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Nuclear Power in its Global Context

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Abstract

Nuclear power is often recommended to the general public by reason of two benefits: nuclear power would be a vital component of a secure energy supply for centuries to come, and it would be indispensable for climate change mitigation.

Energy security and climate change mitigation are physical issues important at a global scale and with a long-time horizon, so an assessment of these benefits should be independent on political, economic and military considerations. For that reason, this study is based on a two-track physical analysis of the current nuclear energy system and advanced nuclear technology concepts. Novel notions are introduced: the energy cliff of nuclear power, the thermodynamic quality of uranium ores and the CO_2 trap.

Based on this analysis the significance of the two benefits in the long run are assessed.

Key words

Thermodynamic assessment; greenhouse gas emissions; prospects; energy cliff; CO_2 trap

Findings

Nuclear power is generated from a mineral found in nature by means of the most complex system of industrial processes ever designed, with a cradle to grave period of 100–150 years. Energy security and climate change by anthropogenic greenhouse gas emissions are global issues. Assessment of the role nuclear power currently plays and might play in the future requires a thermodynamic analysis of the nuclear energy system over its full cradle to grave period with an indefinite time horizon.

Thermodynamic quality—The thermodynamic quality of a uranium resource is defined as the amount of electricity that can be generated from 1 kg uranium minus the direct plus indirect energy inputs consumed by the industrial processes required to produce nuclear fuel from that resource as present in nature. The thermodynamic quality of uranium resources depends on several geologic variables; it declines exponentially with declining ore grade.

Energy cliff—The inputs of materials and energy per kg recovered uranium rise exponentially with declining ore grade. Consequently, the net energy production of the nuclear system depends on the thermodynamic quality of the uranium resources feeding the system: it declines exponentially with declining ore grade. At a grade below 0.2 gram of U per kg ore the net energy production falls to zero and the nuclear energy system becomes an energy sink instead of an energy source. The relationship between the net energy production of the nuclear energy system and the uranium ore grade is called the energy cliff.

Uranium-for-energy resources—Uranium-for-energy resources present in nature, resources that are suitable as energy source, are limited by their thermodynamic properties, set by the Second Law of thermodynamics. Consequently, unconventional uranium resources, such as shales and phosphates cannot be classified as nuclear energy sources. Feeding the nuclear energy system by uranium from the oceans would also turn the system into an energy sink—if large-scale extraction of 10,000s of tonnes of uranium a year from the oceans would be technically possible at all.

Closed-cycle reactor systems—Concepts of closed-cycle reactor systems, designed to fission a large part of natural uranium (30–60% versus 0.6% in the present reactors), and systems designed to use thorium as nuclear fuel are implicitly based on assumptions that conflict with the *Second Law of thermodynamics*. Therefore, the breeder function of these closed-cycle systems is inherently impossible. These systems, as whole, would have a negative energy balance: they would consume more energy than they could produce.

Reprocessing of spent fuel—Reprocessing of spent fuel is an exceedingly polluting process consuming massive quantities of energy and chemicals. Decommissioning and dismantling of closed-down reprocessing plants will be extremely expensive and time consuming, and will require exceedingly high investments of energy, materials and human effort. No advanced technology will be needed. Decommissioning and dismantling should be included in the energy balance of any nuclear power option that includes reprocessing.

Uranium–plutonium recycling in conventional reactors—The high-energy investments of reprocessing cause a 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 might be saved, provided that all spent fuel of the world were to be reprocessed and all the separated plutonium could be used to produce U–Pu fuel.

From the finding that the uranium-plutonium and thorium-uranium breeder systems are infeasible may be concluded that nuclear power in the foreseeable future must be based exclusively on the technology of the existing conventional thermal neutron reactors and consequently on the conventional uranium resources.

The world average grade of exploited uranium ores is steadily declining with time, because the richest and most easily mineable deposits are always mined first, for these offer the highest return on investments. Thus, the remaining deposits are less easily mineable, have a lower ore grade and consequently a lower thermodynamic quality. Recovery of uranium from these less favourable deposits consumes more energy and auxiliary materials and emits more CO_2 and likely also other GHGs.

CO_2 trap—Below a grade of about 0.2 gU/kg ore the nuclear CO_2 emission surpasses that of fossil-fuelled power stations. This phenomenon is called the CO_2 trap.

Specific material consumption—At present, the specific material consumption of nuclear power comes to about 206 grams of materials per delivered kWh, of which only 5 grams are recyclable, versus 5.2 grams/kWh, all fully recyclable materials, for an equivalent wind power farm producing an equal amount of electricity. These figures do not include materials consumed during operation of the systems (cooling water, maintenance and refurbishments), nor the materials for the required electricity grid and backup power systems.

Specific CO_2 emission of nuclear power—The specific CO_2 emission of nuclear power is estimated at 90–150 gCO_2/kWh at the present conditions. The numerical spread is mainly caused by uncertainties regarding construction and dismantling of the nuclear power plant. These figures do not include the upstream losses of the fossil fuels consumed by the industrial processes of the nuclear chain.

The nuclear CO_2 emission figures published by the nuclear industry are much lower than found in this study, even lower than wind power, these fig-

ures sound unrealistic in view of the high specific material consumption of nuclear power compared to wind power.

GHG emissions other than CO_2—In the publications of the nuclear industry no statements are found that refer to the possibility of GHG emissions other than CO_2 by nuclear power. Also, absent in the open literature are reports proving that the nuclear process chain does not emit GHGs other than CO_2. This absence seems to suggest that nuclear power does not emit other greenhouse gases. However, absence of published GHG data does not mean absence of GHG emissions. Assessment of various chemical processes that are indispensable for the generation of nuclear power proves it is inconceivable that the nuclear process chain would not emit other greenhouse gases.

Krypton-85—Large amounts of the radioactive noble gas krypton-85 are emitted into the atmosphere by the nuclear energy system. Apart from its harmful health effects, the gas gives rise to unforeseeable effects for weather and climate; it causes the formation of tropospheric ozone, a greenhouse gas causing also smog and health problems.

Nuclear mitigation share—For the year 2014, this study found a nuclear mitigation share of 4.9% of the global CO_2 emissions, down from 5.8% in 2010, assumed nuclear power is CO_2 free; the real share is significantly lower because nuclear power does emit CO_2. The above figures include the mitigation of upstream losses of the fossil fuels, and ignore the emissions of GHGs other than CO_2.

Potential nuclear mitigation share—Three scenarios of the potential nuclear mitigation share in the future are:

1. Continuation of the current trend of declining global nuclear capacity. There are no signs that this declining trend would reverse in the foreseeable future. If it would continue the nuclear mitigation share would approach zero by the year 2060–2070.
2. In one scenario of *International Atomic Energy Agency* (IAEA) the world nuclear capacity would remain constant at the present level. In this scenario, the nuclear share of climate change mitigation would decline to 1.4–2.6% by the year 2050, depending on the growth rate of the world energy consumption (3.5%/year respectively 2%/year).
3. In its most optimistic scenario the IAEA projects a nearly threefold global nuclear capacity by the year 2050, from an effective 333 GWe in 2014 to 964 GWe by 2050. In this high scenario, the mitigation share would be 4.2–7.6% by the year 2050.

The IAEA high scenario would imply an average construction rate of 27 GWe of new reactors per 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.

The CO_2 emission figures in *scenarios 2* and *3* are based on the assumption that nuclear power is free of GHG emissions, which it is not. As a result of the depletion of thermodynamically high-quality uranium resources, the CO_2 trap, the specific nuclear CO_2 emissions will rise with time. In *scenario 2*, constant nuclear capacity, the nuclear CO_2 emission would surpass that of fossil fuels by the year 2070–2080. In *scenario 3*, constant nuclear share, the nuclear energy system would reach the CO_2 trap by the year 2050.

Any growth scenario of the nuclear capacity and GHG mitigation share seems unlikely, unless millions of tonnes of thermodynamically high-quality uranium resources would be discovered during the coming decades. Such discoveries seem unlikely from a geologic point of view.

1. Introduction

For decades, nuclear power has been a component of the energy supply in many countries of the world. What role could civil nuclear power play in the future for society and the global environment? The old promises from the 1960s and 1970s of 'too cheap to meter' and 'toute électrique, toute nucléaire' faded away. Now newly stated benefits are put forward by the nuclear industry to recommend investments in nuclear power: nuclear power would be a vital component of a secure energy supply for centuries to come, and it would be indispensable for climate change mitigation.

Climate change mitigation and energy security are physical issues at a global scale and with a long-time horizon, so a scientific assessment of the twofold claim, independent on political, economic and variable assumptions, requires a physical analysis of the complete sequence of industrial activities making nuclear power possible. A physical analysis is based on unambiguously defined physical quantities, such as the conserved quantities energy and mass.

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 supply. 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; therefore, the results of this study may still be valid for the year 2014, the base year of this study; moreover, 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, for nuclear power is an energy supply system and could only substitute fossil fuels as energy source. Emissions of other GHGs are briefly addressed.

The thermodynamic assessment of the issues of the nuclear GHG mitigation share and energy security comprises two independent tracks, represented in *Figure 1*. Thermodynamics is the science of energy conversions and is at the basis of natural sciences, such as physics, chemistry, biology, and geology.

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 emissions of CO_2 and other GHGs are assessed by means of a thermodynamic analysis coupled to a life cycle assessment (LCA) of the complete system of industrial activities required to generate electricity from uranium and to safely manage the radioactive wastes.

Based on this analysis three novel notions are introduced: the energy cliff, the CO_2 trap and the thermodynamic quality of uranium resources, notions that set physical boundaries to the world uranium resources that can be called 'uranium-for-energy resources'.

In addition, the hypothetical contribution of nuclear power to mitigation of GHG emissions in the future is assessed in two scenarios: constant global nuclear capacity and a growth scenario proposed by the nuclear industry. How large could the nuclear contribution to mitigation of global greenhouse gas emissions hypothetically become, assumed nuclear power does not emit CO_2 nor other GHGs?

