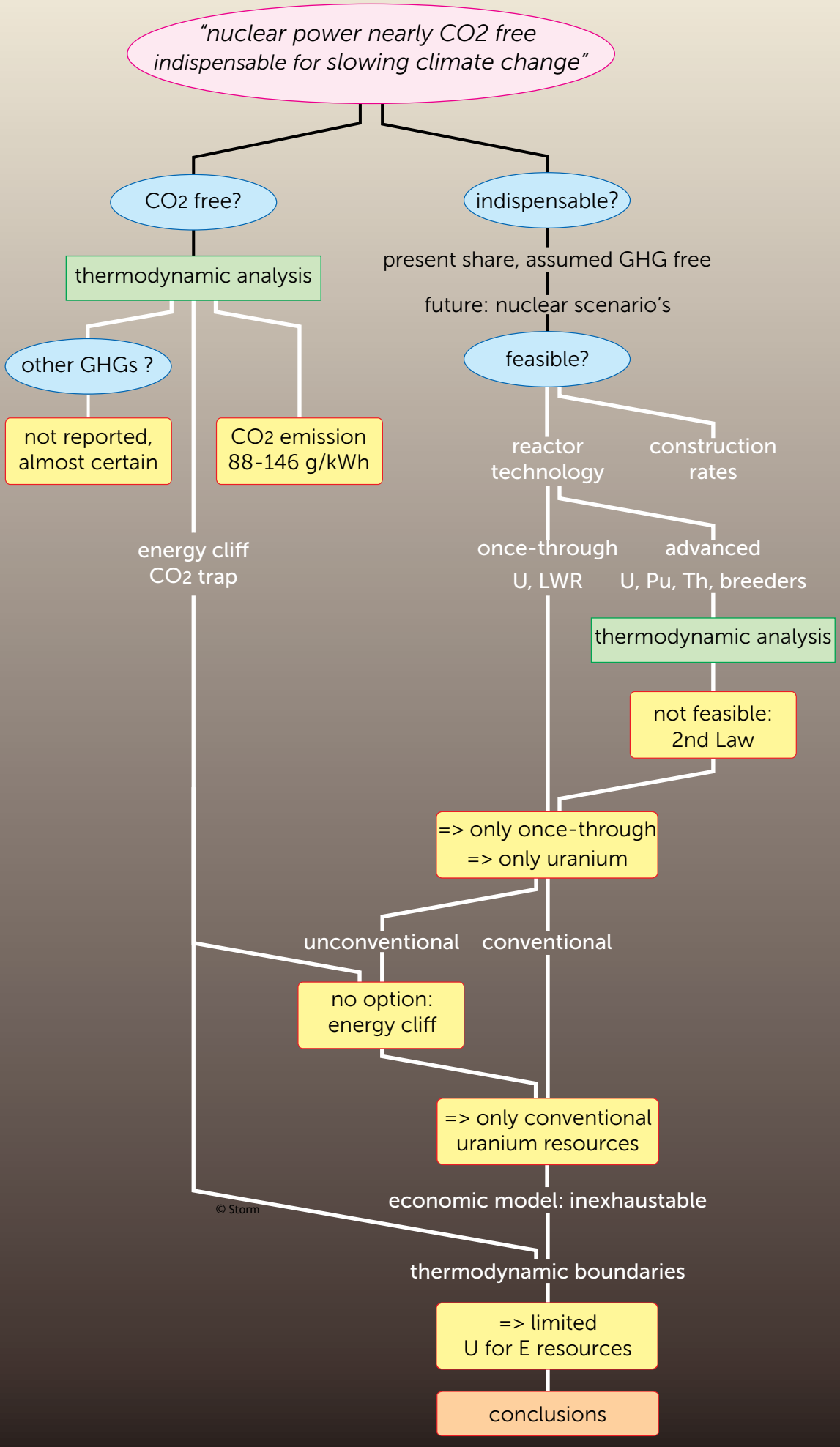
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