Contemporary CO_2 emissions of advanced nuclear power

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Note

In this document the references are coded by Q-numbers (e.g. Q6). Each reference has a unique number in this coding system, which is consistently used throughout all publications by the author. In the list at the back of the document the references are sorted by Q-number. The resulting sequence is not necessarily the same order in which the references appear in the text.

Abstract

Reported lifecycle CO_2 emissions of nuclear power point to different assessment methods. Purpose of this study is to present figures based on an unambiguous physical/chemical analysis of the complete chain of industrial processes making nuclear power possible, taking into account direct and indirect CO_2 emissions. The assessment limits it scope to the emissions of CO_2 contemporary with the construction and operation of nuclear power plants based on the currently operating most advanced reactors and on the EPR design. Future emissions, coupled to waste management and dismantling, are left outside this assessment.
A thermodynamic analysis of the nuclear energy system introduces several novel notions: thermodynamic quality of uranium resources, energy cliff, CO_2 trap, energy debt, contemporary and latent CO_2 emissions. These notions turn out to play a vital part in the prospects of nuclear power: within the lifetime of new nuclear power plants the currently known uranium-for-energy resources would get depleted and the specific nuclear CO_2 emission would surpass that of fossil-fuelled power plants, if the the global nuclear capacity would remain constant at the current level.

Table 0
Specific CO_2 emission (gCO_2/kWh) of the contemporary processes of the reference advanced reactor and the EPR design. This table is identical to Table 4.

process	advanced reactor gCO_2/kWh		EPR design gCO_2/kWh	
	0.10% U_3O_8	0.05% U_3O_8	0.10% U_3O_8	0.05% U_3O_8
mining + milling , soft - hard ores	7.1 - 27.1	15.0 - 57.4	6.2 - 23.7	13.1 - 50.1
refining + conversion	2.81	2.81	2.45	2.45
enrichment	2.60	2.60	2.40	2.40
fuel fabrication	3.40	3.40	2.47	2.47
construction	24.9	24.9	8.4	8.4
OMR	24.4	24.4	18.2	18.2
sum contemporary CO_2 emissions (rounded)	65 - 85	73 - 116	40 - 58	47 - 84

Highlights

- Nuclear power will depend on present reactor technology during the coming decades
- Contemporary CO_2 emissions of advanced nuclear power vary from 65-116 gCO_2/kWh
- Contemporary nuclear CO_2 emissions rise with time
- Nuclear power is energy on credit
- After 2080 no net energy is possible from the presently known uranium resources

Abbreviations and acronyms

c2g	cradle to grave
CO_2	carbon dioxide
EPR	European Pressurised Reactor
FPY	full-power year
GDP	gross domestic product
Gg	gigagram = 1000 metric tons
GHG	greenhouse gas
GWe	gigawatt electric
IAEA	International Atomic Energy Agency
I/O	input-output
ISL	in-situ leaching
LCA	life cycle assessment, life cycle analysis
LWR	light-water reactor
Mg	megagram = 1 metric ton
MJ	megajoule = 10^6 J
MSWU	million separative work units
NPP	nuclear power plant
O&M	operation and maintenance
OMR	operation, maintenance & refurbishments
PJ	petajoule = 10^{15} J
PWR	pressurised water reactor
SWU	separative work unit
TOE	(metric) ton oil equivalent
U_3O_8	uranium oxide
WHO	World Health Organization
WNA	World Nuclear Association

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Introduction

Within the framework of climate change and electricity generation CO_2 emission figures of nuclear power are reported in a range of 2 to 228 gCO_2/kWh, a factor of more than 100. Such differences point to different assessment methods, presuppositions and assumptions. Aim of this study is to eliminate ambiguities as much as possible by presenting figures resulting from an umambiguous physical/chemical analysis of the nuclear process chain, starting from basic process data. Climate change resulting from anthropogenic greenhouse gas emissions is a long-term global issue. For that reason the assessment of the CO_2 emission of nuclear power in this study is based on world-averaged conditions and on proven technology.

The presently operating nuclear power plants of the world are based on thermal-neutron reactors in the once-through mode. The most advanced operational power reactors cannot fission more than about 5 grams of uranium nuclei per kilogram of natural uranium.
According to the nuclear industry breeder reactors would be able to fission 30-50% of the nuclei in natural uranium. However, an operating breeder cycle has still never been proved in practice, after six decades of research in seven countries and investments of hundreds of billions of dollars. Even if the breeder concept would become operational by 2050, it would take many doubling times, covering a period of one to two centuries, before the present world nuclear generating capacity, based on once-through reactors, could be replaced by breeders. Potential use of thorium as net energy source is even more remote than of uranium-plutonium breeders

The nuclear process chain has three main parts: front end, mid section and back end. The front end (also called upstream processes) comprises the industrial processes required to fabricate nuclear fuel (enriched uranium) from uranium ore as found in nature. The mid-section encompass the construction of the nuclear power plant and its operation, maintenance and refurbishments (OMR). The back end (downstream processes) includes the industrial processes needed to safely dispose of all radioactive wastes, generated by the reactor and other processes of the process chain: the nuclear legacy.
This study divides the industrial processes related to a given nuclear power plant (NPP) into two categories: *contemporary processes*, occurring in advance of or during operation of the NPP, and the *future processes*, that are to be performed after final closedown of the NPP.
Each process of the nuclear chain consumes materials and energy and emits CO_2 and possibly also other greenhouse gases (GHGs). Fission of uranium in the nuclear reactor is the only process in the chain that does not emit CO_2. Emissions of other GHGs by the nuclear system are not mentioned by the nuclear industry, although a number of processes of the nuclear chain most likely do emit also other GHGs.

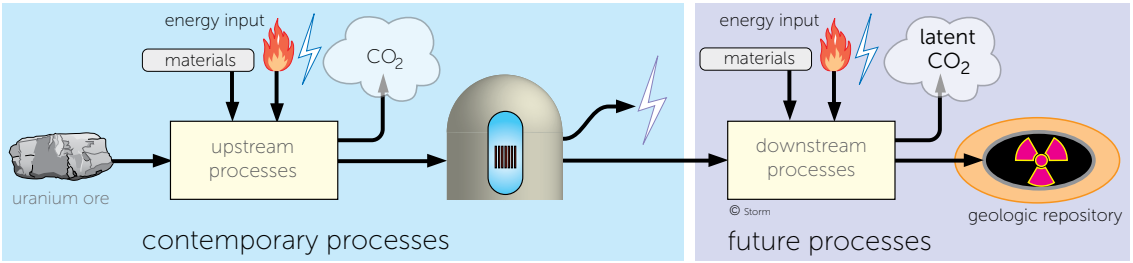

Figure 1
Outline of the nuclear energy system from cradle to grave, as analysed in this study. The query symbolises the uncertain future of the nuclear legacy.

A nuclear power plant of 1 GWe irreversibly generates each year an amount of human-made radioactivity equivalent to about 1000 exploded atomic bombs of about 15 kilotons (Hiroshima bomb). Each year the civil nuclear power plants of the world add some 300000 atomic bomb equivalents to the world inventory, in 2018 amounting to roughly 12 million bomb equivalents: the nuclear legacy. These amounts of human-made radioactivity are present in spent fuel, in construction materials and in auxiliary materials. Radioactivity cannot be destroyed nor can be made harmless.
During the disasters of Chernobyl and Fukushima jointly about 0.01% of the world civil inventory of human-made radioactivity has been released into the biosphere. This corresponds with the amount of artificial radioactivity generated by one nuclear power plant of 1 GWe during one year at full power. The irreversible and harmful consequences of these disasters are noticeable on continental scales, affecting hundreds of millions of people, costing hundreds of billions of dollars, and will continue for centuriess into the future.
Adequate fulfilment of the downsteam (back-end) processes of nuclear power plants is a *conditio sine qua non* to avoid dispersion of the remaining 99.99% of the *nuclear legacy* into the biosphere and to keep vast areas on the Northern Hemisphere habitable. Fulfillment of the back-end processes may take a period of 100-150 years after closedown of the nuclear power plant, according to estimates by large nuclear institutes.

Energy investments and CO_2 emissions of the downstream processes, can be fairly reliably assessed, because no advanced technology is required. Concerning the future processes this assessment introduces the novel notions *energy debt* and *latent CO_2 emission*. To limit its scope and length the future processes are not addressed in this article.

The structure of the thermodynamic analysis is represented by Figure 2.

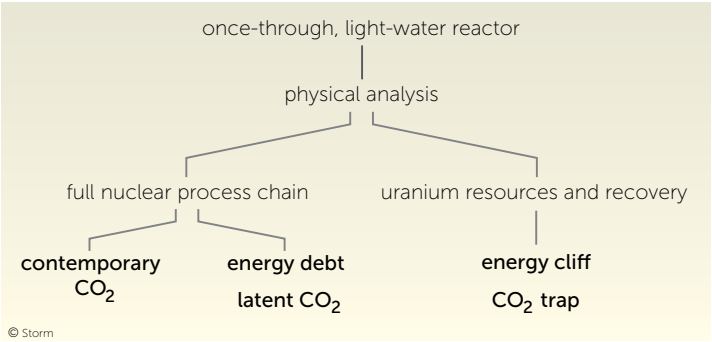

Figure 2
Outline of the physical assessment of nuclear power in this study.

Finally this study compares the CO_2 emission of the reference advanced reactor with those of a number of other recent studies, and with the official EPR design.

1 URANIUM MINING + MILLING

Assessment of the sequence of the mining + milling processes in this study starts from a comprehensive process analysis of the Ranger mine in Australia, one of the cheapest operating mines in the world, due to its favourable conditions. Many open-pit and underground uranium mines in the world are operating according a similar process sequence.

Conditions determining the specific energy input and CO_2 of emission of uranium mining + milling vary greatly from mine to mine. Apart from the specific variables regarding mining and milling, discussed in the following sections, the energy input and CO_2 emission of an operating uranium mine depends on some general parameters, such as:

- Size of the ore body and construction of the mine. Smaller mines have a relatively larger fixed energy input, due to its construction, including the processing plant and equipment.
- Availability of fresh water; a uranium mine consumes large volumes of fresh water.
- Location: the transport distances of the supplies to the mine vary over a wide range and may be thousands of kilometers in some cases. Remote uranium mines have longer supply routes and consequently have a higher specific energy consumption.
- Local climate and other conditions.

1.1 Mining

The reference uranium mine in this study is an open pit mine that may be taken as a world-averaged mine. Underground mining is generallly more energy intensive than open pit mining, in-situ leaching (ISL) may be less energy intensive in some cases. Differences in specific energy consumption and CO_2 emission between individual uranium mines are substantial, so it seems not very useful to discern different types of mines in this assessment: the figures exhibit a significant range of values anyhow.
Energy consumption and CO_2 emission per Mg mined ore of the mining of uranium ore from the earth's crust (mining), depends on a number of variable conditions, such as:

- Overburden ratio (= stripping ratio), determines the mass of waste rock to be removed per Mg ore. The overburden ratios of open pit mines vary roughly from 3-50. An overburden ratio (or stripping ratio) of 3 means that for every Mg ore 3 Mg of waste rock has to be removed. Variations in overburden ratios may introduce a range in the values of the energy requirements with a factor of 5 [Chapman 1976b], with the same type of ore.
- Haulage distance: the distance the waste rock and ore has to be transported to the waste rock dumping site respectively to the ore processing plant. The hauling distance for ore may vary from a couple of kilometers to more than 200 km.
- Specific consumption of explosives (kg explosives per Mg rock).

The hardness of the rock to be mined is difficult to quantify, and for that reason this study discerns two main types of ore: soft ores and hard ores. Variable rock properties may introduce considerable variations in the specific energy requirements and CO_2 emissions of mining from mine to mine. Some consequences of the mining of harder rock are, among other:

- Higher energy consumption per Mg rock removed by excavators.
- Higher wear of equipment, such as drill rigs and excavators, causing more time in the shop and a higher rate of replacement of components and higher use of consumables. These increased rates mean an higher direct and indirect energy consumption per Mg rock mined.

- Higher specific consumption of explosives: harder rock needs more explosives per Mg rock. The Ranger mine uses about 0.25 kg explosives per Mg rock. Likely many mines have significant higher explosives consumptions. This study assumes an explosives consumption rate of 1 kg/Mg rock in mines with hard ores and in underground mines .

The specific thermal energy consumption of mining per Mg of soft ore can be calculated by equation B1 in Annex B. The figures are derived from the process analysis of the Ranger mine, based on the publications [ERA 2006], [ERA-AR 2005], [Rotty et al.1975] and [Mortimer 1977]. The resulting figures may be considered a low estimate of the world average uranium mine with soft ores, in view of the favourable geologic conditions at Ranger.

1.2 Ore processing (milling)

Specific energy consumption and CO_2 emission of the extraction of uranium from the ore, per Mg recovered uranium, depends on a number of variable conditions, such as:

- Ore grade, determines the dilution factor: the mass of ore to be processed per Mg uranium; the ore grade of the currenty operating mines varies from roughly 20% to 0.01% U_3O_8, a factor of 2000. The world average ore grade of currently operating uranium mines is about 0.1-0.05% U_3O_8. Consequently the ore grade determines the energy consumption of crushing and grinding and the amount of chemicals consumed per kg U for leaching and extraction. Lower grade means the need to grind the ore to a finer mesh and to use more chemicals per Mg uranium, and consequently the specific energy consumption per Mg ore increases.
- Extraction yield (= recovery factor): fraction of uranium that is actually extracted from the ore.
- Mineralogy of the ore, determines the hardness of the minerals to be crushed and grinded and the chemical refractoriness of the uranium minerals to be dissolved.
- Chemical composition of the ore, determines the type of chemicals used, for example acid leaching or alkaline leaching, and reaction conditions, such as high or ambient temperature. The world average includes alkaline ores. The leaching of alkaline ores takes much more energy than acidic ores (as at Ranger), due to the elevated temperatures (60-80 °C) and the consumption of chemicals with high embodied energy, such as sodium hydroxide and sodium carbonate.