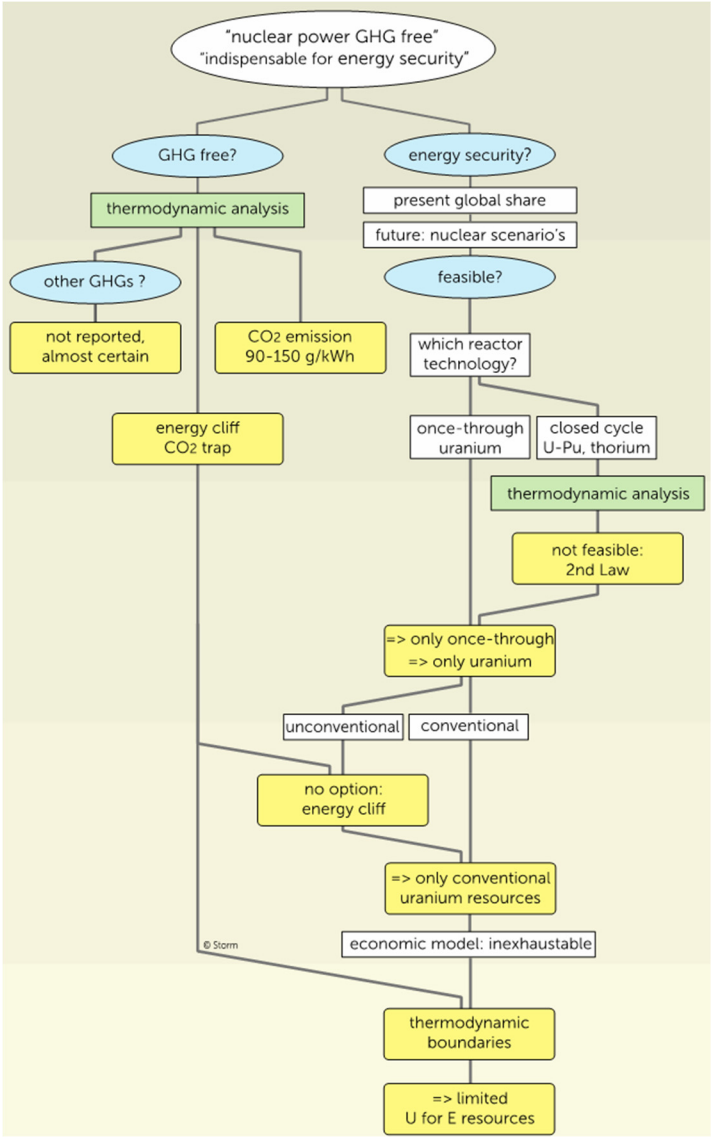

Figure 1 – Outline of the assessment of this study, with two independent analysis tracks
Designed by STORM VAN LEEUWEN, J. W. (2016)

In the second line of the thermodynamic analysis an important component in the prospects of nuclear power is the subject: the application of advanced nuclear technology, such as closed-cycle reactors and thorium reactors. Specific features of the proposed advanced nuclear concepts that limit their application are identified by means of a thermodynamic analysis.

Assessment of the energy security nuclear power might offer in the long run is possible using the results of both lines of analysis.

2. Contribution of nuclear power

2.1. Assessment method

Nuclear power is said to be carbon-free and would be indispensable for mitigation of the climate change, due to the emission of greenhouse gases (GHGs) by human activities. This claim of the nuclear industry suggests on one hand that nuclear power does not emit carbon dioxide CO_2, nor other GHGs, and on the other hand that the nuclear contribution to the world energy supply can grow significantly beyond the current level and will remain a safe, reliable energy source for many decades to come.

Assessment of the question whether nuclear power does not, or virtually not, emit carbon dioxide CO_2, nor other GHGs requires a thermodynamic analysis of the complete system of industrial activities required to generate electricity from uranium and to safely manage the radioactive wastes. A thermodynamic analysis charts the flows of materials and different kinds of energy involved in the nuclear energy system. By means of this analysis also the claim can be assessed that nuclear power would offer a safe and reliable energy source at a globally significant scale for many decades to come. After a brief description of the complete nuclear energy system in *Chapter 3*, *Chapter 4* discusses the thermodynamic analysis of the nuclear energy system, represented by the left track of the analysis outline in *Figure 1*.

Assumed nuclear power is GHG-free, as stated by the nuclear industry, the current nuclear contribution to the mitigation of GHG emissions can be estimated based on just two data sets:

1. sources of the global GHG emissions, and
2. 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 share and the prospects by the year 2050, based on the assumption that nuclear power does not emit GHGs, in two scenarios as envisioned by the *International Atomic Energy Agency* (IAEA).

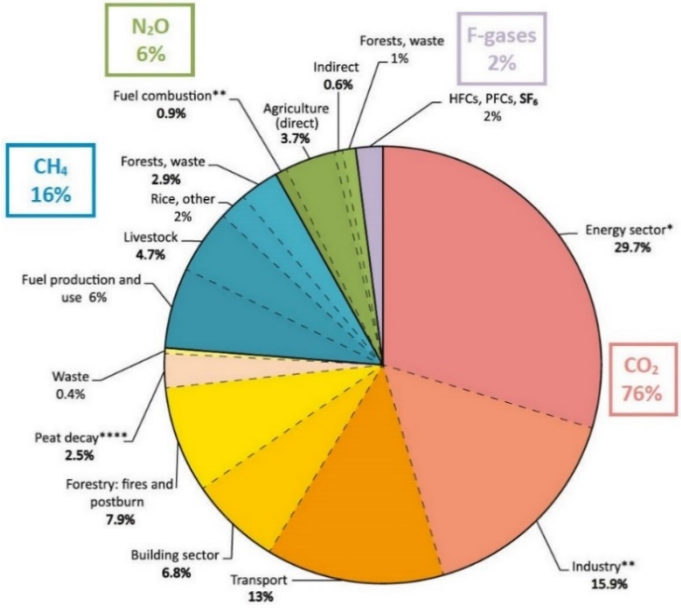

Figure 2 – Sources of global GHG emissions in 2010, weighted by their global warming potential (GWP). F-gases are fluorinated gases

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

Source: (UNEP, 2012)

2.2. 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 gram CO_2-equivalent. *Figure 2* shows for the year 2010 (UNEP, 2012) the shares of the main categories of GHGs: carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O and fluorinated compounds.

In 2010, the CO_2 emission of the energy sector, presumably the generation of electricity from fossil fuels, was 29.7% (rounded 30%) of the global GHG emissions. The other sectors emitting CO_2 by burning fossil fuels are industry (15.9%), transport (13%) and a part of the building sector. The sum of CO_2 emissions from burning fossil fuels in 2010 was 61%, according to IEA/a (2012), see *Figure 3*.

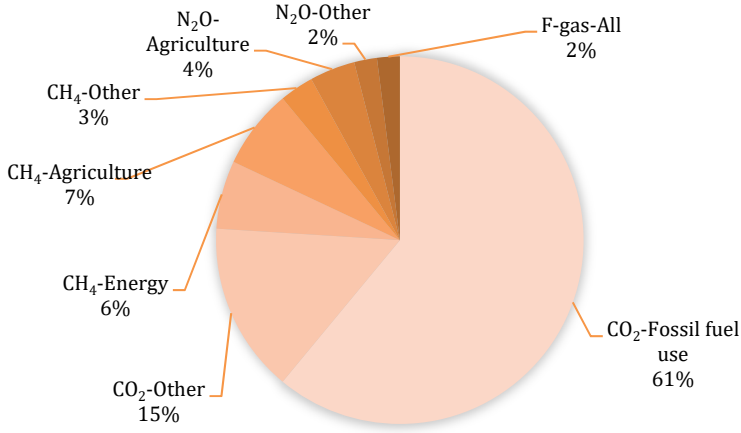

Figure 3 – Global greenhouse gas (GHG) emissions by gas/source in 2010, weighted by their global warming potential (GWP)

Source: (IEA/a, 2012), the most recent available data on the global emissions of greenhouse gases concerned the year 2010. Chart designed by BOKOR, L. *(2016)*

In 2010, 76% of the global warming potential was caused by CO_2: 61% CO_2 originating from burning fossil fuels and 15% from other sources (forestry, other land use, industrial processes: for example, cement production emitted 3% of the global greenhouse gases (IEA/a,

2012). At the time of writing of this paper the most recent data on the global GHG emissions were from the year 2010. Likely the mutual ratios of the various sources of GHGs did not change significantly in the years following 2010.

No data are available on the emissions of non-CO_2 GHGs by nuclear power, although emissions of fluorinated gases, most of which are powerful GHGs, are almost certain. For that reason, the assessment of the potential role of nuclear power as primary energy source in mitigation of the global GHG emissions has to be limited here to the CO_2 emissions from power generation by use of fossil fuels: 30% of the total global GHG emissions, or 30/61 = 49% of the CO_2 from burning fossil fuels.

2.3. Current nuclear share of the world energy supply

As it turns out the published figures concerning the world energy supply and its nuclear component are not always consistent; this will be explained in the following sections.

In 2010 the world gross energy production was about 517 EJ (1 exajoule = 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 *(Figure 4)*. The total world energy production is not exactly known, for the energy consumption of traditional biomass (wood, dung, straw, peat, organic waste) in a number of developing countries can only be roughly estimated. In the energy statistics of BP (2011) only traded energy flows are listed: fossil fuels, hydro power, nuclear power and modern renewables. Data on non-traded combustibles, especially biomass and waste, are taken from IEA/b (2012).

Usually the energy flows in world energy statistics are given in million tonnes oil equivalent, 1 MTOE = 42 PJ (1 petajoule = 10^{15} J). In most statistical energy reviews, for example BP (2011) and IEA/b (2012), and in publications of the nuclear industry the electricity generated by nuclear and hydro is converted into thermal equivalences, measured in 'primary energy' units, by multiplying with a

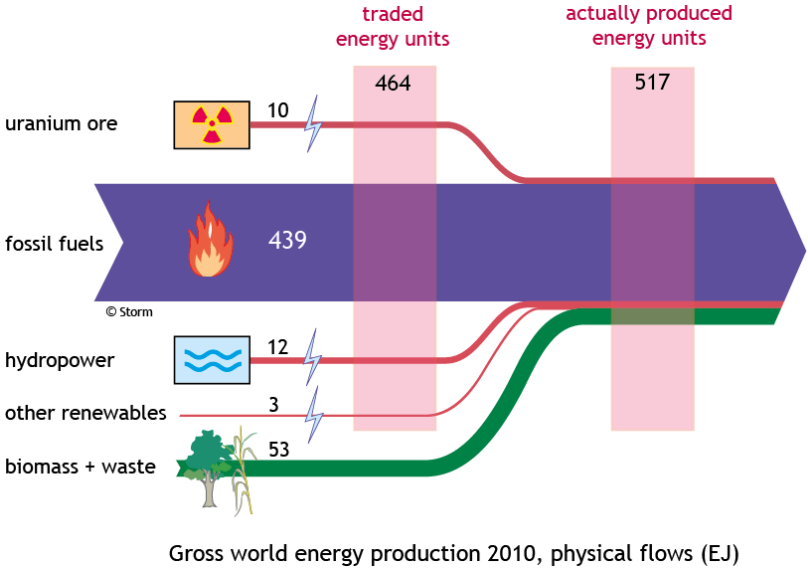

Figure 4 – Actually delivered, usable energy (in exajoules EJ) to the world economy in 2010. *This diagram is based on Table 1. The numbers are rounded. Designed by STORM VAN LEEUWEN, J. W. (2016); Source of traded energy figures: (BP, 2011). The figure of traditional biomass (53 EJ) is not accurately known; source: (IEA/b, 2012). Other renewables comprise: solar (PV and CSP), wind, small hydro, geothermal and 'modern' biomass.*

factor f = 2.64, as if the electricity has been generated from fossil fuels at a conversion efficiency of 37.8% (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; in other publications these conversion factors may still be used. Electricity from photovoltaics (PV), wind or *Concentrating Solar Power* (CSP) is usually not converted into 'primary energy' units MTOE.

The heat from a nuclear reactor cannot be used directly. The only form of usable energy from a nuclear power plant is the electricity it delivers to the grid. A hydropower plant does not produce heat at all. Applying the conversion into 'primary units', the contribution of nuclear power to the world energy supply seems to be nearly 3 times larger than the actually delivered quantity of useful energy units.

Conversion to thermal equivalence units would imply that 1 joule electricity from a nuclear power plant would generate nearly 3 J of heat in an electric heater and that 1 Joule electricity from a wind turbine would deliver 1 J of heat. Electricity is not labelled: 1 Joule nuclear electricity has exactly the same work potential as 1 Joule wind-generated electricity. One joule of electricity, from whatever source, can be converted into not more than exactly one joule of heat, as follows from the First Law of thermodynamics.

Above conversion introduces also variable and arbitrary assumptions, making the energy statistics unreliable for physical computations, because virtual energy units are added to the actually delivered energy units. In thermodynamics, one cannot add quality to quantity. Quality is not a conserved quantity in physics, like mass and energy, and it cannot be defined unambiguously, nor quantified.

This study presents all physical energy quantities of the world energy flows in exajoules (1 EJ = 10^{18} joule), as shown in *Table 1*, without using the notions 'primary energy units' and 'thermal equivalence'. The electricity production figures of nuclear, hydro and other renewables are also listed in the actual measurement unit terawatthour (1 TWh = 3.6 PJ). Terawatthours and million tonnes oil equivalent cannot be added, so at least one of the two has to be converted. In *Table 1*, all figures are converted into joules, that can be added up. Thermodynamics draws no distinction between 1 joule of electric energy and 1 joule of whatever other form of energy (heat, potential energy, mechanical energy, radiation), a consequence of the First Law of thermodynamics. The quality of a given quantity of energy is determined by variable human preferences, so quality cannot be added to a conserved quantity.

In 2010, the nuclear share of the world gross energy production was 1.9%, as calculated in *Table 1* and shown in *Figure 5*. Most energy statistics give another figure; for example, BP (2011) cites a share of 5.2%. This divergence has two causes:

- *1)* BP lists only the traded energy (464 EJ in 2010) and ignores the non-traded energy supply by traditional biomass and waste.

- *2)* BP uses the thermal equivalence of the world nuclear electricity production by multiplying it by a factor f = 2.64. This method of calculation results in a number of virtual energy units, which is thermodynamically incorrect, as explained above.

Table 1 – Energy made available in 2010 to the global economic system

Sources: BP (2011) and IEA/b (2012).

	energy source	electricity TWh	combustibles MTOE	EJ	fraction (%)
1	nuclear	2,762.2		9.94	1.9
2	hydro	3,427.7		12.34	2.4
3	other renewables	701.0		2.52	0.5
4	oil		4,028.1	169.18	32.7
5	natural gas		2,858.1	120.04	23.2
6	coal		3,555.8	149.34	28.9
7	sum fossil fuels (4+5+6)		10,442.0	438.56	84.9
8	sum traded energy units (1+2+3+7)			463.37	
9	biomass + waste		1,271.7	53.41	10.3
10	world total (8+9)			516.78	100.0

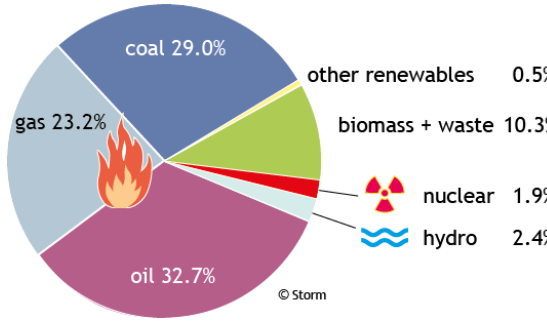

Figure 5 – World primary energy production in 2010 was about 517 EJ (exajoule), of which 464 EJ traded energy. The share of nuclear power was 1.9% in 2010 and is steadily declining

Sources: BP (2011) and IEA/b (2012). In 2014 the nuclear contribution had declined to 1.6% of the world energy supply, and the declining trend continues.

2.4. World final energy use

It may be helpful to look first at the final energy use of the world to determine which fraction of the fossil fuel production theoretically could be displaced by nuclear power.

A portion of the fossil fuels is 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, M. *et al*. (2009). IEA/b (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 came 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. This figure is based on data from BP (2011) and the methodology of FRANKLIN, W. D. *et al*. (1971). Indirect energy use and losses due to flared and spilled fuels are not included so it may be a low estimate. This loss fraction will increase with time, as the most easily recoverable resources available are exploited first and will be depleted first; the remaining resources are less easy to exploit and consequently will consume more useful energy per unit of extracted fuel. In addition, the share of liquefied natural gas (LNG) is increasing, leading to higher upstream energy losses.
- *Conversion losses*. In 2010 the average conversion efficiency of fossil fuels into electricity was about 38% (BP, 2011), so 62% of the energy content of the fossil fuels are lost as waste heat into the environment.
- The *average transmission losses* of electricity are estimated at about 6%.

The final energy consumption of the world, that is the gross energy production minus above mentioned losses, amounted to about 326 EJ in 2010. *Figure 6* represents the various energy flows.

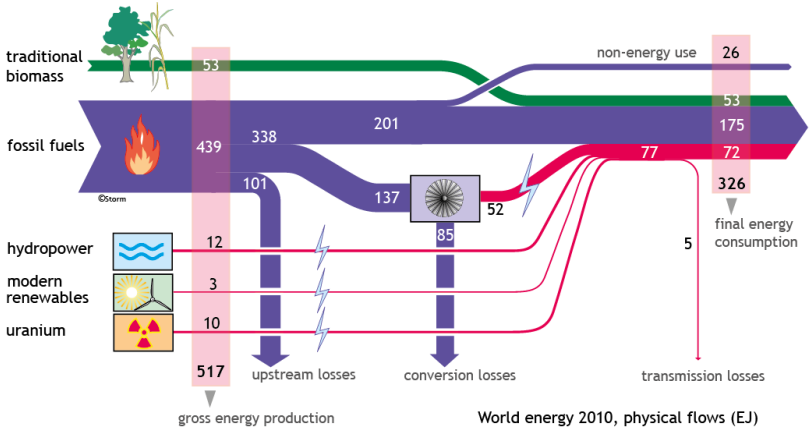

Figure 6 – Physical energy flows of the world in 2010, in exajoules (EJ). *Not accurately known are the amounts of energy embodied in traditional biomass and in the upstream losses of the fossil fuels. Therefore, the world final energy consumption, here presented as 326 EJ, has a significant uncertainty range. Designed by STORM VAN LEEUWEN, J. W. (2016)*

A part of the extracted, transported and refined fossil fuels is used to generate electricity. BP (2011) presents an amount of 52 EJ of fossil-fuelled electricity generation, assumed that a negligible amount of electricity is generated from traditional biomass or agricultural residues. BP (2011) assumes a world averaged conversion efficiency (thermal energy to electricity) of 38%, so the amount of potential energy in fossil fuels consumed by the electricity generation in 2010 was 137 EJ.

2.5. Nuclear contribution to GHG emission mitigation in 2010

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 CO_2 emission and climate change mitigation.

Coupling *Figures 2*, *3* and *6* in a simplified model we assume that

the input of 137 EJ of fossil fuels for generation of 52 EJ of electricity plus a proportional part of the upstream losses (137/338) x 101 = 41 EJ, amounting to a total of 178 EJ, would correspond with 30% of the world CO_2 emission *(Figure 2)*. Because it is uncertain how UNEP (2012) calculated the data presented in *Figure 2*, it is not clear to what extent the above assumption is reliable.

In 2010, nuclear power generated 10 EJ of electricity; this would displace a fraction of (10/52) x 178 = 34 EJ of fossil fuels, corresponding with a mitigation of the global CO_2 emission of (10/52) x 30 = 5.8%, 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 chapters. Evidently this way of calculating the mitigation of GHG emissions is also valid for renewables and for hydro power.

The nuclear contribution to the global usable energy supply in 2010 was 1.9% and the nuclear CO_2 mitigation share is estimated at 5.8%, assumed nuclear power is CO_2-free. In 2014, the nuclear contribution had declined to 1.6% of the world energy supply, and consequently the nuclear mitigation share declined to 4.9%. Because nuclear power does emit CO_2 and almost certainly also other GHGs, the mitigation shares in practice would be substantially lower than above estimated percentages. Moreover, the specific nuclear CO_2 emission most likely will rise (CO_2 trap), as will be explained in the following chapters.

In 2014, the global nuclear generating capacity comprised 388 operating reactors with a joint capacity of 333 GWe (SCHNEIDER, M. – FROGGATT, A. 2015) producing 2,410 TWh of electricity. IAEA (2015) mentions higher figures of the number of reactors (438) and total generating capacity (376 GWe). To get this higher number, the IAEA considers 40 reactors in long-term outage as 'in operation'; BP (2015) cites a higher figure of the nuclear electricity production in 2014 (2,537 TWh); this study uses the IAEA figure of the production (2,410 TWh) and the data of SCHNEIDER, M. – FROGGATT, A. (2015) of the operating reactors (333 GWe).

The global nuclear electricity generation of 2,410 TWh formed 1.6% of the world energy production in 2014.

2.6. Prospects

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

On this issue, no figures were found in the open literature, for that reason this study estimates the mitigation consequences of 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.

IAEA (2015) expects a growth rate of the global energy consumption of 2–3.5%/yr until 2030. Here we assume that this growth rate will continue until 2050 and that the electric share will grow at the same rate. Conveniently we assume also that the global GHG emissions will grow at an equal rate of 2–3.5% per year. Consequently, each scenario has two variants: one at an assumed growth of 2%/yr and the other at a 3.5%/yr growth.

This study assesses two recent scenarios of the IAEA that can be considered typical of the views within the nuclear industry, and assumed nuclear power is free of emissions of CO_2 and of other GHGs (which it is not).

2.6.1. IAEA low, constant nuclear capacity

The low scenario of the IAEA as published in IAEA (2015) corresponds with a nearly constant nuclear generating capacity until 2050 *(Figure 7)*. In this *scenario 1* we conveniently assume that the global operating nuclear capacity would remain flat at the current level of 333 GWe and the annual electricity production would remain 10 EJ/year.

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 114 EJ/yr. The nuclear contribution would have declined then to 10/1137 = 0.9% of the world energy supply.