Ore grade and extraction yield are two quantifyable variables in the assessment of the energy consumption and CO_2 emission of the exraction of uranium from its ore. The different ore types are simplified to two classes: soft ores and hard ores. World average figures of other variables and parameters are used.

For ore processing (milling) at Ranger (based on [ERA 2006] and [ERA-AR 2005] this study found a low estimate, for several energy inputs of the ore processing are not included, see Annex B. For that reason this study applies the somewhat higher figure of [ERDA-76-1] for soft ores.

For hard ores this study applies the figures based on [Kistemaker 1976] and [Kistemaker 1975]. Kistemaker published figures for the milling of hard ores, based on the data of 1974 supplied by NUFCOR (Nuclear Fuels Corporation), responsible at that time for the mining and milling activities at the South African uranium mines. The Kistemaker figures include the embodied energy of a number of chemicals, not all, but do not include the energy input of equipment and capital goods.

1.3 Extraction yield

The *extraction yield Y*, also called the *recovery factor* or *recovery yield*, is the ratio of the mass of uranium

actually extracted over the mass of the uranium present in the treated amount of rock. Reported yield data are not always unambiguous. In many cases it is not clear on which quantity of uranium the reported yields are based. Some mining companies published data which would result in yields of 100% or higher.
The data used in Figure 5 may seem obsolete, but during the past 4-5 decades the extraction techniques applied in the uranium industry have hardly changed. The study of [Mudd 2011] proves the curve of Figure 3 to be at the upper limit of the current practice. In practice nearly all uranium mines achieve substantially lower extraction yields at a given ore grade than suggested by the curve of Figure 3.

Extraction is governed by basic physical and chemical laws, which cannot be circumvented by technology. A low yield at low grades may be improved by application of more selective separation processes, at the expense of much higher specific energy requirements per mass unit recovered uranium.
The extraction of any metal from its ore involves a number of physical and chemical equilibria. From the Second Law of thermodynamics follows that these equilibtria never go to completion. That means that a complete separation is not possible, there always will be losses. The decline of the extraction yield at lower grades is a direct consequence of this observation. The lower the concentration of uranium in the pregnant liquor, the higher its entropy and the more energy is required to extract a certain amount of uranium from that liquor. The higher the entropy of the uranium, the less complete its separation from the liquor and the greater the fraction lost in the waste streams.

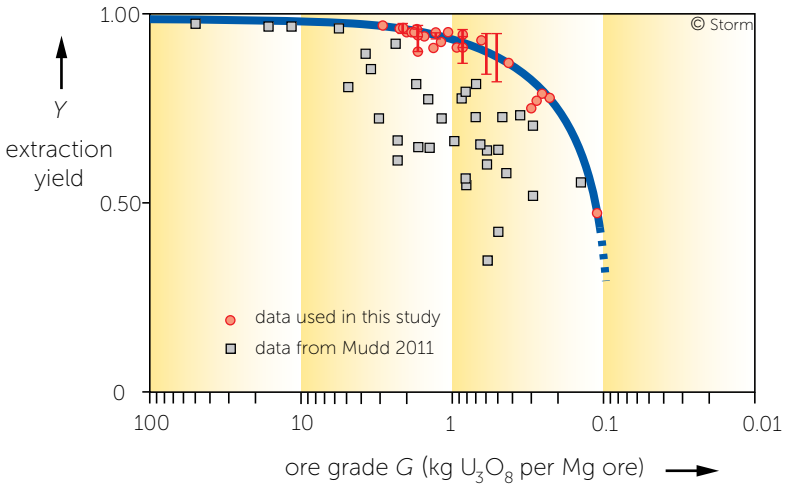

Figure 3
The extraction yield of uranium from ore as function of the ore grade. The red dots are the highest reported figures from the literature, based on actual mining operations. The blue curve may be seen as the upper limit of the attainable extraction yields using the current extraction technology. The grey squares are empirical data from [Mudd 2011].
The data used in this study (red dots and bars) have been taken from: [Burnham *et al.* 1974], [Franklin *et al.* 1971], [GJO-100 1980], [Huwyler *et al.* 1975], [James & Simonson 1978], [James *et al.* 1978], [Kistemaker 1976], [Kistemaker 1975], [Mutschler *et al.* 1976], [Rombough & Koen 1975], [Ross & Guglielmin 1968], [Rotty *et al.* 1975], [Simonson *et al.* 1980], [SRI 1975].

1.4 Results of the process analysis

From the specific thermal energy input the specific CO_2 emission of uranium mining and milling can be calculated (see also Annex B). The specific CO_2 emissions of mining + milling of uranium from ore in the ore grade range of 0.1- 0.05% U_3O_8, the present world average, related to the advanced reference reactor and the EPR design are summarised in Table 1.

Table 1

Lifetime data on the specific CO_2 emission of uranium mining + milling.

quantity	unit	advanced reactor	EPR design
input mass of natural uranium, $m(U_{nat})$	Mg	5748	17880
gross electricity production, E_{gross}	kWh	$219*10^9$	$780*10^9$
total CO_2 emission, soft ores G = 0.1-0.05% U_3O_8	Gg	1551 - 3283	4823 - 10214
total CO_2 emission, hard ores, G = 0.1-0.05% U_3O_8	Gg	5937 - 12527	18467 - 39106
specific CO_2 emission, soft ores, G = 0.1-0.05% U_3O_8	g CO_2/kWh	7 - 15	6 - 13
specific CO_2 emission, hard ores, G = 0.1-0.05% U_3O_8	g CO_2/kWh	27 - 57	24 - 50

1.5 Energy cliff

The thermodynamic quality of a uranium resource is the determinant of being a net energy source or not. Here we define the thermodynamic quality of a uranium resource as the net quantity of useful energy that can be extracted from 1 kg natural uranium from that resource, that is the amount of electricity available to the consumer, minus the useful energy (in thermodynamics: work) required to extract 1 kg pure uranium from that resource. If the extraction of 1 kg uranium requires as much work as the amount that than can be generated from that uranium, the uranium resource in question is not an energy source, but an energy sink. The minimum amount of extraction work is governed by basic physical laws. Advanced technology may come closer to the thermodynamic minimum, at the expense of more useful energy, but never can surpass the minimum.

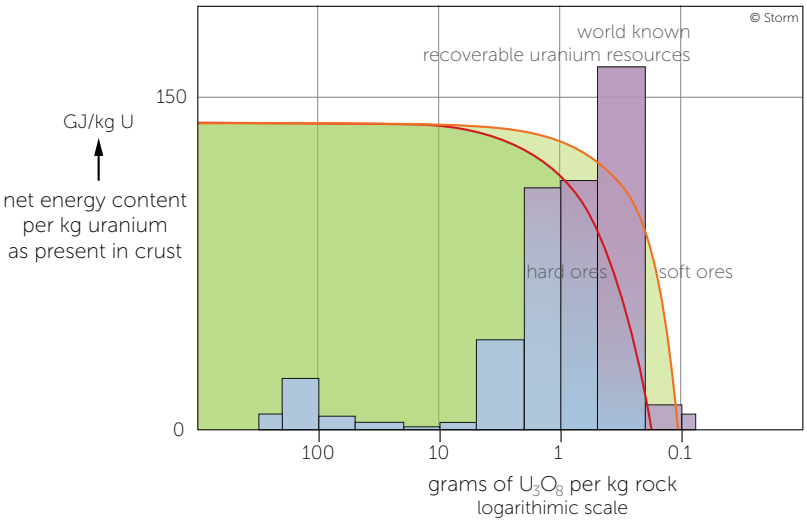

Figure 4

Energy cliff. Net energy content of natural uranium as function of the ore grade. The net energy content is defined as the amount of useful energy that can be generated per kg uranium minus the energy required for recovery of 1 kg uranium from the earth's crust. Beyond a grade of about 0.1 g uranium per kg ore no net energy generation from a uranium deposit is possible. The bar diagram represents the grade distribution of the currently known recoverable uranium resources. The leanest reported uranium ores contain about 2000 times less uranium per kg rock than the richest ones: 0.1 g U/kg ore vs about 200 g U/kg ore. The world average grade of the presently operational mines lies in the range of 1 to 0.5 g U/kg ore.

Advanced power reactors cannot fission more than about 5 g/kg U of the nuclei in natural uranium (see Annex A). This figure sets a practical limit to the energy content of natural uranium. The fission heat and radiation is not directly useable and has to be converted into electricity in order to become work (useful energy). The thermodynamic quality of uranium *in situ* is the amount of useful energy extractable from 1 kg of extracted uranium, minus the energy required to recover 1 kg of uranium from that resource.

Energy investments of uranium recovery rise exponentially with decreasing ore grade. Consequently the thermodynamic quality of uranium resources declines exponentially with decreasing ore grade. It becomes zero at a certain ore grade: this is called the *energy cliff*, see Figure 4. For soft ores the cliff falls to zero at a grade of about 0.01% U_3O_8, corresponding with 85 g uranium per Mg rock, and for hard ores the cliff lies at a higher grade. In practice there are various types of uranium ores, so the thermodynamic quality of the currently exploited uranium resources lay within the range between the two curves.

1.6 CO_2 trap

Coupled to a rising energy consumption with decreasing ore grade appears a rising CO_2 emission per kg recovered uranium. Figure 5 represents the curves derived (see Annex B) for hard ores and soft ores, valid for the reference advanced reactor. For many uranium mines the figures will be between the two curves, due to different conditions from mine to mine. The differences between the advanced reactor and the EPR design lie within the range of the used figures. At a grade of 200-100 g U/Mg ore the specific CO_2 emission of nuclear power surpasses that of gas-fired electricity generation, this is called the *CO_2 trap*.

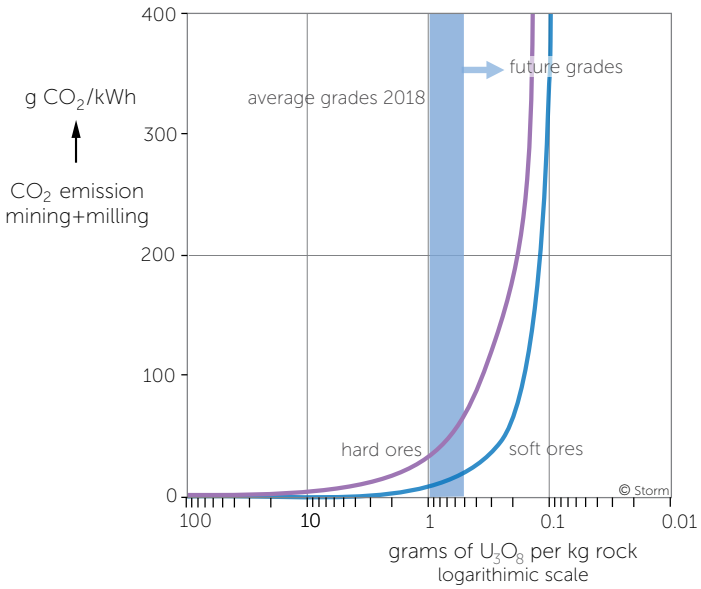

Figure 5

Specific CO_2 emission of the recovery of uranium from soft and hard ores as function of the ore grade. Differences between the curves concerning the advanced reactor and the EPR design are minor and remain within the range of the data the curves are based on.

1.7 Consequences

As indicated in the diagram of Figure 5, the world average ore grade (1 - 0.5 gU/Kg ore) of the operational uranium resources decreases with time. The most easily exploitable ore deposits with highest grades are mined first, because these offer the highest return on investment for the mining company, so the remaining

resources are of lower thermodynamic quality. As a result the specific energy consumption and CO_2 emission of uranium recovery rises with time.

The larger a uranium resource in the earth's crust, the lower its grade, a common geologic phenomenon regarding mineral resources. Uranium deposits tend to be harder, consisting of more refractory minerals, the lower grade; this phenomenon occurs also with other mineral resources. From a geologic viewpoint uranium resources may seem inexhaustable, their thermodynamic quality sets boundaries to the uranium-for-energy resources and consequently to nuclear generated electricity. During the past decades virtually no new high-quality deposits of significant size have been discovered; the chances of such discoveries seem dim for several reasons.
Figure 6 represents the depletion of the currently known uranium resources, assumed that no new significant high-quality uranium deposits will be discovered during the next decades and that the the world nuclear generating capacity remains constant at the present level. With the decreasing ore grade the hardness of the ores increases. Within the operational lifetime of new nuclear power plants the energy cliff would be reached and the nuclear energy system would become an energy sink instead of an energy source. Figure 7 shows the coupled CO_2 emission in two scenarios: one with a growing capacity and constant share of the world energy production (1.6% in 2018) and the second if the world nuclear capacity would remain constant.

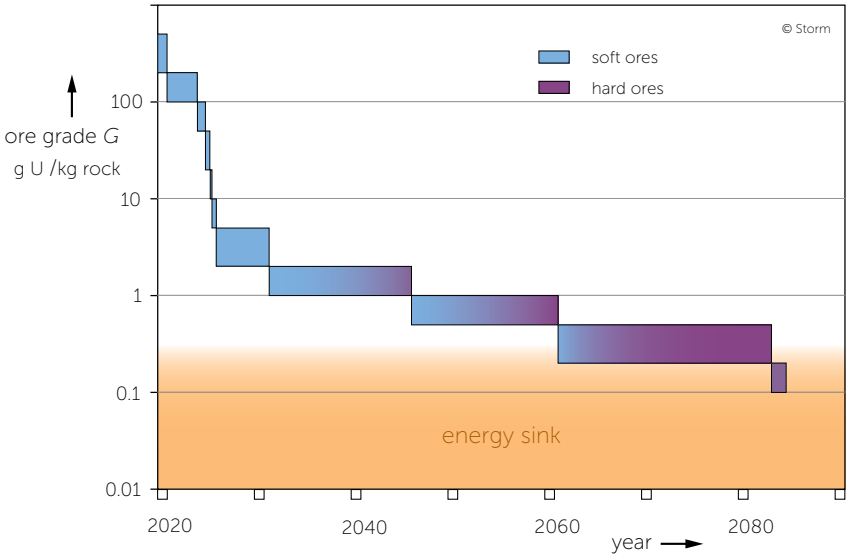

Figure 6
Simplified representation of the depletion of the currently known uranium-for-energy resources if no new high-quality resources would be discovered, assumed that the world nuclear capacity would remain constant at the current level.