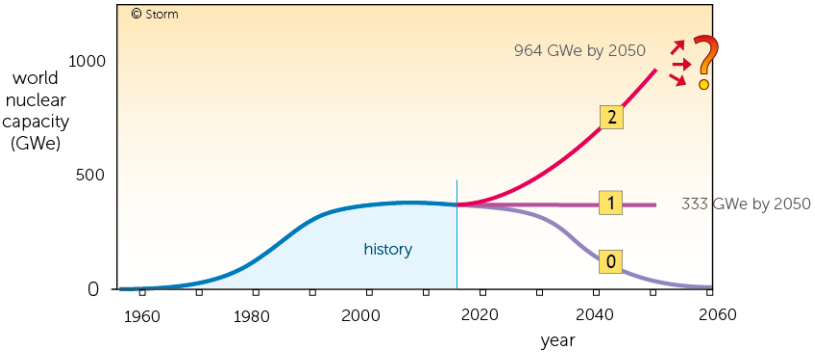

Figure 7 – Three scenarios of the nuclear capacity until 2050. *Scenario 0 represents phase-out of the existing nuclear capacity in the coming decades. Although the global capacity trend is declining, Scenario 0 is a hypothesis and is not discussed in the text. Scenario 1 represents the IAEA low scenario, 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.*
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The nuclear mitigating contribution would decline to about (10/114) x 30 = 2.6% by 2050, if both the global energy production and the CO_2 emissions rose 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 10/2068 = 0.5% of the world energy supply. The nuclear mitigating contribution would decline to about (10/208) x 30 = 1.4% by 2050, if both the global energy production and the CO_2 emissions rose at 3.5%/yr.

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 will reach the end of their operational lifetime within that period, meaning that during the next decades, each year 7–8 GWe of new NPPs have to come on-line, two times the current global construction rate of 3–4 GWe/year.

2.6.2. IAEA high, nuclear capacity grows to 964 GWe

In its high scenario, IAEA (2015) foresees a nuclear capacity of 964 GWe by 2050, nearly three times the current global capacity of 333 GWe. If the new nuclear power stations operated at the same load factor as the currently operating NPPs, the electricity generation would be 29 EJ/yr by 2050.

This scenario would imply an average 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. 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 29/1137 = 2.6% of the world energy supply.

The nuclear mitigating contribution would rise to about (29/114) x 30 = 7.6% by 2050, if both the global energy production and the CO_2 emissions rose 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 29/2068 = 1.4% of the world energy supply.

The nuclear mitigating contribution would decline to about (29/208) x 30 = 4.2% by 2050, if both the global energy production and the CO_2 emissions would rise at 3.5%/yr.

From the mitigation figures in 2050 follows that *scenario 2* may be roughly described as the 'constant share' scenario, and *scenario 1* as the '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. Because nuclear power does emit CO_2 and most likely also other GHGs, as will be explained in the following chapters, the real

mitigation share would be considerably less than the figures of the IAEA scenarios by 2050, summarised in *Table 2*.

***Table 2 – Summary of the two nuclear scenarios through 2050**, both at a global growth rate of energy consumption and GHG emissions of 2% respectively 3.5%, assumed nuclear power does not emit CO_2, nor other GHGs.*
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scenario		Global growth rate (%/year)	Nuclear capacity In 2050 (GWe)	nuclear E production in 2050 (EJ/yr)	world energy in 2050 (EJ/yr)	fossil-fuelled electricity in 2050 (EJ/yr)	CO_2 emission mitigation in 2050 (%)
1a	IAEA low	2	333	10	1,137	114	2.6
1b	IAEA low	3.5	333	10	2,068	208	1.4
2a	IAEA high	2	964	29	1,137	114	7.6
2b	IAEA high	3.5	964	29	2,068	208	4.2

2.7. After 2050

The future does not end in 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.

In the most pessimistic view, all nuclear construction activities would cease in 2050, which is likely not the intention of the nuclear industry. All nuclear power plants then operating should be able to complete their normal operational lifetime. For that reason, the scenarios are to be extended up until 2100 in order to assess the minimal requirements for the availability of fissile material. The last plants

coming on line in 2050 would reach their end of life by about the year 2100. The extended scenarios, based on the assumption of no new nuclear build after 2050, are illustrated by *Figure 8*.

Chapter 6 returns to these scenarios and assess their viability based on the results of the thermodynamic analyses discussed in the following chapters.

Obviously, the nuclear share of GHG mitigation after 2050 would decline in all scenarios depicted in *Figure 8*.

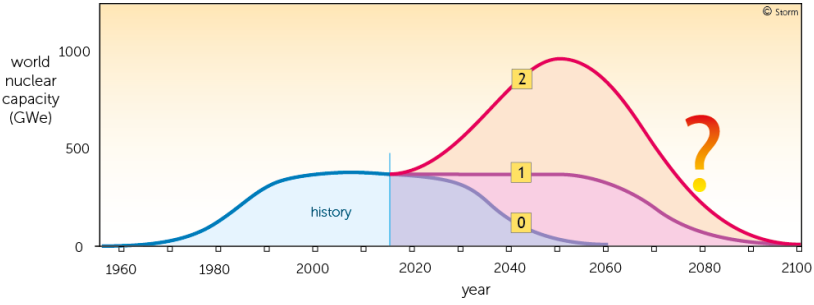

Figure 8 – Development of the global nuclear capacity in scenarios 1 and 2 assumed that after 2050 the nuclear capacity would be phased out

Scenario 0 represents the phase-out of the current nuclear capacity.

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3. The nuclear energy system

3.1. The nuclear process chain

Nearly all current nuclear power plants (NPPs) in the world are operating in the once-through mode, without recycling used nuclear fuel. Only a few NPPs use also MOX fuel (Mixed OXide) containing plutonium from reprocessed nuclear fuel. Expansion of the use of MOX fuel in the future is doubtful.

A nuclear power plant is not a stand-alone system, it is the central part of a sequence of industrial processes comprising three sections: the front-end processes, the production process itself and the back-end processes, a sequence called the nuclear process chain.

- The front-end of the nuclear chain includes the processes to produce nuclear fuel from uranium ore. Nuclear power is based on a mineral energy source, uranium. This radioactive metal has to be extracted from special rocks found at some places in the *Earth*'s crust, a process comparable to the recovery of most other metals. The raw metal has to be purified and processed and enriched in the fissile isotope uranium-235, in order to make it suitable as fuel in a nuclear reactor.
- The midsection encompasses the construction of the nuclear power plant (NPP) and the operation, maintenance and refurbishments (OMR) of the plant. At closedown, most components of an NPP have been replaced by new ones, except the nuclear reactor; the operational lifetime of an NPP is set by the nuclear reactor.
- The back-end comprises the processes needed to handle the materials containing the radioactivity generated by the nuclear reactor and the radioactive materials mobilised in the front-end processes. The purpose of the back-end processes, including dismantling of the radioactive parts of the power plant after final shutdown, is to keep the radioactivity out of the human environment as effectively as possible and as long as needed.

A flowsheet of the full nuclear process chain, as it ought to be, is presented in *Figure 9*. As this diagram 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.

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 be isolated from the human environment forever. Most activities of the-back-end of the nuclear process chain will be demanding tasks, requiring large investments of

energy, materials and economic means.

Only a few processes of the back-end are operational. In the thermodynamic analysis of this study all processes indicated in *Figure 9* are included as if they were operational.

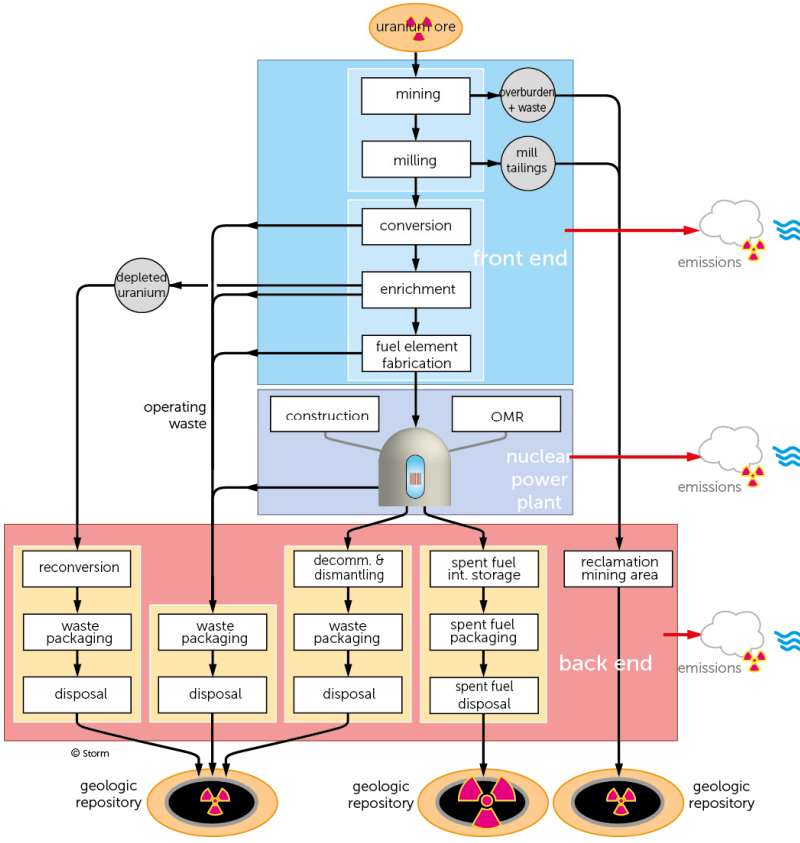

Figure 9 – Full process chain of a light-water reactor (LWR) nuclear power plant in the once-through mode from cradle to grave. *The black arrows represent flows of radioactive materials. Calculations in this study are based on this full chain. In the back-end of the nuclear chain only packaging of operating waste and interim storage of spent fuel are operational in the present practice. Designed by* STORM VAN LEEUWEN, J. W. *(2016)*

This study is an update and an extension of earlier studies, see for example STORM VAN LEEUWEN, J. W. (1985).

3.2. Cradle-to-grave period

The life cycle assessment (LCA) in this study comprises all processes related to a given nuclear power plant from cradle to grave, regardless of time and place of the individual processes. The period involved is here called the cradle-to-grave period, or shortened the c2g period. In *Figure 10* the c2g periods of a fossil-fuelled power station and a nuclear power station are compared. Each has three sections: construction, operational lifetime (both 40 years) and back-end. The front-end processes coincide with the operational lifetime.

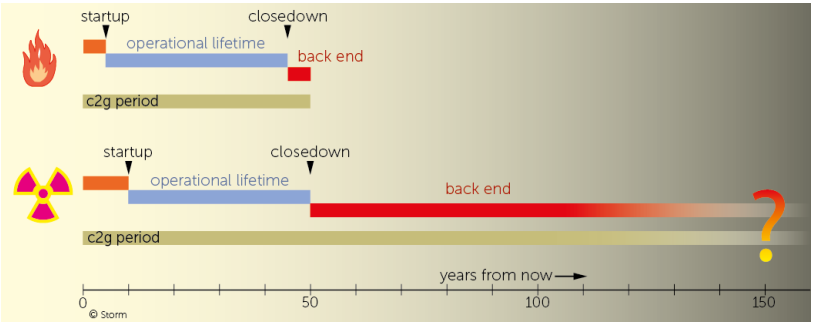

Figure 10 – Time frames (c2g periods) of a fossil-fuelled power plant and of a nuclear power plant, each with a nominal operational lifetime of 40 years
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The c2g period of a fossil-fuelled plant is 50 years or less: the construction takes a few years and the backend, decommissioning, dismantling and site clean-up takes another few years. The nuclear c2g period proves to become extremely long: some estimates mention 150 years or even longer. Nowhere in the world the process chain of a particular nuclear power plant has ever been finished.

3.3. Materials consumed by the nuclear energy system

All materials entering the nuclear energy system are extracted from the biosphere and all materials leaving the nuclear system will end up in that same biosphere 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. Each nuclear power plant generates a per year per GWe amount of radioactivity equivalent to about 1,000 exploded *Hiroshima* style bombs.

The human-made radioactivity is mainly contained in the spent fuel elements, but a part of it leaves the nuclear system dispersed over large volumes of construction materials as a consequence of neutron irradiation and contamination with radionuclides. In addition to the generation of human-made radioactivity the nuclear system mobilises vast amounts of natural radionuclides from the uranium ore. During operation and thereafter the nuclear system discharges radioactive and non-radioactive wastes into the environment.

The material flows leaving the nuclear system and entering the human environment *(Figure 11)* 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 used in mining and milling, most of it contaminated with toxic chemicals, radioactive and non-radioactive; cooling water of the reactor during operation not included;
- materials lost forever, due to radioactivity;
- waste rock.

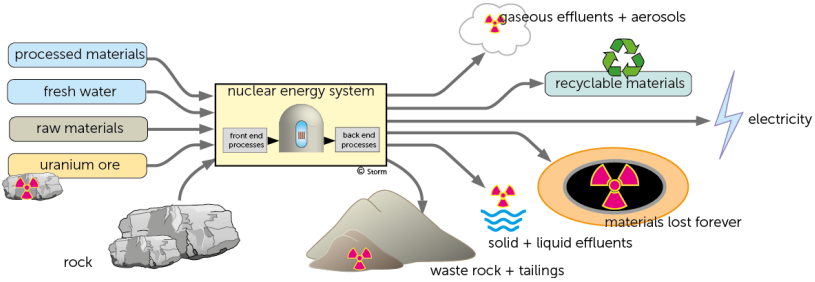

Figure 11 – Outline of the flows of materials of the complete nuclear energy system from cradle to grave.

Radioactive materials are assumed to be disposed of definitively in geologic repositories, except the intentional operating discharges (including the complete fresh water input) and unintentional discharges (leaks, accidents) into the environment. In the current practice, all radioactive wastes are still present in mobile condition within the human environment, including the 'materials lost forever', that are the materials that cannot be reused for any purpose because of their radioactivity.

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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 12* shows 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.

The cooling water for the nuclear power plant is also not accounted for.

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.

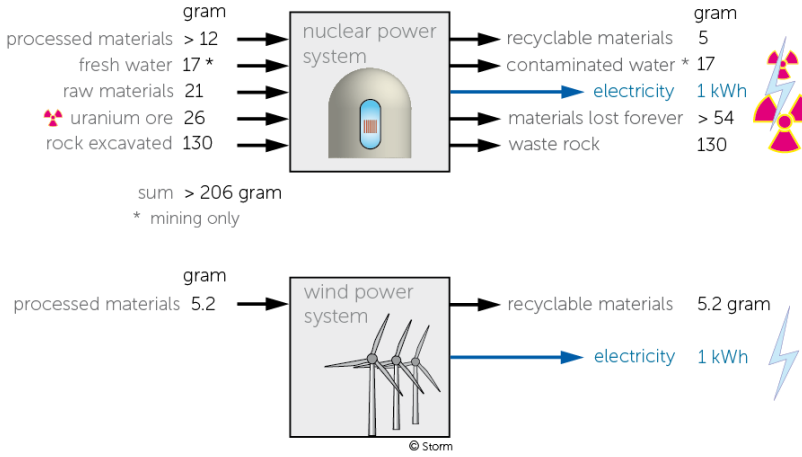

Figure 12 – Material balances of a generic nuclear energy system and an offshore wind farm of current operational technology

Both systems are assessed from cradle to grave. The uranium ore has an assumed grade of 1 gU/kg rock, slightly higher than the current world average. The input of processed materials (construction materials, chemicals) of the nuclear system is indicated by >12 gram/kWh, because the input is not exactly known, but certainly more than 12 g/kWh. Designed by STORM VAN LEEUWEN, J. W. (2016)

4. Nuclear greenhouse gas emissions

4.1. Energy costs energy

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.

Figure 13 represents a simplified outline of the nuclear process chain as shown earlier in *Figure 9*. The input of the central part of the nuclear chain, the power plants itself, is enriched uranium assembled in fuel elements ready to be placed in the reactor. The materials and energy needed for construction, operating, maintenance and refurbishments of the NPP are included in the inputs of the front-end processes. The lifetime output of the NPP is electricity and a massive

amount of radioactive materials, including a part of the NPP itself. This study takes the view that all radioactive wastes generated by the nuclear system are to be isolated from the biosphere for a geological timespan in a geologic repository, in *Figure 13* represented by a symbol. Those back-end processes will also consume materials and energy, for example packaging the radioactive wastes, construction of deep geologic repository, disposal of the wastes in the repository and closure of it. The back-end processes also include the decommissioning and dismantling of the NPP after its closedown and disposal of the radioactive debris and scrap in a geologic repository.

None of the back-end processes do need advanced technology, so their consumption of energy and materials can reliably be estimated by comparison with similar industrial processes that are operational, such as the construction of an underground mine.

The sum of the direct and indirect energy inputs needed to operate the full nuclear chain is the energy investment of the system. An informative parameter of energy systems is the Energy Return on Energy Investments (EROEI), that is the ratio of energy output over energy input. In the next chapter, we return to this quantity.

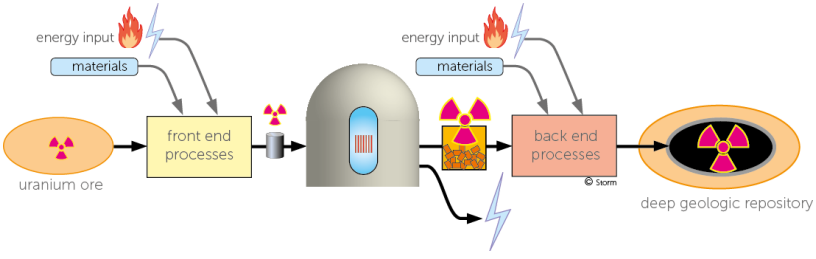

Figure 13 – Simplified outline of the nuclear energy system with the complete process chain from cradle to grave, as it ought to be, including the safe isolation of the radioactive wastes from the biosphere

The analysis of this study is based on this outline. In practice, no nuclear process chain has ever been finished.

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4.2. 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 energy of these materials form the indirect input. By means of a thermodynamic analysis the direct and indirect energy inputs of the full nuclear system from cradle to grave can be quantified.

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 (for example 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-fuel-generated electricity. 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 emphasised that this steady-state model is hypothetical, because no commercial NPP has ever been dismantled completely.

By this convention the energy analysis of this study deviates from analyses of other energy systems, such as wind power and solar photovoltaics, in which the CO_2 emission associated with the generation from fossil fuels of the electricity consumed for construction is included in the total specific GHG emissions.

4.3. Full-power years FPY

To avoid discussions on load factor, capacity factor and availability factor—these factors are not always consistently defined or used by the nuclear industry – the operational lifetime of a nuclear power plant in this study is not given in calendar years, but in full-power years FPY. A full-power year is here defined as the period in which the reactor

produces a fixed quantity of electricity equalling the production during 1 year continuously at full power. The electricity produced by a nuclear power plant with a nominal power of 1 GW_e during one FPY is:

1 FPY = 1 GW_e.year = 8760 x 10^6 kWh

The time-period measured in calendar years of an FPY varies among different nuclear power plants, and usually also with time at a particular one.

4.4. CO_2 emission of the nuclear energy system

The thermodynamic analysis of the reference nuclear power station, representative of the newest currently operating NPPs, from cradle to grave with a lifetime productivity of 25 full-power years makes it possible to estimate the specific CO_2 emission of the nuclear energy system. The current world average productive lifetime of NPPs is about 23 FPY.

Table 3 – 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
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	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	23.2 ± 11.6
4	operation, maintenance & refurbishments OMR	24.4
5	constant back-end processes	12.08
6	decommissioning & dismantling	34.8 ± 17.4
7	mine rehabilitation (ore grade dependent)	7.57
	sum (mean with uncertainty range)	117 ± 29

The results are summarised in *Table 3*, assumed that the nuclear system is fed by uranium from ore at a grade of 0.05% U (0.5 gram uranium per kg ore, about the current world average).

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, rounded 90–150 g/kWh.

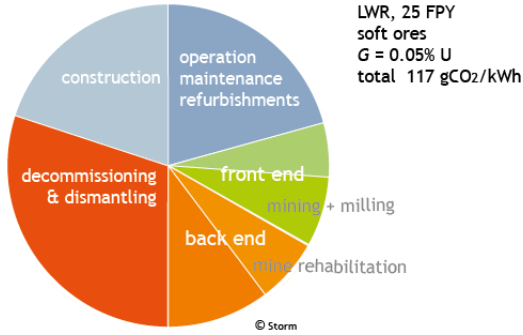

Figure 14 – Contributions to the cradle-to-grave (c2g) CO_2 emission of the nuclear energy system based on the reference LWR in baseline case, operational lifetime 25 full-power years (FPY), using soft uranium ores at an ore grade of 0.05% U (about the present world average)

The seven main components are represented as in Table 3. The contribution of mining + milling and mine rehabilitation are ore grade dependent.
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Figure 14 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 3*, 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 processes 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 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 these activities from its estimates of costs, energy consumption and specific CO_2 emission, or uses unrealistically low figures.

4.5. Other greenhouse gases

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, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and SF_6.

In 2001, the USA's enrichment plants alone had a specific GHG emission of 5 grams CO_2-equivalents per kilowatt-hour of Freon 114, as follows from data from EIA-DOE (2005). Apart from these we found no data in the open literature on the emissions of fluorine- and chlorine-related chemical compounds by the nuclear industry. The report EPD (2007) noticed the absence of data on emission of greenhouse gases by processes needed to convert uranium ore into nuclear fuel.