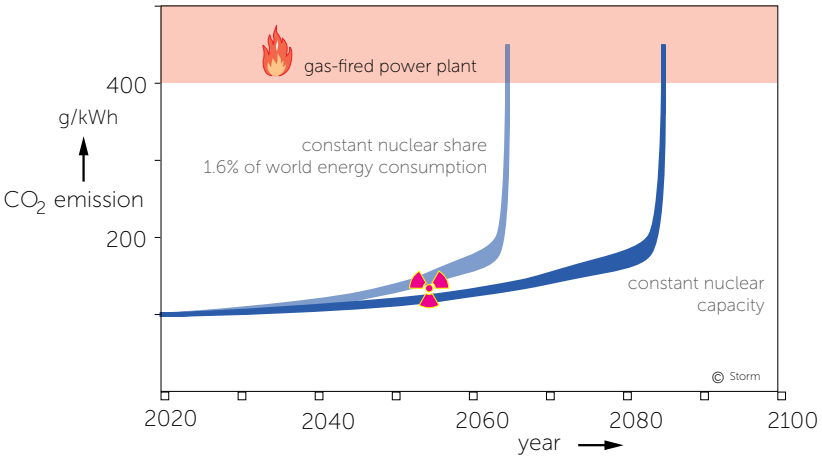

Figure 7

Specific CO_2 emission of nuclear power during the next decades, if no new high-quality uranium resources would be discovered. Two scenarios: one if the world nuclear capacity would grow at the same rate as the world energy consumption. the second if the capacity would remain at the current level.

2 NUCLEAR FUEL PRODUCTION

2.1 Refining and conversion into UF_6

Yellowcake, the product of the uranium mine, has to be refined and converted into very pure uranium hexafluoride UF_6. before enrichment is possible. Estimate of the specific energy consumption of this process is based on [ERDA-76-1]. The electric input has to be balanced with the gross electricity production of the nuclear power plant, the thermal energy input is the origin of the CO_2 emission.

2.2 Enrichment

Although enrichment by gas diffusion is still being applied, this assessment assumes all enrichment occurs by ultracentrifuge (UC). Enrichment by UC has a lower direct energy use than gas diffusion, but costs of operation and maintenance are higher because of the relative short technical life of the centrifuges. The UC process produces more wastes [INFCE-2 1980], [INFCE-7 1980], [Crossley 1980]. Becker *et al*. 1982]. The net difference in specific energy consumption - including construction, operation and maintenance - with the gas diffusion process is not large. According to [Crossley 1980] both processes cost roughly the same per SWU. US Department of Energy (DOE) expected that UC would prove more competitive in the future. Specific investment costs for both processes were about the same. This means that the operational costs, and consequently also the energy consumption, of the UC process must be higher than those of gas diffusion.
Energy requirements for operation and maintenance (O&M) are not included in the figures given by [Kolb *et al*. 1975], [Kistemaker 1975] and [Mortimer 1977]. This study uses the figure for UC from [Kistemaker 1975], which includes the energy consumption for construction of the plant and assumes that the energy consumption for O&M of a UC plant is twice that of a gas diffusion plant, as given by [Rotty *et al*. 1975]. The electric input has to be balanced with the lifetime gross electricity production of the nuclear power plant, the thermal energy input is the origin of the CO_2 emission.

2.3 Fuel fabrication

In the fuel fabrication plant the enriched uranium hexafluoride UF_6 is converted into uranium oxide UO_2. The pellets made from the UO_2 are packed in Zircaloy tubes, which in turn are assembled with Zircaloy spacers into fuel elements. The fuel elements can be placed into the reactor core. Zircaloy is an aloy of zirconium with a few percents of another metal, such as tin or nickel.
This study adopts the figure of specific energy consumption of fuel fabrication from [ERDA-76-1] Q109. Likely the figure of ERDA does not include the production of zirconium and of zircaloy, see also Annex C. Process data on the production of Zircaloy from zirconium are scarce in the open literature.

Zirconium for fabrication of nuclear fuel elements has to be extremely pure and free of hafnium. Purification is done by destillation of gaseous zirconium tetrachloride $ZrCl_4$. The destillation process plus the conversion of $ZrCl_4$ into metallic zirconium might emit significant amounts CO_2, in addition to the emission coupled to the production of zirconium from its ore. Data from [Lundberg 2011] are included in the figures of Table 2.

2.4 Summary fuel production

Table 2 gives the summary of the lifetime specific CO_2 emissions of the three front-end processes, refining + conversion, enrichment and fuel fabrication. See also Annex C.

Table 2

Summary of the specific CO_2 emissions of the production of nuclear fuel from natural uranium for the reference advanced reactor and the EPR design.

quantity	unit	advanced reactor	EPR design
refining and conversion	g CO_2/kWh	2.81	2.45
enrichment	g CO_2/kWh	2.60	2.40
fuel element fabrication, including Zircaloy production	g CO_2/kWh	3.40	2.47
sum nuclear fuel production	g CO_2/kWh	8.81	7.32

3 CONSTRUCTION AND OMR

3.1 Construction of the nuclear power plant

The CO_2 emission attributable to the construction of a nuclear power plant comprises not only the CO_2 emission of the construction acivities at the site, but also the embodied CO_2 emissions of the construction materials, such as concrete and steel, plus the CO_2 emissions of the production of all components and their transport to the construction site. The construction of a nuclear power plant is a very complicated sequence of activities involving high-quality materials and equipment. This study did not find a detailed assessment of the energy consumption and CO_2 emissions of these activities and associated production of materials, just rough estimates.
The embodied energy in only the steel and concrete of the nuclear power plant can be calculated with the specific values of steel and concrete, taken from [IAEA-TecDoc-753 1994], [IPCC 2006] and [NRMCA 2012]. This study estimated the masses of these two construction materials of the reference advanced reactor and the EPR design, summarised in Table D1 in Annex D. The figures are based on a number of studies: [Rombough & Koen 1974], [ORNL-TM-4515 1974], [Shaw 1979], [Crowley&Smith 1982], [IAEA-293 1988], [Lako 1995], [Uchiyama 2002], [Ecoinvent 2003], [MPR-2776 2005]. Due to its double containment the construction mass of the EPR design is assumed to be higher than of the reference advanced reactor.
To the chemical contributions of steel and concrete should be added the chemical emissions of CO_2 and other greenhouse gases of the processing of numerous other materials, such as stainless steel, aluminium, copper, zirconium, other metals and synthetic materials.

The CO_2 emission of construction could be estimated from the emissions coupled to the total energy investments. In the past numerous studies were published with widely different results: figures found in 21 studies, dating from 1974 to 2011, vary from 0.7 to 26 PJ/GWe (many in primary energy units). Five of these studies were based on unknown data, four on data from 1980 and later, and twelve studies, including [WNA-*eroi* 2016], were based on LWR power plant designs from 1970-1974, not on actally built nuclear power plants. Since 1970 the capacity of a generic LWR power plant evolved from 20-100 MW(e) to 1000-1600 MW(e) in 2018. The mass of construction materials evolved from some 100-200 Gg in 1970 to 800-1300 Gg in the 1990s. Construction mass further increased for nuclear power plants built, and being built, after the Twin Tower attacks of 9/11 2001. The range in the figures of energy investments point to different assessment methods, in addition to different data bases. Embodied energy in the materials is not always accounted for.

This study assumes that the direct plus indirect energy inputs and CO_2 emissions related to the construction of the nuclear power plant, such as: manufacturing, transport, construction, pipes, electric cables, electronic components, services, etcetera, are included in the figures found by the method used to estimate the overall energy investments and CO_2 emissions of construction, see Annex D. It seems unlikely that the chemical CO_2 emissions of the production of steel, concrete and other materials have been incorporated into the data used to estimate the construction energy, so these emissions are to be added to the construction emissions.
Assessment of the construction of the reference advanced nuclear power plant in the study [Storm&Smith 2005 & 2008] Q6 resulted in the following estimate of the construction energy investments, with a large uncertainty range, see also Annex D. This study uses the average value:

$$E_{construct} = E_{th} + E_e = 80 \pm 40 \text{ PJ}$$

Although this figure is criticized by some other studies, e.g. [Beerten *et al*. 2009] and [Lenzen *et al*. 2006], this study maintains it because no better assessment methods are presented and because of the uncertainty range in the used data. The figure of $E_{construct}$ includes the direct energy consumption during construction at the construction site, according to [Vattenfall Q2001a, 2001b, 2005], [WNA-*eroi* 2016] and [Setterwall 2005]. Several of the published life cycle assessments of nuclear power used the Vattenfall figure as the total energy investment of construction.

For the EPR design this study assumes a construction energy investment of 1.2 times that of the advanced reactor.
In this study the electric components of the construction energy are assumed to be provided by nuclear power and are to be balanced with the gross electricity production of the nuclear power plant.

3.2 Operation, maintenance and refurbishments (OMR)

This study found no figures on the energy investments of OMR of a nuclear power plant, only costs of operation and maintenence (O&M). [Rotty *et al.* 1975] mentioned a value of 3.1% per year, more recent studies, [Thomas 2005] and [Thomas *et al.* 2007] and [MIT 2003 & 2009], reported a cost of operation and maintenance at 2.3% of the construction cost per year in the USA. This study estimates the cost of O&M at 2.3% of the construction cost per year.
Extensive refurbishments of the nuclear power plant are required to reach an effective lifetime of 25 full-power years (FPY), for example replacing steam generators, implementation of new, updated control systems and updated safety measures. Extension of the operational lifetime beyond 25 FPY might require even more replacements: most parts of the nuclear power plants have to be replaced during the operational lifetime of the nuclear power plant, except the reactor vessel. The reliability of the reactor vessel determines the operational lifespan of a NPP. The quality of the vessel deteriorates over time by stress, corrosion and neutron capture. In view of the operational experience it seems highly unlikely that the reactor vessel of an EPR could reach the designed productive lifetime of 55 FPY.
It is not clear if the refurbishment costs are included in the O&M figures reported above. From numerous published reports follows that these replacements and updates may cost about 20-80% of the original construction costs. This study assumes that the mean lifetime refurbishment costs are 50% of the mean construction costs and are to be spent over an operating period of 25 FPY. Then the average annual refurbishment costs would be 2% of the mean construction costs per FPY.
The sum of the costs of operation + maintenance + refurbishments (OMR) would then become 4.3% of the construction cost per full-power year. If OMR together are taken as an average economic activity in de sector new construction - that may be an underestimate inview of the high-quality materials and equipment involved - the total energy requirements of this part of the nuclear chain would be 4.3% of the mean construction energy requirements per full-power year.

Table 3
Specific CO_2 emissions of construction and OMR of the reference advanced reactor and the EPR design.

quantity	unit	advanced reactor	EPR design
specific CO_2 emission construction, only concrete + steel	g CO_2/kWh	2.19	0.73
total specific CO_2 emission construction	g CO_2/kWh	24.9	8.4
specific CO_2 emission OMR	g CO_2/kWh	24.4	18.1
sum specific CO_2 emissions construction + OMR	g CO_2/kWh	49.3	26.5

4 CONTEMPORARY GREENHOUSE GAS EMISSIONS

4.1 CO_2

Based on Tables 1, 2 and 3 the specific CO_2 emissions of the processes contemporary with the operation of a nuclear power plant can be estimated. The CO_2 emission figures are summarised in Table 4.

Table 4

Specific CO_2 emission (gCO_2/kWh) of the contemporary processes of the reference advanced reactor and the EPR design.

process	advanced reactor gCO_2/kWh		EPR design gCO_2/kWh	
	0.10% U_3O_8	0.05% U_3O_8	0.10% U_3O_8	0.05% U_3O_8
mining + milling , soft - hard ores	7.1 - 27.1	15.0 - 57.4	6.2 - 23.7	13.1 - 50.1
refining + conversion	2.81	2.81	2.45	2.45
enrichment	2.60	2.60	2.40	2.40
fuel fabrication	3.40	3.40	2.47	2.47
construction	24.9	24.9	8.4	8.4
OMR	24.4	24.4	18.2	18.2
sum contemporary CO_2 emissions (rounded)	65 - 85	73 - 116	40 - 58	47 - 84

The range of the possible values of the contemporary specific CO_2 emission is considerable, due to different ore grades and the shift from soft to hard ores. For the reference advanced reactor the full range of the contemporary specific CO_2 emission due to different conditions of the currently mined uranium ores is:

γ = 65 - 116 g CO_2/kWh.

For the EPR design the range would be:

γ = 40 - 84 g CO_2/kWh.

The figure of the specific CO_2 emission of construction of the nuclear power plant has also a considerable uncertainty range, of similar magnitude as the range of the mining + milling values. In Table 4 the average value is shown, the uncertainty range (see Annex D) is not indicated.