A chemical assessment of the industrial processes needed to make nuclear power generation possible proves it inconceivable that the nuclear process chain does not emit a gamut of fluoro and chloro compounds and it seems also inconceivable that no greenhouse gases are among them. Also in view of the large input of processed materials, see *Figure 11*, it seems unlikely that the nuclear energy system does not emit GHGs other than CO_2.

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

4.6. 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 ionising 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 (WMO, 2001).

Naturally, 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, J. *et al*. 2012; THE SENECA EFFECT, 2015).

Being chemically inert, krypton and the other noble gases are usually not 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 characterised by low blood solubility, high lipid solubility and rapid diffusion in tissue.

Exceptions to the biologically inert characterisation 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, 1975). During the 40 years following this publication, no investigations of the health and climate effects of krypton 85 are reported, as far as known.

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 understand better the implications of long-term Kr-85 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 ionising radiation in the induction of skin cancer (NCRP, 1975).

4.7. Specific CO_2 emission and uranium ore grade

Table 1 shows that the specific CO_2 emission of the nuclear energy system that is attributable to the recovery of uranium from the *Earth*'s crust amounts to 8.41 + 7.57 = 15.98 = 16 g/kWh if the nuclear system

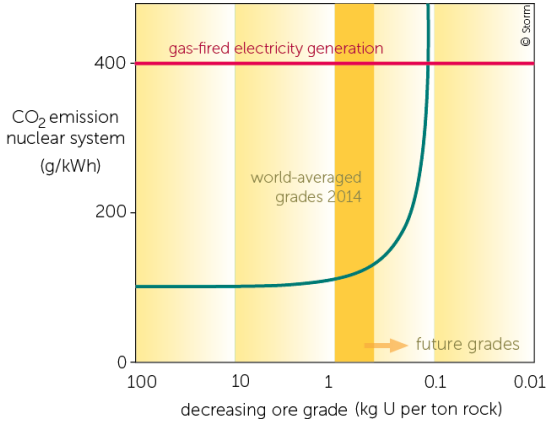

Figure 15 – Specific CO_2 emission of the nuclear system (baseline case) as function of the uranium ore grade

At present the world-averaged ore grade is 0.1–0.05% U. This diagram is called the 'CO_2 trap'. At grades approaching 0.01% U (100 g U per ton rock) the nuclear CO_2 emission surpasses that of fossil fuelled electricity generation. 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. From the thermodynamic analysis follows that the critical ore grade hardly depends on the energy consumption and CO_2 emissions of the other parts of process chain, such as construction and dismantling of the NPP.
Designed by STORM VAN LEEUWEN, J. W. (2016)

is fed by uranium from ore at currently average grade. This figure is ore grade dependent: the CO_2 emission rises exponentially with decreasing ore grade, as shown by *Figure 15*.

4.8. Energy cliff

Future nuclear generating capacity during the coming decades will rely on the present reactor technology. Based on this reactor technology the amount of useful energy extractable from 1 kg natural uranium has a fixed value: roughly 500 GJ/kg natural uranium thermal energy, from which about 170 GJ/kg U electricity can be generated; slight variations are possible due to different reactor types. The reference reactor of this study, a pressurised water reactor (PWR) corresponding with the newest types of light water reactors (LWRs) in operation, cannot fission more than 0.6% of the nuclei in natural uranium; a higher figure in the future is unlikely.

The energy input of the nuclear system increases exponentially with decreasing thermodynamic quality of the uranium ore. For that reason, the net energy delivered by the nuclear system to the economy as a whole decreases with falling ore grades. At a certain grade the energy input of the system equals the energy content of natural uranium. The use of ores at that critical grade results in a zero-net energy production by the nuclear system: the *energy cliff*.

Below a grade of 0.2–0.1 gU/kg rock no net energy can be generated by the nuclear system as a whole from a uranium resource. The diagram of *Figure 16* suggests that exploration for new uranium deposits may look worthwhile only at grades higher than 0.3 gU/kg rock, from an energy point of view.

The ore grades of the known uranium resources—ores are by definition economically recoverable—vary widely: from nearly 200 down to 0.1 gU/kg rock. A part of the resources that are classified by the IAEA as 'recoverable' are very close to or even beyond the energy cliff, such as *Valencia* and *Trekkopje mines* in *Namibia*. The energy cliff sets the thermodynamic boundary of uranium-for-energy resources, see the bar diagram in *Figure 16*. The ore grade distribution

and total amounts of recoverable resources at known grades have little changed, because few new significant resources have been discovered during the past decades, if any.

Thermodynamic analysis proves that the energy cliff hardly depends on the energy requirements for construction and dismantling, nor on the operational lifetime of a nuclear power plant. 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 16*, the energy cliff has been superimposed onto the ore grade distribution of the world known uranium resources graph, as function of the ore grade.

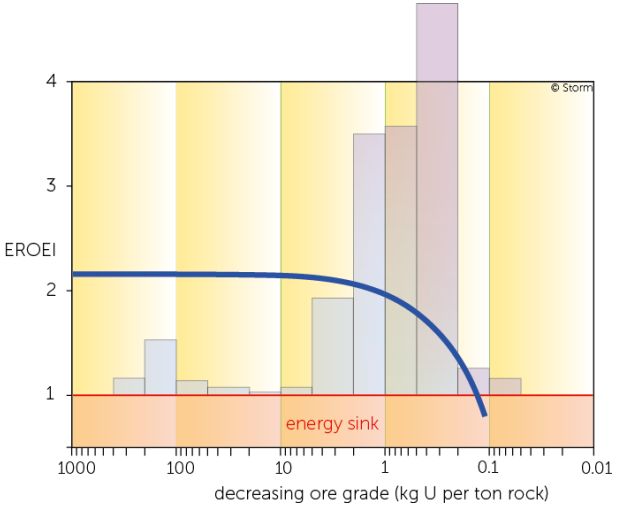

Figure 16 – The energy cliff

EROEI of the nuclear energy system as function of the uranium ore grade. Note the descending logarithmic scale on the horizontal axis. At uranium ore grades below 10 g U/kg rock the EROEI of nuclear power starts declining at an increasing rate and becomes zero at grades between 0.2–0.1 g U/kg rock. The bar diagram in the background represents the grade distribution of the world known uranium resources. The world average grade of available ores (currently 1–0.4 g U/kg rock) is declining because the richest and easiest recoverable resources are always mined first.
Designed by STORM VAN LEEUWEN, J. W. (2016)

4.9. Energy returned on energy invested, EROEI

An important quantity qualifying any energy system is the Energy Returned on Energy Invested (EROEI), also called Energy Return on Investment (EROI), which is defined as the ratio of the lifetime useful energy output over the lifetime useful energy input. This definition covers the full cradle-to-grave (c2g) period of the energy system, implying that the system boundaries include all energy investments related to a given NPP, regardless of place and time, even if occurring many decades from now.

4.10. Thermodynamic quality of uranium resources

Based on the thermodynamic analysis the thermodynamic quality of a uranium resource is defined as the amount of useful energy (direct + indirect energy inputs) to be invested for the recovery of a 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 of the host rock;
- location of the uranium occurrence: availability of fresh water, climate, transport distances for chemicals, auxiliary materials, equipment and for the products of the mine.

Due to 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.

4.10.1. Dilution factor

The ore grade is defined as the uranium content of the uranium-bearing rock, usually given as mass-% U, or in grams of 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.

4.10.2. Coal equivalence

At an ore grade of 0.2 gU/kg rock, 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*.

4.10.3. Extraction yield

The *extraction yield*, also called the *recovery factor* or *recovery yield,* is the ratio of the mass of uranium 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 types 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 specialised 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 0.2 gU/kg rock the extraction yield rapidly declines to very low values, making uranium extraction by means of the current technology practically infeasible. 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.

4.10.4. 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.

4.10.5. 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 15* 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.

4.11. CO_2 trap

At ore grades of 0.2–0.1 gU/kg rock the CO_2 intensity of nuclear power surpasses the CO_2 intensity of fossil-fuelled power, eliminating the low-carbon profile of nuclear power.

The world average grade of the mined ores is steadily declining with time. If no new large uranium ore deposits of high thermodynamic quality are discovered during the next decades, the nuclear CO_2

emission will surpass the specific CO_2 emission of gas-fired stations, and even coal-fired stations, within the lifetime of all new nuclear builds. *Figure 17* gives a rough impression of the CO_2 trap over time. Very likely the average ore quality of the available uranium resources will decline in the future and consequently the specific CO_2 emission by the nuclear energy system will rise over time.

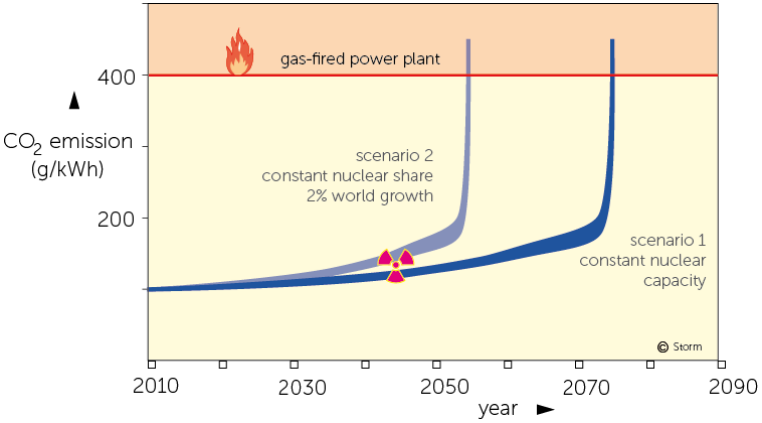

Figure 17 – The CO_2 trap: the nuclear CO_2 emission over time

The specific CO_2 emission of nuclear power rises with time due to decreasing thermodynamic quality of the uranium ores. If no new large high-quality uranium resources will be discovered during the next decades, the specific nuclear CO_2 emission may surpass that of fossil-fuelled electricity generation within the lifetime of new nuclear build. The coloured bands represent the uncertainty ranges regarding ore quality, mainly the difference between soft ores and hard ores.
Designed by STORM VAN LEEUWEN, J. W. (2016)

Thermodynamic analysis proves that the 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, and the development of the global nuclear generating capacity. Sooner or later the nuclear energy system will run aground in the CO_2 trap.

4.12. CO_2 emission figures from the nuclear industry

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

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

The IAEA cites specific emission figures far lower than this study: 5.6–19.7 gCO_2eq/kWh with a median value of 14.9 gCO_2eq/kWh. Notably, the specific CO_2 emission of just the construction of the *Sizewell* B NPP in the *UK* amounted to 11–15 gCO_2/kWh, according to EXTERNE-UK (1998), this study found a figure of 12–35 gCO_2/kWh for the construction. It is completely unclear how the figures of the IAEA are established and for what reason the results of the EXTERNE-UK (1998) study are not included. See also the publication of SOVACOOL, B. K. (2008) who compares a number of publications concerning nuclear GHG emissions, some of which find a higher figure than this study *(Figure 18)*.