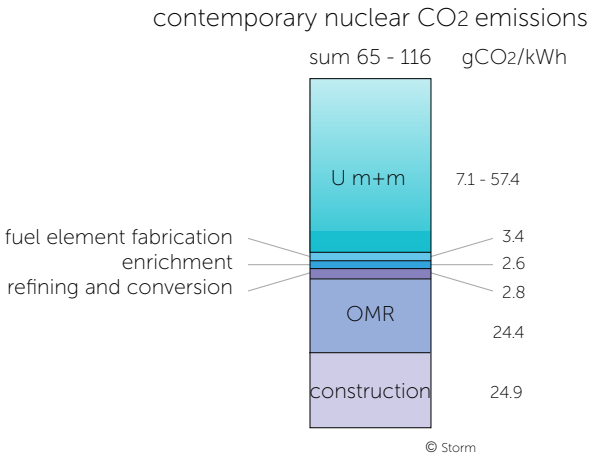

Figure 8

Contemporary specific CO_2 emissions of nuclear power

4.2 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 greenhouse gases have a global warming potential (GWP) thousands of times larger than CO_2 (see Annex E) so even tiny emissions of such gases may have a large effect [EIA-G 2001], [EPA 2002]. A zero-carbon process may have a significant contribution to anthropogenic global warming if it emits high-GWP greenhouse gases.

In all processes from uranium ore to nuclear fuel substantial amounts of fluorine, chlorine and compounds of these elements are used, often in combination with organic solvents. Fluoro-compounds are essential in these processes, because enrichment of uranium requires uranium hexafluoride (UF_6), the only gaseous compound of uranium. The [Vattenfall EPD 2005] noticed the absence of data on emission of greenhouse gases by processes needed to convert uranium ore into nuclear fuel.
Unknown are the amounts of fluoro and chloro compounds used in other processes of the nuclear process chain. As with all chemical plants, significant amounts of gaseous and liquid compounds from the processes will be lost into the environment, due to unavoidable process losses, leaks and accidents. No chemical plant is leakproof. From a chemical point of view, it is likely that in several processes of the nuclear chain potent GHG's arise or are used, or that GHGs are formed when they react with materials in the environment after release. Notably halocarbons have GWPs many thousands of times stronger than carbon dioxide [Blasing & Jones 2003], [Blasing & Smith 2006].

4.3 Krypton-85, another nuclear climate changer

Krypton-85 is a radioactive isotope of the noble gas krypton. Although krypton is not a greenhouse gas in itself the presence of krypton-85 in the atmosphere gives rise to unforeseeable effects for weather and climate. Kr-85 is a beta emitter and is capable of ionizing the atmosphere, leading to the formation of ozone in the troposphere. Tropospheric ozone is a greenhouse gas, it damages plants, it causes smog and health problems [WMO 2000].

By nature krypton-85 is present in minute quantities in the atmosphere due to natural processes. In nuclear reactors massive amounts of krypton-85 are produced, as one of the major fission products. A small portion of it escapes into the atmosphere at the reactor site during operation, more will escape during storage of spent fuel in cooling pools and dry casks, for the number of leaking fuel elements increases with time due to unavoidable ageing processes. When spent fuel is reprocessed all Kr-85 is discharged from the spent fuel into the atmosphere. As a result of human nuclear activities the inventory of Kr-85 in the atmosphere has risen by a factor of 10 million and this quantity shows a rising trend, according to [Ahlswede *et al.* 2012], see also [Seneca 2015].

5 COMPARISON WITH OTHER STUDIES

5.1 Survey

A survey of a number of recent life-cycle assessments (LCA) gave the following figures of the specific CO_2 emission of nuclear power, listed in Table 5.

Table 5
Specific CO_2 emission (g CO_2/kWh) of nuclear power according to a number of studies.

	source	full chain gCO2/kWh	notes
1	this study, comtemporary CO_2 reference advanced reactor	65 - 116	range caused by different uranium ore properties
2	this study	2.2	only concrete + steel for construction of NPP
3	ExternE 1998	11 - 15	only construction of Sizewell B
4	IPCC-ar5 2014	3.7 - 12 - 110	AR5, Table A.III.2, Annex III, p.1335
5	IAEA-ccnap 2018	11 - 12 (median) - 14 5 - 20	figures from Ecoinvent 3.3 (referenced) Fig.10 p.35 as cited in executive summary, p.3
6	Ecoinvent 3.3 2016	11 - 14	12 median value, as cited in [5], p.58 ref [31] database not free accessible
7	NREL 2013a & 2013b	25 - 60 4 - 110	40 harmonized value, most recent NREL figures 12 average; as cited in [5], p.58 ref [60]
8	EPD 2013	3.5 - 5.5	as cited in [5] p.60 ref [59]
9	CRIEPI 2010 (in Japanese)	19 - 22	20 median value, as cited in [5] .p.58 ref [61]
10	UNEP 2016	max ~110 or ~220 4 - 14	see Figure 1.3, p.55, see text 9.5 average, as cited in[5], p.59 ref [34] [35]
11	WNA-CO2 2016	9 - 21	p.2, from IAEA 2000
12	Sovacool 2008	1.4 - 288	66 mean, p.2940
13	Warner & Heath 2012	3.1 - 223 –› 3.7 - 113.7 3.1 - 223 –› 3.7 - 113.7 3.7 - 29.7 –› 4.6 - 16.6	LWR as reported –› harmonized, PWR as reported –› harmonized BWR as reported –› harmonized
14	Lenzen 2008	10 - 130	65 average, p.2178 and p.2195
15	Voorspools et al. 2000	7 maximum 3 (order magnitude)	Fig 7, p.324 construction + maintenance + demolition, p.307
16	Dones 2007	5-12 18-21	Table 1, p.3 starting from ISA 2006 = [14], p.3
17	Pehl et al. 2017	3.5 - 11.5 2.7 - 4.1	'within range of nuclear, wind and solar', p.940 Supplementary Table 2 of [17]
18	Odeh et al. 2013 = Ricardo-AEA	5.8 2.4	in 2010 p.70 no range indicated in 2050

Values found in the listed publications on the CO_2 emissions of nuclear power show a range from 1.4 to 228 gCO_2/kWh. Such a range is hardly explicable as a statistical range of inaccuracies in a series of data found by using the same measurement method. Divergence of the results of the various assessments in Table 5 can be traced back to differences in the applied methods, models and assumptions. Important factors determining the results of any life-cycle assessment (LCA) are for example:

- which processes of the chain are included and which are not: how are the system boundaries of the assessed system defined
- assumed state of technology: currently mature or to become available in the future
- data based on world average figures or on one special situation
- are the input data based on practical performance or on as-designed figures
- are only direct energy inputs and CO_2 emissions accounted for, or are indirect energy inputs and CO_2 emissions (embodied in materials and equipment) also included in the applied models
- including or excluding indirect CO_2 emissions from chemical reactions
- source of thermal energy inputs
- assumed operational lifetime of the nuclear power plant and other performance characteristics
- explicite and implicite assumptions
- including or excluding emissions of greenhouse gases other than CO_2
- method of estimation of energy investments
- mathematical models used to process input data
- mixing physical models with economic notions

5.2 Notes to Table 5

- This study is based on a physical LCA of the complete system of contemporary industrial processes required to generate useful energy from uranium, starting from basic data.
- This study assumes uranium supply from soft ores at a grade of G = 0.1% uranium, the most favourable conditions available.
- Other studies do not refer to a specified type of ore, nor to a range of possible values due to different ore properties.
- The LCA of this study is based on a clearly definied reference reactor, corresponding with most advanced currently operating reactors; performance of the reference reactor corresponds with the world average of the currently operating reactors. Especially the operational lifetime, counted in full-power years, is an important parameter, determining the effective amount of net useful energy that can be extracted from a given uranium resource.
- None of the other studies mentions the operational lifetime of the reference reactor of the study.
- Only a few studies include an independent and original phyical life cycle assessments (LCA) of the nuclear energy system; some of these early LCAs are based on data from the early 1970s.
- Most studies on nuclear CO_2 emissions take the results from earlier studies and process these data applying a variety of mathematical models and statistical methods.
- From a scientific viewpoint it seems not very significant to statistically process data resulting from widely diverging assessment methods.
- Often the statistical processing is accompanied by rejection of the results from some studies resulting in high values, that are arbitrarily labeled as 'outliers', without scientific arguments.
- This study limited its scope to the emission of CO_2 from burning fossil fuels used in the industrial processes of the nuclear system and from the production of concrete and steel and some other materials.
- None of the listed studies mentioned the emission of GHGs other than CO_2, although these studies used the unit gCO_2eq/kWh instead of the unit gCO_2/kWh, implying that all kinds of greenhouse gases were taken into account.

5.3 EPR design

For comparison this study assessed also the contemporary specific CO_2 emission of the EPR design according to the specifications from [UK-EPR-*Dsum* 2007], [UK-EPR 2007] and [Areva 2012].

able 6

Summary of the contemporary specific CO_2 emissions (g CO_2/kWh) of nuclear power based on presently operating most advanced reactors and on the EPR as designed. No operational data on the EPR exist. The emission of the future processes of the back end of the advanced reactor and EPR design are not assessed in this study. To present the lowest estimate the uranium mining + milling figure is based on the most favourable conditions of uranium recovery currently available (uranium supply from soft ores at a grade of 0.1% uranium). OMR = operation, maintenance, refurbishments.

reactor type	uranium m+m	other front end	construct NPP	OMR	total contemp.	future proc.	full chain
advanced operational, this study	7.1	8.81	24.9	24.4	65.2	-	› 65.2
EPR as designed, this study	6.2	5.2	8.4	18.1	37.9	-	› 37.9
EPR as designed only concrete construction			0.73				
EPR as designed, Kunakemakorn 2011	n.a.	n.a.	0.595	0.035	0.947	1.036	1.983

n.a. = not available

5.4 Summary

From the survey of other studies follows:

- Reported specific CO_2 emissions of nuclear power vary over a range with a factor of more than 100. Such a wide range cannot be explained as a statistical dispersion of measured values, but points to different applied assessment methods.
- In many of the recent publications it remains unclear how the CO_2 emissions of the various components of the nuclear chain are calculated.
- A tendency can be noticed to publish preferably low figures of CO_2 emissions and to omit high values from other studies, that are easily qualified as 'outliers', without scientific arguments.
- It remains unclear how the low reported figures could be reconciled with the figures found in this study that are based on empirical data.

Conclusions and policy implications

- The sum of the CO_2 emissions of the contemporary processes required to make nuclear power possible varies from 65 - 116 gCO_2/kWh for advanced reactor systems, and for the EPR design from 40- 84 gCO_2/kWh.

- The range in the emission figures is mainly caused by different geologic conditions at the currently operational uranium mines.

- Energy investments and CO_2 emissions of uranium mining + milling per kilogram recovered uranium increase exponentially with declining ore grade.

- Contemporary CO_2 emissions increase with time as more uranium is extracted from the earth's crust.

- Extraction of uranium from ores at grades below 0.02-0.01% U_3O_8 requires as much energy as can be generated from that uranium (energy cliff).

- The energy cliff might be reached within the lifetime of new nuclear power stations at the present conditions.

- Uranium resources may seem inexhaustable from a geologic point of view, but uranium-for-energy resources are subject to thermodynamic constraints.

- During the next decades civil nuclear power has to rely on thermal-neutron once-through reactors that cannot fission more than 0.5% of the nuclei in natural uranium.

- Uranium-plutonium and thorium-uranium breeders cannot contribute to civil energy supply in the foreseeable future, if ever.

- By about 2080 no net energy generation is possible from the presently known uranium resources, assumed the global nuclear capacity remaining constant at the current level.

- The existing nuclear power plants leave behind after final closedown a nuclear legacy implying an energy debt and latent CO_2 emission of similar order of magnitude as the contemporary energy investments and CO_2 emissions. Nuclear power is energy on credit.

ANNEX A

REFERENCE REACTOR

Basic parameters

This study compares the specific CO_2 emissions of the full life cycles of two different nuclear power plants, both using a Pressurized Water Reactor (PWR), and both operating in the once-through mode, without recycling of uranium and/or plutonium.
On a global scale the use of MOX (MixedOXide, uranium oxide mixed with plutonium oxide as fissile material) in light-water reactors is nearly negligible and the use of MOX is not expected to increase during the next decades, the more so after the Fukushima disaster. For this reason the MOX variant is not included in this study. Closed-cycle reactors (^{238}U-^{239}Pu breeders) and thorium-fuelled reactors (^{232}Th-^{233}U breeders) are unlikely to be available for commercial application during the next decades, and are also left outside of the scope of this study.
The reference reactor is based on a PWR corresponding with the most advanced currently operating power reactors. The emissions of the reference reactor is compared with those of the EPR, also a PWR. In Europe this reactor design was called European Pressurized Reactor, and the internationalised name was Evolutionary Power Reactor, but it is now simply named EPR. At the time of writing (2019) no EPR in the world has ever operated, so its performance parameters as designed are yet to be proved in practice. Some basic parameters of the reference advanced reactor and the EPR design are summarised in Table A1.

Table A1
Primary parameters of the reference advanced reactor and the EPR design. Sources primary EPR data: [UK-EPR-*Dsum* 2007], [UK-EPR 2007], [Areva 2012].

quantity	symbol	advanced reactor	EPR design	unit
net power, electric (at grid connection)	P_e	1.00	1.62	GW_e
power, thermal	P_{th}	2.94	4.50	GW_{th}
thermal efficiency	e	34	36	%
nominal burnup	B	46	60	GW_{th}.day/Mg
lifetime	T	variable	60	years
load factor	L	variable	92%	–
effective operational lifetime, full-power years	$T_{100} = T*L$	25	55	FPY (1)
tails assay of enrichment process	x_t	0.30	0.30	% U-235
fresh fuel enrichment assay	x_p	4.2	5.0	% U-235

Effective operational lifetime

Use of the unit full-power year (FPY) to quantify the lifetime useful energy production of a nuclear power station avoids ambiguities regarding the effective operational age of the reactor in calender years, load factor, availability factor and other variables. A full-power year is defined as the period in which a reactor, with a nominal power of P_e GW_e generates a fixed amount of electricity, equalling the amount if the reactor operated during a full year continually at 100% of its nominal power. The electricity produced in one FPY, J_{100} , is:

$J_{100} = P_e$ GW.year = P_e*31.536 PJ/FPY = P_e*8760*10^6 kWh/FPY eq A1

The reference advanced eactor in this study has a nominal power of P_e = 1 GW_e, so the amount of electricity corresponding with one FPY is:

J_{100} = 31.536 PJ = 8760*10^6 kWh/FPY

The EPR design has a nominal power of P_e = 1.62 GW_e, so the amount of electricity corresponding with one FPY is:

J_{100} = 51.088 PJ/FPY = 14.19*10^9 kWh/FPY

The effective operational lifetime T_{100} of a given reactor can be calculated by the following equation A2:

$$T_{100} = \frac{E_{life}}{J_{100}}$$

T_{100}	=	operational lifetime: number of full-power years	FPY
E_{life}	=	lifetime electricity production (put into the grid)	PJ
J_{100}	=	electricity production during 1 year at 100%	PJ/FPY

eq A2

In 2017 the average operational lifetime of the world nuclear power plants was estimated at 23-24 FPY, a figure that only slightly rised during the past decade. Evidently some individual reactors may have reached higher values of T_{100}. The reference advanced reactor has an assumed effective operational lifetime of T_{100} = 25 FPY, slightly higher than the world average. The EPR design, with an assumed lifetime of 60 calender years and a load factor of 92%, would have an operational lifetime of T_{100} = 0.92*60 = 55 FPY (rounded). This figure seems highly unlikely in view of the empirical evidence from the past 60 years of civil nuclear power. Not one nuclear power station in the world has ever reached an effective operational lifetime of 55 FPY.

Because global warming and CO_2 emissions are global issues, the potential contribution of nuclear power to the mitigation of the greenhouse gas emissions should be estimated on the basis of empirical world-average figures, not on hypothetical figures of one individual yet-to-be-proved concept.

Table A2

Secondary parameters of the reference advanced reactor and the EPR design.

quantity	symbol	advanced reactor	EPR desigm	unit
enrichment feed/product ratio	F/P	9.51	11.46	–
specific separative work	S_{spec}	5.66	7.20	SWU/kg U
lifetime separative work	S_{life}	3.352	11.004	MSWU
nominal burnup	B	3.974	5.184	PJ_{th}/Mg U_{enrich}
full power thermal energy production rate	J_{100} (th)	92.75	141.9	PJ_{th}/FPY
full power electric energy production rate	J_{100} (e)	8.760E9	1.419E10	kWh/FPY
lifetime thermal energy production	E_{th} (life) = J_{100} (th)*T_{100}	2319	7805	PJ_{th}
lifetime electric energy production	E_e (life) = J_{100} (e)*T_{100}	219*10^9	781*10^9	kWh
lifetime enriched uranium in reactor	$m_0 = E_{th}$ (life)/B	583.4	1506	Mg U_{enrich}
lifetime natural uranium consumption (1)	m_3	5748	17880	Mg U_{nat}
average specific electricity generation	$J_e = E_e / m_3$	3.810E7	4.365E7	kWh/ Mg U_{nat}
specific enriched uranium consumption	m_0/kWh	0.002664	0.001930	g U_{enrich}/kWh
specific natural uranium consumption	m_3/kWh	0.0262	0.02291	g U_{nat}/kWh

(1) see section uranium balance

Enrichment

In the enrichment process natural uranium is separated into two fractions: one small fraction is enriched in fissile uranium-235, the other, larger fraction is depleted in U-235.

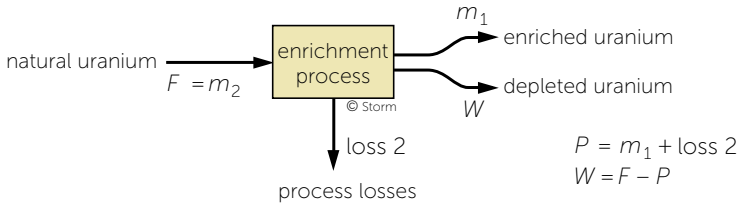

Figure A1

In the enrichment process the feed *F* of natural uranium is separated into the product fraction *P* (enriched uranium) and the waste fraction *W* (depleted uranium)

The ratio of feed mass *F* and product mass *P* depends on the product assay and tails assay and can be calculated by equation A3:

$$\frac{F}{P} = \frac{x_p - x_t}{x_f - x_t}$$

F	=	feed mass uranium	kg
P	=	product mass uranium	kg
x_f	=	feed assay	fraction U-235
x_p	=	product assay	fraction U-235
x_t	=	tails assay	fraction U-235

eq A3

Separative work *S* (unit: SWU) can be calculated by equation 4 [DOE/EIA 1997]. If *F* and *P* are given in kg, de unit is SWU/kg U.

$$S = P \bullet V(x_p) - F \bullet V(x_f) + (F - P) \bullet V(x_t)$$

$$V(x) = (2x - 1) \bullet \ln\left(\frac{x}{1 - x}\right)$$

S = separative work kg SWU = separative work unit

eq A4

In this study a tails assay of $x_t = 0.0030$ (fraction U-235) is assumed. A tails assay of 0.30% U-235 is common practice at low uranium prices, according to [MIT 2003-2009].
Feed assay, natural uranium $x_f = 0.0071$,
product assay of reference advanced reactor $x_p = 0.042$,
product assay of EPR design $x_p = 0.050$.

Uranium mass balance

In the front-end processes uranium as found in nature is converted into nuclear fuel to be placed into a reactor. To assess the energy equirements and specific CO_2 emissions of the front-end processes the mass balance of uranium of the nuclear energy system during its operational lifetime has to be calculated.

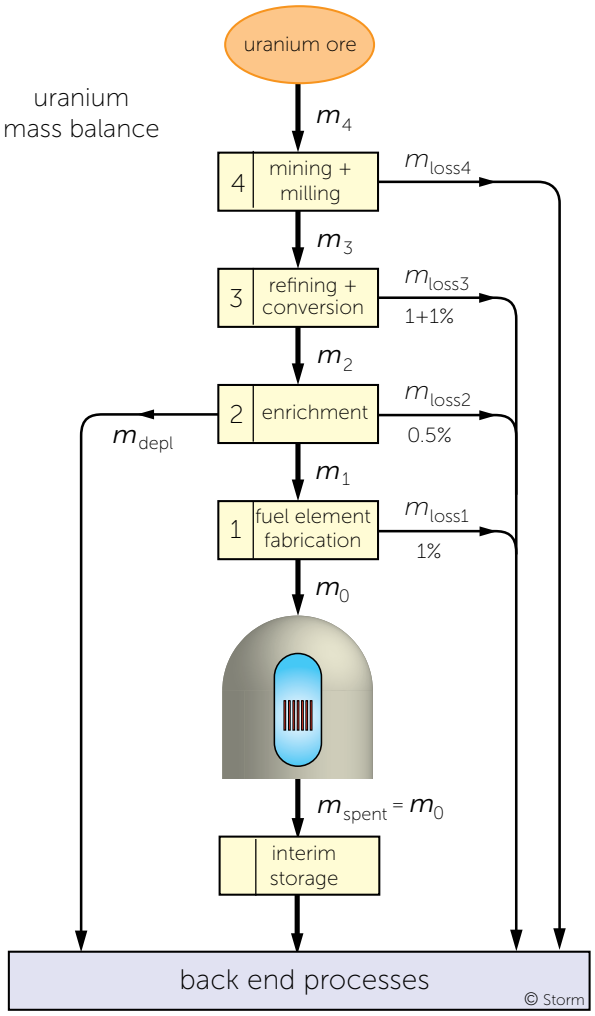

Figure A2

Mass balance of uranium to be processed in the front end, including the losses of each process. Process losses derived from: [Jan & Krug 1995], [Scheidt 1995], [DOE/EIA 1997], [ERA 2006] and [ERA-*AR* 2005].

The mass of enriched uranium consumed by the reactor during its operational lifetime, indicated by m_0 in Figure A2, can be calculated from the lifetime thermal energy production and the nominal burnup of the nuclear fuel. In practice the effective burnup averaged over the operational lifetime may be lower than the nominal burnup rate.

Table A3 summarises the figures of the uranium mass balances of the advanced reference reactor and the EPR design.

Table A3

Lifetime uranium mass balances of the advanced refrence reactor and the EPR design in the once-through mode. Assumed recovery yield of the uranium mining and milling Y = 90% , grade of the processed ore G = 0.085% U.

process	symbol	unit	advanced reactor x_p = 4.2%	EPR design x_p = 5.0%
processed ore	m_{ore}	Tg	7.514	23.37
input mining+milling	m_4	Mg U_{nat}	6387	19867
loss mining + milling	$\Delta = m_4 - m_3$	Mg U_{nat}	639	1987
input refining + conversion	m_3	Mg U_{nat}	5748	17880
loss refining and conversion	$\Delta = m_3 - m_2$	Mg U_{nat}	115	358
enrichment feed	$m_2 = F$	Mg U_{nat}	5633	17522
feed/product ratio	F/P	-	9.51	11.46
enrichment product	P	Mg U_{enr}	592	1529
depleted uranium	$m_{depl} = W$	Mg U	5041	15993
specific separative work	S (kg)	SWU/kg U_{enr}	5.66	7.20
lifetime separative work	S (life)	MSWU	3.352	11.009
loss enrichment	$\Delta = P - m_1$	Mg U_{enr}	3	8
fuel element fabrication	m_1	Mg U_{enr}	589	1521
loss fuel fabrication	$\Delta = m_1 - m_0$	Mg U_{enr}	6	15
lifetime input reactor	m_0	Mg U_{enr}	583	1506
uranium utilization ratio *	R (U-235)	% of U-235	60	59
fissioned fraction *	$R_{fission}$	% of U_{nat}	0.50	0.54

* see sections below

Uranium-235 utilisation ratio

The uranium-235 utilisation is in this study defined as the ratio of the mass of the uranium-235 entering the reactor over the mass of the mass of uranium-235 in the natural uranium leaving the mine:

$$R_{(U\text{-}235)} = \frac{\text{mass U-235 into reactor}}{\text{mass U-235 leaving mine}} = \frac{m_{0\,(U\text{-}235)}}{m_{3\,(U\text{-}235)}} \qquad \text{eq A5}$$

m_0 (U-235) = x_p*m_0

m_3 (U-235) = x_f*m_3 = 0.0071*m_3

advanced eactor:

m_0 (U-235) = 0.042*583.4 = 24.50 Mg

m_3 (U-235) = 0.0071*5748 = 40.81 Mg

R (U-235) = 24.50/40.81 = 0.6003 = 60%

EPR design:

m_0 (U-235) = 0.050*1506 = 75.30 Mg

m_3 (U-235) = 0.0071*17880 = 126.95 Mg

R (U-235) = 75.30/126.95 = 0.5931 = 59%

These results mean that 40% respectively 41% of the U-235 recovered from the earth's crust in natural uranium is lost in the waste streams of the front-end processes and is not placed into the reactor.

Fissioned fraction

The fissioned fraction is in this study defined as the fraction of the natural uranium, U-235 + U-238, leaving the mine that is actually fissioned in the reactor.

The average specific heat generation by fission of fissile nuclides $J_{fission}$ is:

$J_{fission}$ = 81.08 GJ/g = 81.08 PJ/Mg

The total mass of the nuclides fissioned during the lifetime of the reactor can be found by equation A6:

$$m_{fission} = \frac{\text{gross lifetime heat generation}}{\text{specific fission heat generation}} = \frac{E_{th(life)}}{J_{fission}} \qquad \text{eq A6}$$

The lifetime fissioned fraction $R_{fission}$ is given by equation A7:

$$R_{fission} = \frac{\text{mass of fissioned U}}{\text{mass of U leaving mine}} = \frac{m_{fission}}{m_3} \qquad \text{eq A7}$$

advanced reference reactor:

$m_{fission}$ = 2319/81.08 = 28.60 Mg

$R_{fission}$ = 28.60/5748 = 0.004976 = 0.50%

EPR design:

$m_{fission}$ = 7805/81.08 = 96.26 Mg

$R_{fission}$ = 96.26/17880 = 0.005384 = 0.54%

These results mean that in the currently available advanced light-water reactors not more than about 0.5% of the uranium nuclei in natural uranium can be fissioned for useful energy generation.

ANNEX B

URANIUM MINING + MILLING

Flowsheet

Recovery of uranium from the earth's crust, usually called mining + milling of uranium ore, occurs in a sequence of physical and chemical processes. Figure B1 represents the flowsheet of the Ranger mine in Australia, one of the cheapest operating mines in the world, due to its favourable conditions; this flowsheet is used as reference uranium mine in this study. Many open-pit and underground uranium mines in the world operate according a similar flowsheet.