The *World Nuclear Association* (WNA) comes in its assessment of the nuclear CO_2 emissions to about the same figures as the IAEA: 9–21 CO_2-eq/kWh in WNA (2014) and 10–26 g CO_2-eq/kWh in WNA/a (2015). Although WNA gives more details on the LCAs, on which the figures are based, than the IAEA in its report, it remains completely unclear how the CO_2 emission figures are derived by WNA or in the publications cited by WNA.

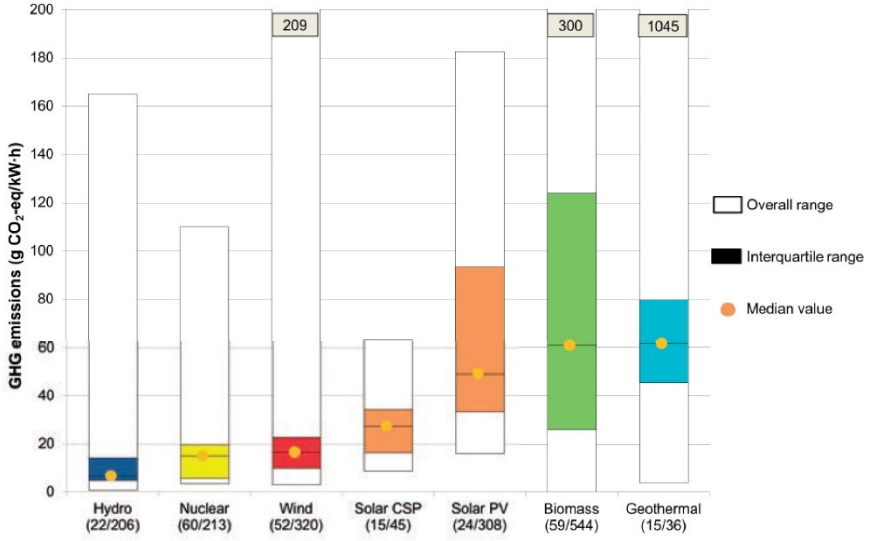

Figure 18 – Greenhouse gas emissions from nuclear power and renewable energy systems

The data source of this diagram from IAEA (2014) is an unpublished IAEA report

Noticeably absent from the publications of the IAEA and WNA are statements on the ore grade dependency of the nuclear CO_2 emissions, although this has been confirmed by PRASSER, H. M. *et al.* (2008).

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

- the original studies from which the used data were taken by the IAEA remain undisclosed;
- no life cycle assessment (LCA) is included;
- no system boundaries are defined;
- no time horizon of the study is defined;
- no CO_2 sources of the nuclear system mentioned.

Remarkably absent in the publications of the nuclear industry is any statement referring to the possibility or impossibility of GHG emissions other than CO_2 by nuclear power. This absence seems to suggest

that nuclear power does not emit other greenhouse gases. However, 'not reported' does not mean 'no emissions'.

This false suggestion is confirmed by the consistent use of the unit gCO_2eq/kWh (gram CO_2 *equivalent* per kilowatt-hour) in the nuclear publications. The unit gCO_2eq/kWh is the unit of the global warming potential of all kinds of GHGs, for example 1 g/kWh methane (CH_4) corresponds with 23 gCO_2eq/kWh. In scientifically correct publications the IAEA and the nuclear industry should consequently use the unit gCO_2/kWh as long as the nuclear industry not has unambiguously *proved* that nuclear power does not emit GHGs other than CO_2.

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.

5. Thermodynamics of closed-cycle nuclear systems

5.1. Advanced nuclear concepts

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. Theoretically the demand for uranium could be reduced by developing substitutes, recycling and more efficient use of the uranium. According to WNA/b (2015) this could be accomplished by:

- Reprocessing of spent fuel and recycling of uranium and plutonium in light-water reactors (LWRs).
- More efficient use of uranium by implementation of 'fast reactors' (breeder reactors) that would be able to fission 50–100 times more nuclei from natural uranium than the current generation of reactors (mainly LWRs).
- Development of reactors that use thorium as fertile material to breed fissile uranium-233. Via this conversion thorium could theoretically 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% being the non-fissile uranium-238 atoms with traces of uranium-234 (also non-fissile). By means of advanced nuclear technology, involving closed-cycle nuclear power generation, it would be theoretically possible to fission a much larger part of the nuclei in natural uranium: according to the nuclear industry, 50–100 times more than in an LWR at the current state of technology. In its prognoses and promises the nuclear industry is usually talking only about advanced reactor technology, but reactors are just a part of the technological challenge.

There are serious obstacles on the road to the materialisation of these technical dreams, such as:

- technical infeasibility of the breeder system;
- negative energy balance of the breeder cycle as a whole;
- uncontrollable and high risk of plutonium terrorism and the proliferation of nuclear technology.

A thermodynamical analysis, represented by the right track of the analysis outline in *Figure 1*, examines the technical feasibility of the advanced concepts in the following sections.

5.2. Reprocessing of spent fuel

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

Separation of spent fuel into different fractions is possible by an intricate complex of physical and chemical separation processes, called reprocessing *(Figure 19)*.

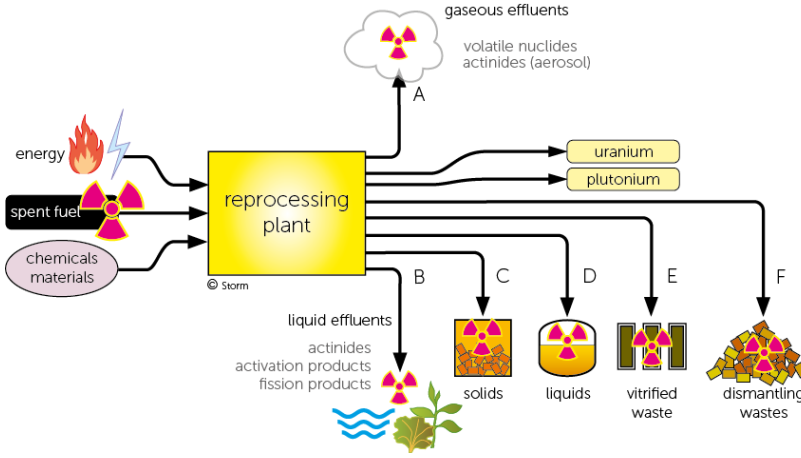

Figure 19 – Outline of the radioactive mass flows of reprocessing of fuel

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 aerosols of some other fission products and actinides; (B) liquid effluents, discharged into the environment (soil, sea, groundwater), 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 also small amounts of undissolved fuel: 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.
Designed by STORM VAN LEEUWEN, J. W. (2016)

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 radionuc-

lides into short-lived ones.

Only applications *2*, *3* and *4* are addressed in this paper.

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.

5.3. 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* fractions without losses, and none of the separated fractions will be 100% pure. Separation of a mixture into fractions 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;
- the constituting species are chemically more alike;
- the solution has a higher level of radioactivity.

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

expense of more specialised 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, because their chemical properties are identical.

Economic considerations and the human factor are left aside here.
The amount of radioactivity in spent fuel does not change with the mechanical and chemical treatments in the reprocessing plant, it simply means a redistribution of the radionuclides from one material to several other materials. Inevitably, mixing any amount of radionuclides, originally compacted in solid spent fuel, with non-radioactive fluids or other substances increases the volume of the radioactive waste, exacerbating the waste disposal problems.

Reprocessing of spent fuel is an exceedingly polluting process consuming massive quantities of energy and chemicals. Decommissioning and dismantling of the ageing reprocessing plants will be extremely costly, and very time and energy consuming. These activities should be included in the energy balance of any option that includes reprocessing.

5.4. U-Pu recycle in LWRs

A limited number the currently operational thermal reactors is partly fuelled (not more than 30%) by uranium-plutonium mixed-oxide fuel (MOX) replacing enriched uranium fuel elements. In addition to the high energy intensity of reprocessing the fabrication of MOX fuel is more energy intensive than the fabrication of fresh nuclear fuel from enriched uranium. Jointly these factors cause a 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 all the separated plutonium could be used to produce MOX fuel.

5.5. Uranium-plutonium breeders ('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 1960s, 1970s and 1980s 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 into practice. The prefix 'fast' refers to the fact that this type of reactor operates with fast neutrons, contrary to the currently operating commercial reactors, in which fission occurs by thermal (slow) neutrons. Now the breeder concept is part of the so-called *Generation IV program*. This program also includes other types of fast reactors without a breeding capacity that are not discussed here.

The nuclear industry promised (and is still promising) that a closed-cycle reactor system (breeder) could fission 50–100 times more nuclei present in natural uranium, and consequently generate 50–100 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 materialisation 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, A. 2007) does not expect the first fast reactor or breeder of *Generation IV* to come on line before 2040.

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. The breeder cycle comprises three components: a breeder reactor, a reprocessing facility and a fuel fabrication plant *(Figure 20)*.

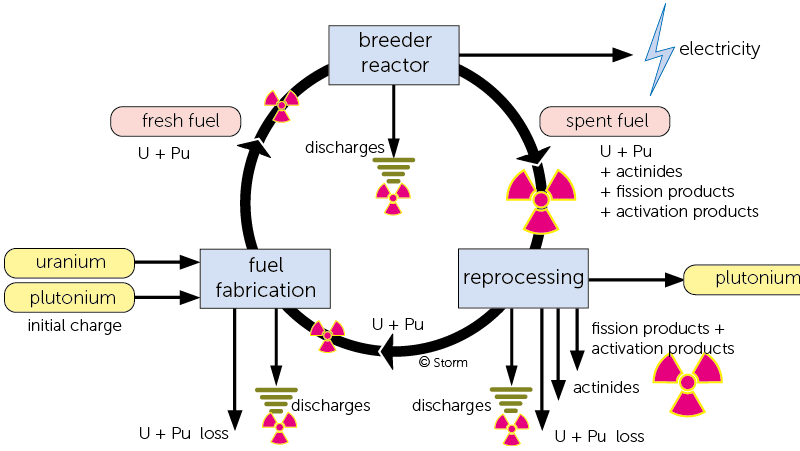

Figure 20 – Outline of the breeder system concept in steady state

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.
Designed by STORM VAN LEEUWEN, J. W. (2016)

Important parameters of the breeder system are, among other:

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

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

All three components of the breeder cycle must operate flawlessly, continuously and exactly tuned to the other two components, in order to let the system actually breed more fissile material from non-fissile uranium-238 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.

Due to the rapidly increasing radioactivity of the spent fuel with each cycle, reprocessing and fuel fabrication become increasingly difficult. The isotopic compositions of the recovered uranium and plutonium become less favourable with each cycle. Due to the unavoidable and increasing separation losses, the cycle produces less fissile nuclides than it consumes. For these reasons, among other, the breeder cycle is technically infeasible.