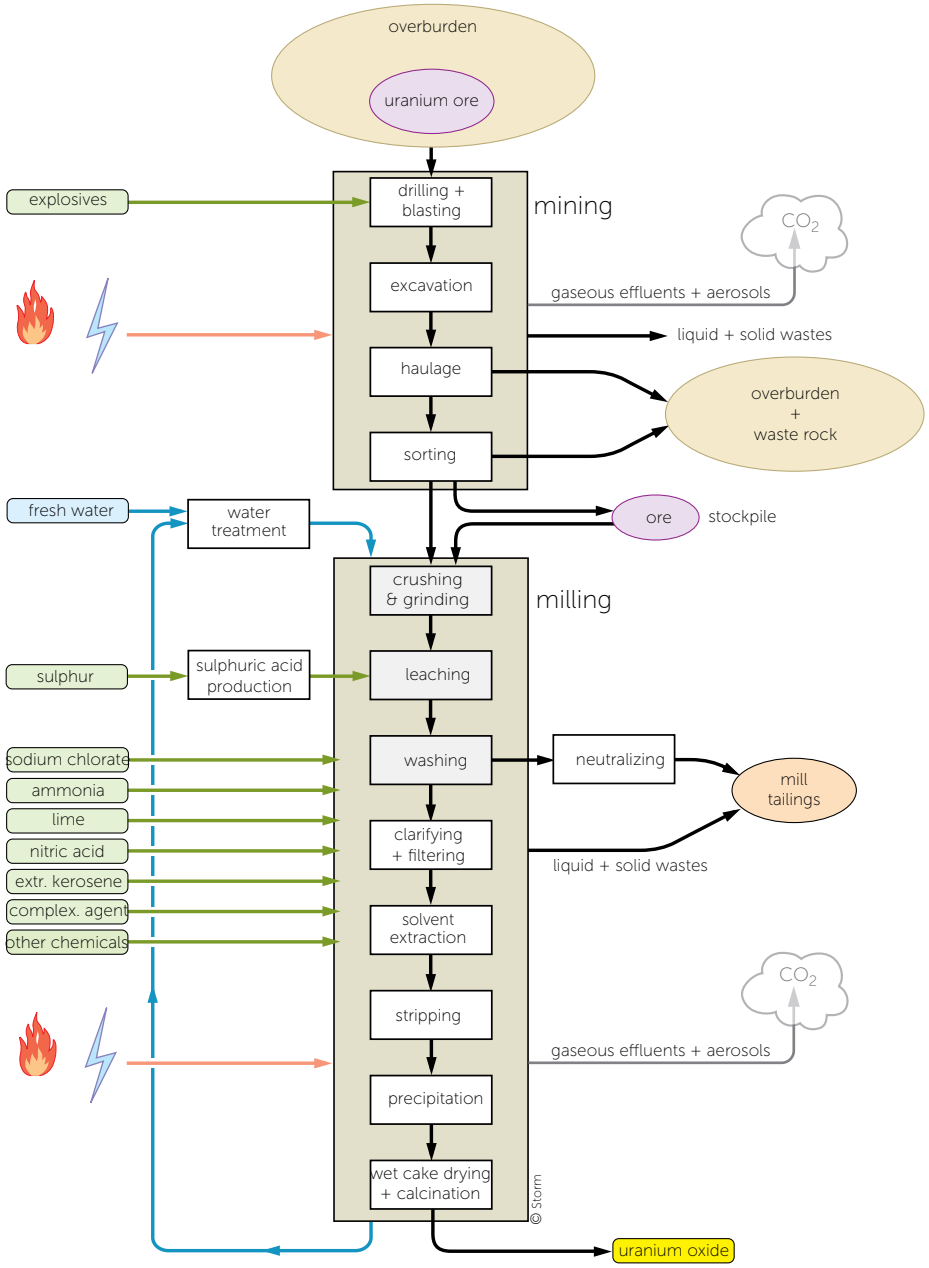

Figure B1

Flowsheet of the Ranger uranium mine, based on data from [ERA 2006]. Most uranium mines in the world are operating according to a similar flowsheet. This study uses this flowsheet as reference uranium mine.

Mines applying the In Situ Leaching (ISL) method have a different flowsheet in some respects. The specific energy consumption and accompanying CO_2 emission of ISL mines are similar to those of open-pit mines. Large numbers of injection and production wells are to be drilled due to clogging and large volumes of leaching liquids are consumed; see also [CSIRO 2004], [Mudd 1998], [Mudd 2000], [Mortimer 1977], [Mudd & Diesendorf 2007]. The harmful impact of ISL on the environment is high [WISE-U 2015] and irreversible.

The reference uranium mine in this study is an open pit mine that may be taken as a world-averaged mine. Underground mining is generallly more energy intensive than open pit mining, ISL may be less energy intensive in some cases. Differences in specific energy consumption and CO_2 emission between individual uranium mines are substantial, due to widely varying conditions, as will be explained in the following sections, and for that reason it seems not useful to discern different types of mines in this assessment: the figures exhibit a significant scatter anyhow.

Apart from the specific variables discussed in the following sections the energy input and CO_2 emission of an operating uranium mine depends on some general parameters, such as:

- Size of the ore body and construction of the mine. Smaller mines have larger fixed energy input, due to its construction, including the processing plant and equipment.
- Availability of fresh water; a uranium mine consumes large volumes of fresh water.
- Location: the transport distances of the supplies to the mine vary over a wide range and may be thousands of kilometers in some cases. Remote uranium mines have longer supply routes and consequently have a higher specific energy consumption.
- Local climate and other conditions.

This study assumes that the electrical inputs at the mining site are provided by stationary oil-fuelled generators at a thermal efficiency of e = 40%, and that the thermal efficiency of diesel engines of mining equipment, dump trucks and excavators is e = 30%.
Specific combustion CO_2 emission of of fuel oil and diesel is assumed to be γ = 75 gCO_2/MJ_{th}.

Dilution factor and coal equivalence

The ore grade is defined as the uranium content of the uranium-bearing rock, usually given as mass-% U_3O_8, or in grams uranium oxide 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 mass unit of uranium, and does not depend on recovery technology nor on ore type.
Actually, more ore has to be processed than the mathematical minimum, due to the unavoidable losses in the extraction process (see section below). The blue curve in Figure B2 illustrates the relationship between the ore grade and the mass of ore to be mined and processed per kg recovered uranium.

At a grade of 0.1% uranium, one megagram (1 Mg = 1 metric tonne) of rock has to be mined and processed to obtain 1 kg uranium in the mill. This is ten times as much as from rock at a grade of 1%, containing 10 kg uranium per Mg rock. Consequently, the mining energy input per kilogram uranium is at least ten times as large. At a grade of 0.01% the energy input is at least 100 times as large.
The horizontal red line represents the mass of coal (2.0 Tg) consumed by a coal-fired power plant to generate the same amount of electricity as the reference reactor during one year (26 PJ). Below an ore grade of 0.02% U_3O_8 the annual mass of uranium ore to be processed to fuel one nuclear power plant equals the mass of coal: the *coal equivalence*.
Figure B2 shows that below the critical ore grade, at which the nuclear system will pass through the coal equivalence, virtually no recoverable uranium resources are been reported.

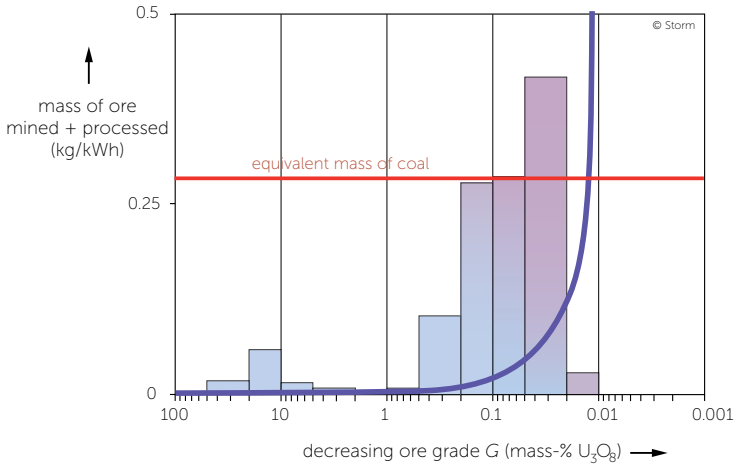

Figure B2

The dilution factor and the coal equivalence. The mass of rock to be processed to fuel one reactor for one year with uranium rises exponentially with falling ore grade. At a grade below 0.02% U_3O_8, 200 ppm, or 200 grams per Mg (metric ton) the mass of ore equals the mass of coal consumed by a coal-fired station to generate the same amount of electricity: this is the coal equivalence. The bar diagram of the known uranium resources as function of the ore grade is added for comparison; its relative scale has no numerical values in this diagram.

Ore types

Uranium occurs in many kinds of minerals in the earth's crust. The nuclear industry distinguishes sometimes two categories of uranium resources, based on economic considerations: conventional and unconventional resources. The term 'ore' is an economic notion: only rock from which uranium can be extracted in a economic way is called 'ore'.
Conventional resources are deposits of the kind now being mined. Examples of unconventional resources are shales, phosphates, granites. Unconventional resources are generally not exploited.

In this study the conventional ores are divided into two groups, based on information from many sources, among other [Orita 1995], [WNA-*Ugeol* 2015], [WNA-mining 2016]:

- soft ores, easily mineable and millable, e.g. sandstones and calcretes, with typical grades ranging from more than 10% down to about 0.02% U_3O_8,
- hard ores, hard to mine and mill, e.g. quartz pebble conglomerates, with grades varying typically from about 0.1% down to the mineralisation limit. Some high-grade vein-type ores are also hard to mill.

Below the mineralisation limit, at grades below 0.01% U_3O_8, the uranium is not present in the form of separate grains of uranium minerals, but dispersed at atomic scale among the other constituents of the rock. To extract uranium from rock types below the mineralisation limit the whole rock has to be brought into solution. If uranium is present as separate minerals the processing starts with selectively dissolving the uranium minerals and subsequently discarding the other minerals from the processed rock.

Mining

Energy consumption and CO_2 emission per Mg mined ore of the mining of uranium ore from the earth's crust (mining), depends on a number of variable conditions, such as:

- Overburden ratio (= stripping ratio), determines the mass of waste rock to be removed per Mg ore. The overburden ratios of open pit mines vary roughly from 3-50. The overburden ratio in the USA averaged 50, according to [Blanchard *et al.* 1982]. An overburden ratio (or stripping ratio) of 3 means that for every

Mg ore 3 Mg of waste rock has to be removed. Variations in overburden ratios may introduce a spread in the energy requirements with a factor of 5 [Chapman 1976b], with the same type of ore.
According to [Mortimer 1977] the waste rock ratios of underground mines vary from 1-5.

- Haulage distance: the distance the waste rock and ore has to be transported to the waste rock dumping site respectively to the ore processing plant. The hauling distance for ore may vary from a few kilometers to more than 200 km.
- Specific consumption of explosives (kg explosives per Mg rock).
- Thermal conversion efficiency of the diesel engines powering the mining equipment and the electricity generators.

A fifth important parameter is the hardness of the rock to be mined. This factor is difficult to quantify, and for that reason this study discerns two main types of ore: soft ores and hard ores. Variable rock properties may introduce considerable variations in the specific energy requirements and CO_2 emissions of mining from mine to mine. Some consequences of the mining of harder rock are, among other:

- Higher energy consumption per Mg rock removed by excavators.
- Higher wear of equipment, such as drill rigs and excavators, causing more time in the shop and a higher rate of replacement of components and higher use of consumables. These increased rates mean an higher direct and indirect energy consumption per Mg rock mined.
- Higher specific consumption of explosives: harder rock needs more explosives per Mg rock. The Ranger mine uses about 0.25 kg explosives per Mg rock. Likely many mines have significant higher explosives consumptions. This study assumes an explosives consumption rate of 1 kg/Mg rock in mines with hard ores and in underground mines .

The specific thermal energy consumption of mining per Mg of soft ore can be calculated by the following equation B1. The figures are derived from a process analysis of the Ranger mine, that is based on the publications [ERA 2006], [ERA-AR 2005], [Rotty et al.1975] and [Mortimer 1977]. These figures may be considered a low estimate of the world average uranium mine with soft ores, in view of the favourable geologic conditions at Ranger.
For conversion of mechanical energy input into thermal energy input, mechanical energy is equated with electrical energy: one unit of mechanical energy equals one unit electric energy, $J_{mech} = J_e$.

$$\begin{aligned} J_{mining} &= (S+1)\bullet\{(J_{d+b} + J_{excav} + d\bullet J_{haul})/e + J_{d+b}(\text{indir}) + J_{excav}(\text{indir}) + J_{explos} + d\bullet J_{haul}(\text{indir})\} = \\ &= (S+1)\bullet\{(0.60 + 4.49 + d\bullet 2.40)/e + 11.00 + 3.18 + x\bullet 69.40 + d\bullet 1.888\} = \\ &= (S+1)\bullet\{(5.09 + d\bullet 2.40)/e + 14.18 + x\bullet 69.40 + d\bullet 1.888\} \end{aligned} \quad \text{eq B1}$$

Here is:	J_{mining}	= total (thermal) energy input of uranium mining	(MJ_{th}/Mg ore)
	J_{d+b}	= direct mechanical energy input of drilling and blasting	(MJ_e/Mg ore)
	J_{excav}	= direct mechanical energy input of excavation	(MJ_e/Mg ore)
	J_{haul}	= direct mechanical energy input of haulage	(MJ_e/Mg ore)
	J_{explos}	= indirect thermal energy input of explosives fabrication	(MJ_{th}/Mg ore)
	S	= overburden ratio (= stripping ratio)	
	d	= haulage distance	km
	e	= thermal conversion efficiency diesel engines $J_{th} \rightarrow J_e$ and $J_{th} \rightarrow J_{mech}$	
	x	= mass ratio explosives over mined rock	kg/Mg rock

The specific CO_2 emission of mining becomes:

$\gamma_{mining} = 75^* J_{mining}$ g CO_2/Mg ore

Figure B3 shows the depence of the specific CO_2 emission of mining in open pit mines on two parameters: the overburden ratio S and the haulage distance d. The diagrams are based on data from the process analysis of the Ranger mine in Australia.

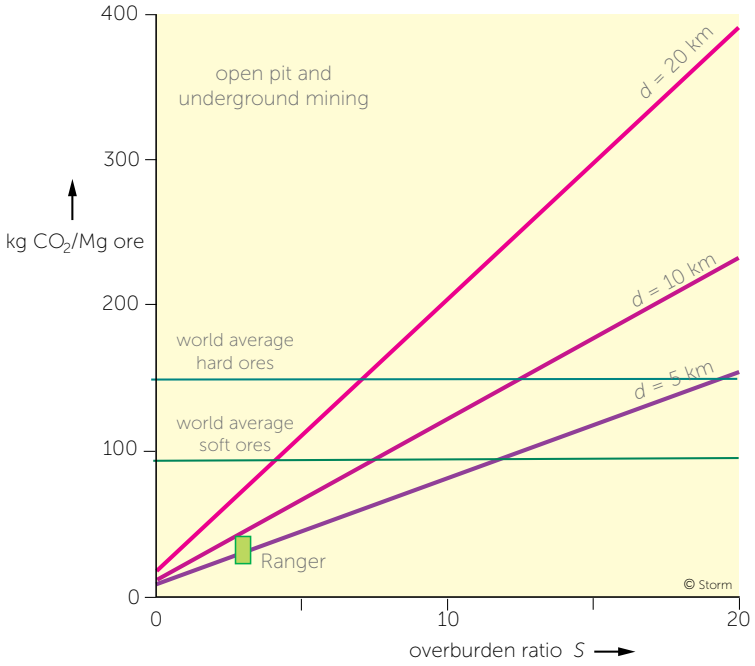

Figure B3

Specific CO_2 emission of mining uranium ore (kg CO_2/Mg ore) as function of the overburden ratio *S*, at three different hauling distances. In this diagram the explosives consumption is assumed *x* = 0.25 kg/Mg; underground mines and open-pit mines with hard ores may consume 1 kg explosives per Mg rock, or more. There are mines with overburden ratios as high as 50. Hauling distances of up to 200 km are reported. Consequently the specific CO_2 emission at many mines in the world might be considerably higher than the world average figure.

Figure B3 shows that the specific energy consumption and CO_2 emission of mining uranium ore can widely differ from mine to mine, due to different overburden ratios and haulage distances. In practice the scatter of the figures might be enhanced by various other factors. The values of the energy requirements given in other studies vary widely, from a low of 0.08 GJ/Mg ore [Franklin *et al.*1971] to a high of 77 GJ/Mg ore [Orita 1995]. The large scatter of values may be partly explained bij individual differences between mines but mainly by methodological differences.

In-situ leaching (ISL) uranium mining

In some places in-situ leaching (ISL) is applied to extract uranium from ore still in the ground. Chemicals are pumped down via injection wells into the ore body and the uranium-bearing liquor is pumped up from production wells, after a residence time of 3-25 years.

ISL has been applied to conventional low-grade ores containing 0.03-0.05% uranium. In common practice sulfuric acid leaching is used at a concentration of 2-5 g/l (0.02-0.05 M H_2SO_4). However, an initial concentration of 15-25 g/l (about 0.15-0.25 molar H_2SO_4) is generally used to reduce the ore preparation period. Often an oxidant is required to dissolve the uranium mineral. Oxidants in use include hydrogen peroxide, nitrate ions (nitric acid) and sodium chlorate. Acid consumption is typically 5-6 kg per Mg rock, but up to 10-15 kg/Mg rock. Overall recovery is typically 50-80% of the in-the ground resource [CSIRO 2004]. Large quantities of chemicals are needed: sulphuric acid, nitric acid, hydrofluoric acid, ammonia and other, together tens hundreds of tonnes (Mg) chemicals per Mg uranium [Mudd 2000].

The reported recovery yield of *Y* = 50-80% refers only to the extraction from the rock. Given the low uranium content of the parent rock and of the pregnant solution pumped from the production wells, the extraction yield of uranium from the pregnant solution may be low. The overall yield, extraction from ore in the ground

to yellow cake, may be in the range of 20-40%.

A major problem of ISL is the large-scale and irreversible contamination of aquifers, not only by the added chemicals, but also by radioactive and toxic elements, such as radium, heavy metals and arsenicum, which are chemically mobilized from the parent rock as well [Mudd 1998]. It might be difficult to reconcile the ISL technique with any sustainable development, for reason of its harmful and irreversible effects in the environment.

A rough impression of the energy requirements embodied in the chemicals for extraction can be figured out. Assuming 100 Mg sulfuric acid plus 3 Mg ammonia are needed to extract one Mg uranium from the ground – in some places two to three times as much is consumed – the embodied energy in these two chemicals alone is: J_{isl} = 0.547 TJ/Mg (U) J_{th}/J_e = 2.8

These figures are based on the specific energy intensities according to [Rotty et al. 1975]:
sulfuric acid H_2SO_4: J_{spec} = 2.87 GJ/Mg J_{th}/J_e = 100
ammonia NH_3: J_{spec} = 86.65 GJ/Mg J_{th}/J_e = 1.41

It should be emphasized that the above figure represents only a fraction of the total specific energy requirements of ISL per Mg extracted uranium. Not included are, for example, the energy requirements of:

- embodied energy in pipes and drilling equipment
- drilling the injection and production wells,
- pumping the fluids into the ground, via injection wells, and from the ground via production wells
- extraction of the uranium from the solution.

The energy requirements of in situ leaching will vary over a wide range, due to widely different geochemical conditions, depth of ore body, number of wells, operational life of each well and ore properties. In addition the energy requirements depend on the ore grade, as with conventional mining and milling. Data on actual ISL mines are scarce in the open literature, so the average values are unknown. Due to clogging the productive life of the wells is short, so during the production lifetime of the mine constantly new wells are to be drilled.

In this study the specific energy requirements of ISL are assumed to be the same as of open pit mining. This assumption may not lead to overestimation of the specific extraction energy of uranium from ore, the average of all mines and mills. [Mortimer 1977], one of the few studies which include ISL, gives figures in the same range as soft ore mining and milling.
The direct energy consumption of the Beverley ISL mine turns out to be as high as that of the Ranger open pit mine, both mines are located in Australia [Mudd & Diesendorf 2007]. Impacts of ISL on the environment are addressed in [WISE-U 2015].

Mining of soft ores

For reason of the wide dispersion in published figures this study uses the figures from [Rotty *et al.* 1975], that may be seen as a world average of uranium mines (open pit, underground, ISL), with average overburden ratio and haulage distance, and with soft ores.

$J_{mining} = J_e + J_{th}$ = 1.06 GJ/Mg ore J_{th}/J_e = 8.0

The figures from Rotty *et al.* are based on an unpublished survey of energy consumption in the USA mining and milling operations, conducted by the US Bureau of Mines in 1973. At that moment virtually all uranium in the USA was recovered from high-grade sandstone deposits. The figures represent the average of 60% open-pit and 40% underground mining and include, according to the authors, indirect energy consumption:

the energy embodied in chemicals and equipment. The figures from Rotty *et al.* are used in [ERDA-76-1], a study also referred to by [WNA-*eroi* 2016]. Rotty nor ERDA made distinction between hard ores and soft ores, e.g. between sandstone and granite, probably because their data base concerned soft ores only, mainly sandstones.

Assumed that the electric input, including that for production of the explosives, is generated by fossil-fuelled power plants with an average thermal efficiency of e = 40%, the total thermal input becomes:

J_{m+m} (Σth, ore) = 1.237 GJ/Mg ore

Assumed an average specific CO_2 emission of γ= 75 g/MJ_{th}, the specific emission of mining soft uranium ore at a world average mine would become:

γ_{mining} = 93 kg CO_2/Mg ore

The specific CO_2 emission of ISL mines (In Situ Leaching) is assumed to be of the same magnitude, based on the studies [Mudd 1998], [Mudd 2000], [Mudd & Diesendorf 2007].

Mining of hard ores

The mining of hard ores consumes more energy and materials than soft ores. The equipment, such as drills, excavators and dump trucks, suffer by heavier wear and more explosives are consumed per Mg rock. For that reason this study assumes the specific mining energy consumption of hard ores at 1.5 times that of soft ores:

$J_{mining} = J_e + J_{th}$ = 1.58 GJ/Mg ore $\qquad$ J_{th}/J_e = 8.0

Assuming the indirect energy consumption of the excavation en haulage equipment would double by heavy wear, an overburden ratio S = 3, a haulage distance d = 30 km and an explosives consumption of x = 1 kg/Mg rock, the specific energy consumption of mining hard ore calculated by equation 1 would become:

J_{mining} = 1.68 GJ/Mg ore.

So the figure of 1.58 GJ/Mg ore seems plausible and not overestimated, but unfortunately no practical data are found to ustain this figure, other than qualitive statements.

Assumed that the electric input, including for production of the explosives, is generated by fossil-fuelled generators at the mining sites, the average total thermal input of mining hard oresbecomes:

J_{th} = 1.843 GJ/Mg ore

and the specific CO_2 emission:

γ_{mining} = 138 kg CO_2/Mg ore

Ore processing (milling)

Energy consumption and CO_2 emission of the extraction of uranium from the ore, per Mg recovered uranium, depends on a number of variable conditions, such as:

- Ore grade, determines the dilution factor: the mass of ore to be processed per Mg uranium; the ore grade of the currenty operating mines varies from roughly 10% to 0.01% U, a factor of 1000. The world average ore grade of currently operating uranium mines is about 0.1-0.05% U_3O_8. The ore grade determines the energy consumption of crushing and grinding and the amount of chemicals consumed per kg U for leaching and extraction. Lower grade means the need to grind the ore to a finer mesh and to use more chemicals per Mg uranium, and consequently the specific energy consumption per Mg ore increases.
- Extraction yield (= recovery factor): fraction of uranium that is actually extracted from the ore.
- Mineralogy of the ore, determines the hardness of the minerals to be crushed and grinded and the chemical refractoriness of the uranium minerals to be dissolved.

- Chemical composition of the ore, determines the type of chemicals used, for example acid leaching or alkaline leaching, and reaction conditions, such as high or ambient temperature. The world average includes alkaline ores. The leaching of alkaline ores takes much more energy than acidic ores (as at Ranger), due to the elevated temperatures (60-80 °C) and the consumption of chemicals with high embodied energy, such as sodium hydroxide and sodium carbonate.

Ore grade and extraction yield are two quantifyable variables in the assessment of the energy consumption and CO_2 emission of the exraction of uranium from its ore. The different ore types are simplified to two classes: soft ores and hard ores. World average figures of other variables and parameters are used.

Milling of soft ores

For ore processing (milling) at Ranger (based on [ERA 2006] and [ERA-AR 2005]) this study found the following figures:

$J_{milling} = J_e + J_{th} = 1.133$ GJ/Mg ore $\qquad J_{th}/J_e = 4.56$

This figure is a low estimate, for several energy inputs of the ore processing are not included:

- fresh water supply
- treatment of process water and pond water
- embodied energy of the extraction chemicals, kerosene and complexing agent
- direct and indirect energy of several partial processes of the ore processing chain, e.g. thickeners and centrifuge
- waste management
- construction of the ore processing facilities.

The energy input of each of these items may be of minor importance, but jointly the inputs may be a significant contribution to the overall specific energy consumption.

For that reason this study applies the somewhat higher figure of [ERDA-76-1] for soft ores:

$J_{milling} = J_e + J_{th} = 1.27$ GJ/Mg ore $\qquad J_{th}/J_e = 7.0$

Usually the electric inputs of uranium mines are generated on site by oil-fuelled generators. Consequently the total thermal energy input is:

$J_{th} = 1.508$ GJ/Mg soft ore

and the specific CO_2 emission:

$\gamma_{milling} = 75 \bullet 1.508 = 113$ kg CO_2/Mg soft ore

Milling of hard ores

For hard ores this study applies the figures based on [Kistemaker 1976] and [Kistemaker 1975]. Kistemaker published figures for the milling of poor hard ores, based on the data of 1974 supplied by NUFCOR (Nuclear Fuels Corporation), responsible at that time for the mining and milling activities at the South African uranium mines. The Kistemaker figures include the embodied energy of a number of chemicals, not all, but do not include the energy input of equipment and capital goods. The electric inputs are generated on site by oil-fuelled generators. Consequently the total thermal energy input is:

$J_{milling}$ (Σth, ore) = 8.67 GJ/Mg hard ore

and the specific CO_2 emission is:

$\gamma_{milling} = 75 \bullet 8.67 = 650$ kg CO_2/Mg hard ore

Extraction yield

The *extraction yield*, also called the *recovery factor* or *recovery yield Y*, is the ratio of the mass of uranium actually extracted and the mass of the uranium present in the treated amount of rock.

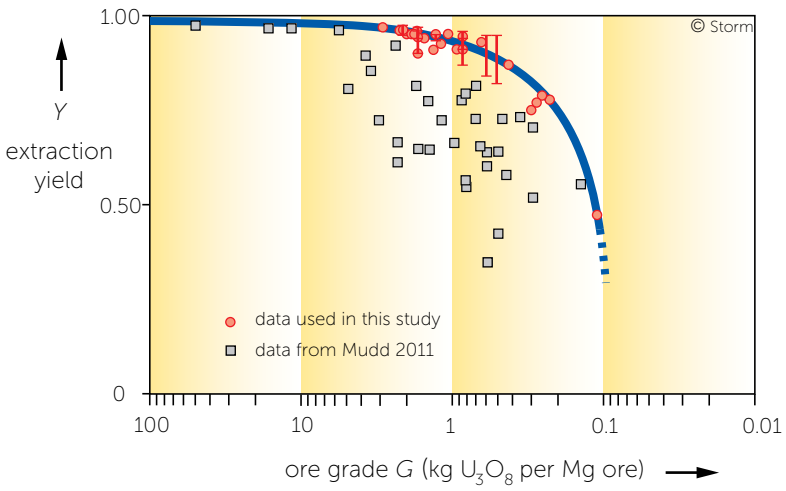

Figure B4

The extraction yield of uranium from ore as function of the ore grade. The red dots are the highest reported figures from the literature, based on actual mining operations. This curve may be seen as the upper limit of the attainable extraction yields using the current extraction technology. The grey squares are empirical data from [Mudd 2011].

The data used in this study (red dots and bars) have been taken from: [Burnham *et al.* 1974], [Franklin *et al.* 1971], [GJO-100 1980], [Huwyler *et al.* 1975], [James & Simonson 1978], [James *et al.* 1978], [Kistemaker 1976], [Kistemaker 1975], [Mutschler *et al.* 1976], [Rombough & Koen 1975], [Ross & Guglielmin 1968], [Rotty *et al.* 1975], [Simonson *et al.* 1980], [SRI 1975].