Breeder systems exist only on paper. Nearly 60 years of intensive research in seven countries (*USA, UK, France, Germany*, former *USSR* now *Russia*, *Japan* and *India*) and investments of more than a 100 billion dollars have failed to deliver an operable breeder cycle, due to insurmountable technical hurdles. The failure of the breeder concept is not caused by protests of environmental activists nor by actions of leftist politicians, nor for economic reasons, as the nuclear industry asserts, but is caused by fundamental technical limitations.

Problems of the breeder system are discussed in more detail by, for example, LIDSKY, L. M. – MILLER, M. M. (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.

5.6. 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 five decades of research there are still no solutions for the basic problems mentioned by ABBOTT, L. S. *et al.* (1978). The fundamental obstacles that render the U-Pu breeder technically infeasible apply also to the thorium breeder. Problems include:

- the high radioactivity of U-233, which is always contaminated with traces of U-232, a strong gamma emitter;
- similar problems in recycling thorium due to the highly radioactive Th-228, a decay product of both Th-232 and U-232;
- technical problems, not yet satisfactorily solved, in reprocessing;
- the use of U-233 as fuel requires specially developed reactors;
- by recycling of U-233 its isotopic composition deteriorates, and so its usefulness, by the increasing generation of the unfavourable isotopes U-232, U-234 and U-236 (ABBOTT, L. S. *et al.* 1978).

Research and development on the thorium cycle has been less intensive than on the U-Pu cycle and never reached the prototype phase, like the U-Pu cycle with the *French Superphénix*.

Among a number of other countries, the *USA* conducted Th-232/U-233 research in the 1960s and 1970s (for example, in the *Shippingport* reactor), the research has not been continued.

To generate sufficiently pure U-233, special reactors are required, likely not appropriate for use as power reactors. It would take decades to construct these reactors and to generate sufficient U-233 to start up

the first operating Th-232/U-233 breeder system. Then it would take 9 doubling times to attain a thorium breeder capacity equalling the current nuclear capacity (370 GWe). Even assuming an unrealistically short doubling time of 20 years, 9 doubling times would mean a period of two centuries.

In this scenario, a perfectly operating breeding cycle is assumed, including the separation processes of the spent fuel and the fuel element fabrication. The high radioactivity of U-233 demand remote operations of the material throughout all steps of the fuel handling. The monetary costs, but also the energy requirements of the fuel cycle will be high.

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.

5.7. Conclusion of Chapter 5

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

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

Not one of these conditions is possible, as a consequence of the Second Law of thermodynamics, and for that reason whatever breeder concept is inherently infeasible.

Consequently, the nuclear generating capacity in the future will completely rely on the conventional technology of thermal-neutron reactors in the once-through mode.

6. Prospects of nuclear power

6.1. Uranium resources

In the *Earth*'s crust uranium is present in the form of numerous different chemical compounds, embedded in various types of host rocks. Uranium in the earth's crust is unevenly distributed among the rocks comprising the crust. The grade distribution of uranium in uranium-bearing rocks in the *Earth*'s crust shows a geologic pattern common to most other metals: the lower the grade of uranium the larger the amounts of uranium present in the crust.

The size distribution of uranium deposits shows a similar pattern as the grade distribution: the larger the size, the rarer the deposits. From a statistical point of view the chances of finding new uranium deposits increase with decreasing ore grade, decreasing ore body size and increasing depth below the surface. In *Figure 16*, the ore grade distribution of the known uranium resources is represented by a bar diagram.

From this aspect of observation, the chance of discovering new resources increases with lower grades and smaller sizes of the deposits. One may assume that the most easily discoverable resources have been found already and that the most easily mineable deposits are already being mined. The chances of discovering new, large, high-grade resources seem low; no such discoveries have been reported during the past decades. Undiscovered high-grade deposits may be present at greater depths than the existing mines and/or in poorly explored areas, such as *Antarctica*.

6.2. Unconventional uranium resources

Usually, the global uranium resources are classified into two categories: conventional and unconventional resources. Phosphates are the main constituent of unconventional uranium resources, other types of uranium-bearing resources (for example black shales) are insignificant on global scale.

Phosphates are irreplaceable for agricultural use, so mining of

these minerals should be tailored exclusively to agricultural needs. Moreover, the thermodynamic quality of phosphates as a uranium-for-energy source lies beyond the energy cliff: no net energy generation is possible by exploitation of phosphate rock.

The nuclear industry places its hope for a future expansion of nuclear power not only on advanced reactor technologies, discussed in the previous chapter, but also on advanced extraction technologies that would make possible the extraction of uranium from seawater in an economically viable way. This would open access to an almost limitless source of uranium. However, extraction of uranium from seawater is also governed by the Second Law of thermodynamics, and lies far beyond the energy cliff—if large-scale extraction (at least some 10,000s tonnes a year in a nuclear expansion scenario) would be possible at all.

6.3. Depletion of uranium resources: a thermodynamic notion

In *Chapter 3*, the thermodynamic quality of uranium *in situ* (as present in nature) has been introduced: below grades of 0.2–0.1 gU/kg rock deposits cannot be classified as energy sources. Uranium-for-energy resources are governed by the basic laws of thermodynamics and not by economic notions and rules.

From a quantitative viewpoint, the uranium occurrences of the world are practically inexhaustible. The depletion of uranium resources as a source of useful energy is a thermodynamic notion. *Figure 21* represents the depletion of the known uranium resources, assumed no new significant deposits would be discovered.

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

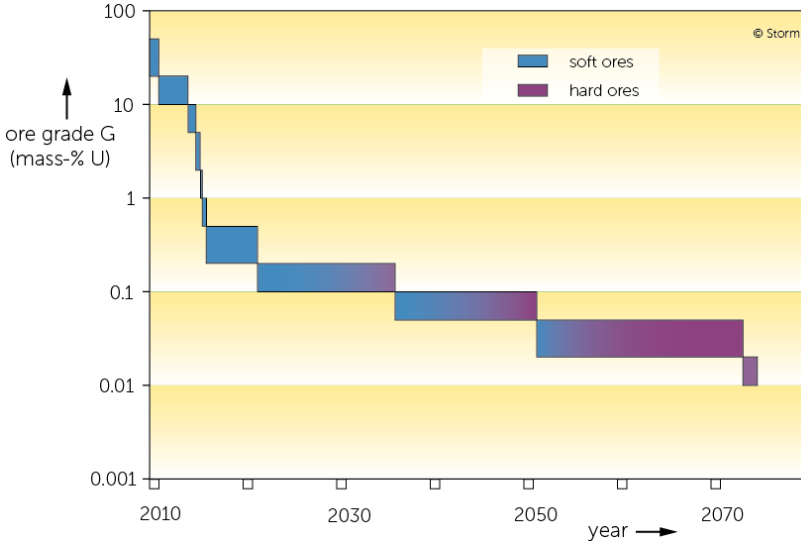

Figure 21 – Depletion of the currently known recoverable uranium resources, at an assumed constant annual uranium consumption of 66 Gg/a

This constant capacity scenario is based on the assumption that no major new resources will be discovered during the next decades, as has been the case during the past three decades, and that the richest available resources are exploited first. This figure is based on the ore grade distribution of the known uranium resources.

Designed by STORM VAN LEEUWEN, J. W. (2016)

6.4. Nuclear climate change mitigation share in the future

This section returns to the nuclear capacity scenarios, as presented in *Figure 8*.

The uranium requirements in the three scenarios are summarised in *Table 4* in teragram Tg (1 Tg = 10^{12} g = 1 million metric tons), assumed that all reactors would be light-water reactors (LWRs) in the once-through mode. In *scenario 2*, roughly corresponding with a constant mitigation share of nuclear power, the total uranium requirements would be some 13.7 Tg. This amount would be nearly ten times the all-time uranium consumption up until today.

Table 4 – Uranium consumption in three scenarios through the year 2100
The figures are rough estimates. The figure of scenario 2 depends on the growth rate of the world electricity consumption. 1 Tg = 1 teragram = 1 million metric tonnes.
Designed by STORM VAN LEEUWEN, J. W. (2016)

scenario	cumulative uranium consumption (Tg)
0 phase-out present capacity	1.6
1 constant capacity, IAEA low, phase out after 2050	4.7
2 constant share, IAEA high, phase out after 2050	13.7

The known recoverable uranium resources amount to, according to *Red Book* (OECD, 2014):

- 2.0 Tg in the cost category up to 80 USD/kgU;
- 5.9 Tg in the cost category up to 130 USD/kgU, including the first category;
- 7.6 Tg in the highest cost category, up to 260 USD/kgU, including the first two categories;
- The market price as of December 2016 was about 50 USD/kgU.

The figures presented by the IAEA in the *Red Book* are not compiled by an independent scientific institute but are submitted by the concerning countries. The *Red Book* does not contain information on the ore grades and other parameters of the listed uranium resources, so the data of the *Red Book* do not allow an assessment of the thermodynamic quality of those resources. Using data from other sources, it becomes clear that large resources in the highest cost segment (1.7 Tg, 130–260 USD/kgU) are near, or sometimes even beyond the energy cliff. This observation would imply that about 6 Tg of known uranium resources could really contribute to mitigation of GHG emissions, assumed nuclear power is GHG free, so *scenario 1* may be considered a realistic one.

In *scenario 2* the nuclear energy system would get stuck in the CO_2 trap halfway its fulfilment. For *scenario 2* more than twice the amount in the cost category up to 130 USD/kgU has yet to be discovered.

The *World Nuclear Association* (WNA) sees no problem: 'the market will do the job'.

"Rising uranium prices will stimulate more exploration, which will result in new uranium discoveries, as is with all other metals."

This viewpoint seems a serious misconception, for it does not account for the thermodynamic quality of the uranium resources.

6.5. Findings of Chapter 6

Two findings important for the future of nuclear power, that result from the thermodynamic analyses conducted in this study, are:

1. The amounts of uranium resources present in nature that are suitable as energy sources are limited by their thermodynamic properties. As a consequence, unconventional uranium resources, such as shales and phosphates and uranium from the oceans are not uranium-for-energy sources.
2. Closed-cycle reactor systems, designed to fission a large part of natural uranium (30–60% versus 0.6% in the present reactors) and systems designed to use thorium as nuclear fuel are implicitly based on assumptions that are in conflict with the *Second Law of thermodynamics*. The conclusion is unambiguous: the as-designed functioning of these closed-cycle systems is inherently impossible.

Moreover, the systems as a whole would have a negative energy balance: they would consume more energy than they could produce.

From these findings, it may be concluded that nuclear power in the foreseeable future has to be based exclusively on the technology of the existing conventional thermal neutron reactors and consequently on the conventional uranium resources. Any growth scenario of the nuclear capacity and GHG mitigation share seems unlikely, unless millions of tonnes of high-quality (in the thermodynamic sense) uranium resources would be discovered during the coming decades. This seems unlikely from a geologic point of view.

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