Reported yield data are not always unambiguous. In many cases it is not clear on which quantity of uranium the reported yields are based:

- the *in-situ* uranium (as present in the undisturbed ore body),
- in the actually mined ore
- in the ore entering the mill (the mined ore minus the waste)
- in the ore entering the chemical separation processes.

Some mining companies published data which would result in yields of 100% or higher.

The data used in Figure B4 may seem perhaps outdated, but during the past 4-5 decades the extraction techniques applied in the uranium industry have not changed significantly. The study of [Mudd 2011] proves the curve of Figure B4 to be at the upper limit of the current practice. In practice nearly all uranium mines achieve substantially lower extraction yields at a given ore grade than suggested by the curve of Figure B4. The extraction is governed by basic physical and chemical laws, which cannot be circumvented by technology. A low yield at low grades may be improved by application of more selective separation processes, at the expense of much higher specific energy requirements per mass unit recovered uranium.

The extraction of any metal from its ore involves a number of physical and chemical equilibria. From the Second Law of thermodynamics follows that these equilibria never go to completion. That means that a complete separation is not possible, there always will be losses. The decline of the extraction yield at lower grades is a direct consequence of this observation. The lower the concentration of uranium in the pregnant liquor, the higher its entropy and the more energy is required to extract a certain amount of uranium from that liquor. The higher the entropy of the uranium, the less complete its separation from the liquor and the greater the fraction lost in the waste streams.

Table B1

Summary of specific energy investment and CO_2 emission of uranium mining + milling at mines with average overburden ratio and hauling distance.

quantity	unit	soft ores	hard ores
total thermal energy investment mining	GJ/Mg ore	1.237	1.843
total thermal energy investment milling	GJ/Mg ore	1.508	8.67
total thermal energy investment mining + milling	GJ/Mg ore	2.745	10.51
CO_2 emission mining + milling	kg CO_2/Mg ore	206	788

Specific energy input of uranium mining + milling

The thermal energy requirements of the recovery of one kilogram of uranium leaving the mill, $J_{m+m}(U)$, as function of the ore grade G, counted in kg uranium per Mg ore, and the recovery yield Y, can be calculated via the following equation B2:

$$J_{m+m}(U) = \frac{J_{m+m}(ore)}{Y \bullet G}$$

$J_{m+m}(U)$ = specific energy consumption, GJ/kg uranium
$J_{m+m}(ore)$ = specific energy consumption, GJ/Mg ore
Y = extraction yield = fraction of recovered U
G = ore grade, kg U/Mg ore

eq B2

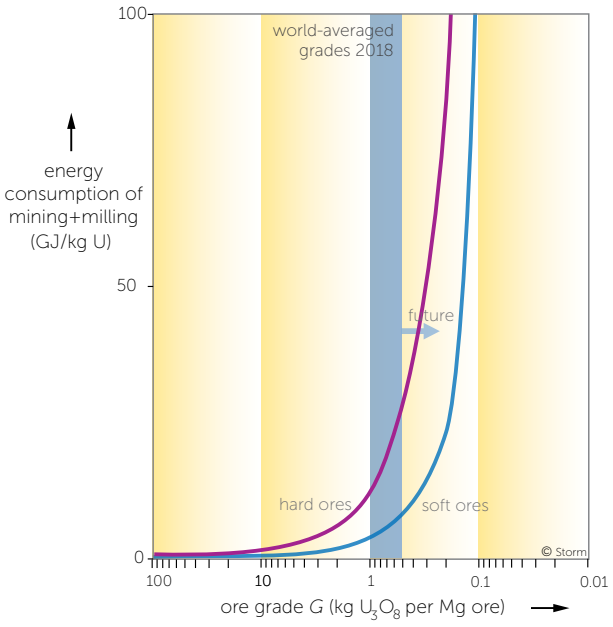

Figure B5

Energy consumption of the recovery of uranium from the earth's crust (mining + milling) as function of the ore grade, in gigajoule per kg recovered uranium. At present the world-averaged ore grade is in the range of G = 0.1-0,05% U_3O_8 and the trend is decreasing over time.

mining + milling soft ores:

J_{m+m} (Σth, ore) = 1.237 + 1.508 = 2.745 GJ/Mg ore

mining + milling hard ores:

$$J_{m+m}\ (\Sigma \text{th, ore}) = 1.84 + 8.67 = 10.51 \text{ GJ/Mg ore}$$

From the this the specific CO_2 emission of uranium mining + milling can be calculated:

$$\gamma_{m+m} = 75 \bullet J_{m+m}(U) \qquad \text{kg } CO_2\text{/kg U}$$

Energy cliff

The thermodynamic quality of a uranium resource is the determinant of being a net energy source or not. Here we define the thermodynamic quality of a uranium resource as the net quantity of useful energy that can be extracted from 1 kg natural uranium from that resource, that is the amount of electricity available to the consumer, minus the useful energy (work) required to extract 1 kg pure uranium from that resource. If the extraction of 1 kg uranium requires as much work as the amount that than can be generated from that quantity ofuranium, the uranium resource in question is not an energy source, but an energy sink. The minimum amount of extraction work is governed by basic physical laws. Advanced technology may come closer to the thermodynamic minimum, at the expense of more useful energy, but never can surpass the minimum.

The previous sections discussed the factors determining the work required to extract uranium from uranium deposits as found in nature. This study took into account: ore grade, extraction yield of milling, and mineralogy of the ore, the latter being simplified to a classification into soft ores and hard ores. Other mining conditions are averaged in the assessment.

Net energy content of a uranium resource

The quantity of potential energy in 1 kg natural uranium that can be released is not unambiguously defined, like the combustion heat of a fossil fuel, because this quantity depends on the applied reactor technology. As pointed out in the introduction, modern power reactors cannot fission more than about 0.5% (5 g/kg U) of the nuclei in natural uranium. This figure sets a practical limit to the energy content of natural uranium.

Assumed that fission of one uranium nucleus releases 200 MeV = $3.2 \bullet 10^{-11}$ J, then the complete fission of 1 g uranium-238 releases $J_{fission}$ = 81.1 GJ/g, and 1 g U-235 releases 82.1 GJ/g. In power reactors 60% of the fission energy comes from U-235 and 40% from plutonium nuclei formed from U-238 by neutron capture.

This study assumes an average fission energy of $J_{fission}$ = 82 GJ/g U.

At a fissioned fraction of 5 g/kg U_{nat} the practical energy content of natural uranium, released as heat and radiation, then becomes:

$$J_{fission} = 5 \bullet 82 = 410 \text{ GJ/kg } U_{nat}$$

The fission heat and radiation is not directly useable and has to be converted into electricity in order to become useful energy. At an average thermal efficiency of 33% the gross content of useful energy of natural uranium becomes:

$$J_U \text{ (gross)} = 0.33 * 410 = 137 \text{ GJ/kg } U_{nat}$$

The thermodynamic quality of uranium *in situ*, that is still present in the earth's crust in a given deposit, is the amount of useful energy extractable from 1 kg of uranium, minus the energy required to recover 1 kg of uranium from that resource:

$$J_U \text{ (net)} = 137 - J_{m+m}(U) \text{ GJ/kg } U_{nat}$$

Figure B5 shows that the recovery energy of uranium, J_{m+m} (U), exponentially increases with decreasing ore grade. Consequently the thermodynamic quality of uranium resources declines with decreasing ore grade and becomes zero at a certain ore grade; this phenomenon is called the energy cliff, see Figure B6. For soft ores the cliff falls to zero at a grade of about 0.01% U_3O_8, corresponding with 85 g U per Mg rock, and for hard ores the zero point lies at a slightly higher grade.

There are various types of uranium ores, so in practice the thermodynamic quality of a currently exploited uranium resource may lay between the two curves. Uranium deposits tend to be harder to mine and mill, consisting of more refractory minerals, the lower their grade, a geologic phenomenon.

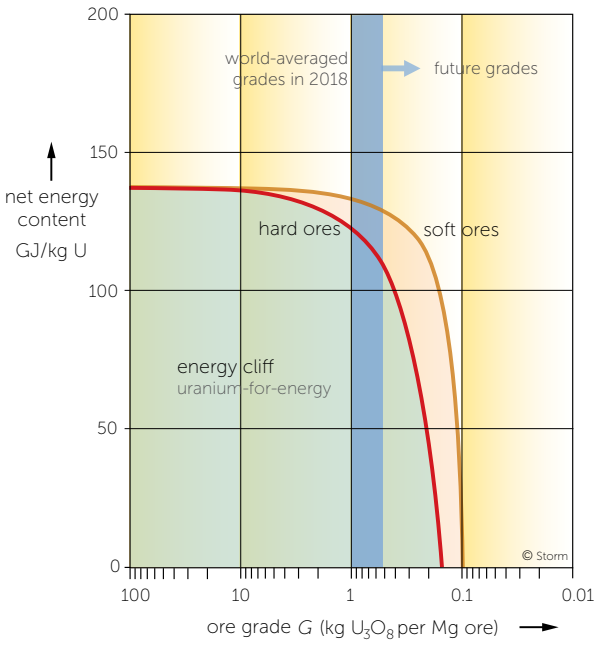

Figure B6

Energy cliff. Net energy content of natural uranium as function of the ore grade. The net energy content is defined as the amount of useful energy that can be generated per kg natural uranium minus the energy required for recovery of 1 kg uranium from the earth's crust, ignoring the remaining processes of the nuclear chain. Beyond a certain grade no net energy generation from a uranium deposit is possible.

The net useful energy content per kg U_{nat} that eventually becomes available to the consumer equals the above defined useful energy content minus the useful energy investments required for the remaining processes of the nuclear process chain.
Taking these energy investments also into account, the curves of Figure B6 would have to be moved to a lower net energy content. In this way the practical energy cliff would become observable.

$$\gamma_{m+m}(U) = 75 \bullet \frac{J_{m+m}(\Sigma th,ore)}{Y \bullet G}$$

$\gamma_{m+m}(U)$ = specific CO_2 emission, kg CO_2 /kg uranium
$J_{m+m}(\Sigma th,ore)$ = specific all-thermal energy consumption, GJ/Mg ore
Y = extraction yield = fraction of recovered U
G = ore grade, kg U/Mg ore

eq B3

mining + milling soft ores: J_{m+m} (Σth, ore) = 2.745 GJ/Mg ore
hard ores: J_{m+m} (Σth, ore) = 10.51 GJ/Mg ore

CO_2 trap

Generally the electricity consumed at uranium mines is generated by oil-fuelled generators, so all energy inputs of mining and miling may be considered to be provided by fossil fuels. This study assumes a thermal-to-electric conversion efficiency of 40% to calculate the all-thermal energy input of mining + milling,

indicated by the quantity J_{m+m} (Σth, U). From the specific thermal energy input of uranium mining and milling the specific CO_2 emission were calculated by equation B3, assumed the specific CO_2 emission of the used fossil fuels (diesel oil and fuel oil) is 75 g CO_2/MJ.

$$\gamma_{m+m}(U) = 75 \bullet J_{m+m}(\Sigma th, U) \qquad \text{kg } CO_2/\text{kg U}$$

The specific CO_2 emission of mining +milling, γ_{m+m}(e) g CO_2/kWh, can be calculated by equation B4.

$$\gamma_{m+m}(e) = \frac{\gamma_{m+m}(U) \bullet m(U_{nat})}{E_{gross}}$$

γ_{m+m}(e) = specific CO_2 emission, g CO_2 /kWh
γ_{m+m}(U) = specific CO_2 emission, kg CO_2 /kg uranium
$m(U_{nat})$ = lifetime consumption of natural uranium, Mg
E_{gross} = lifetime gross electricity production, kWh

eq B4

The specific CO_2 emissions of mining + milling of uranium from ore in the range of 0.1- 0.05% U_3O_8, the present world average, related to the advanced reference reactor and the hypothetical EPR are summarised in Table B2.

Figure B7 represents the curves derived from equation B4 for hard ores and soft ores, valid for reference advanced reactor. For many uranium mines the figures will be between the two curves, due to widely different conditions from mine to mine. The differences between the two reference reactors (advanced reactor and EPR design) lie within the range between the two curves.

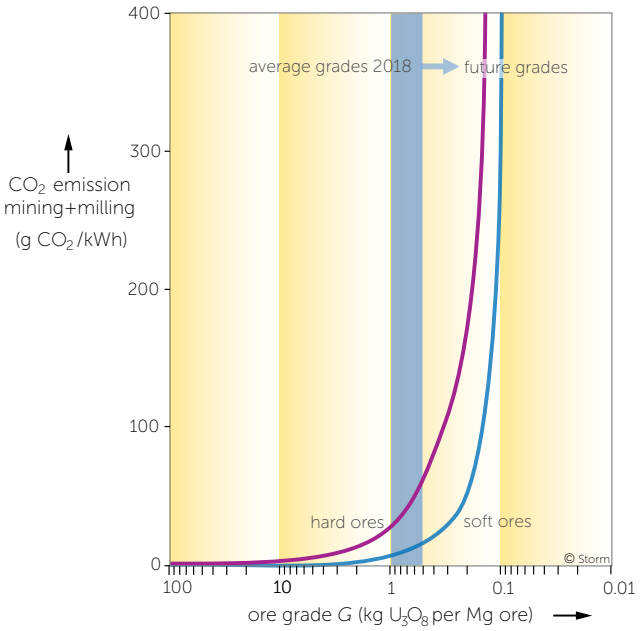

Figure B7

Specific CO_2 emission of the recovery of uranium from ore as function of the ore grade. Differences between the curves concerning the advancedcreactor and the EPR design are minor and remain within the range of the data the curves are based on.

As indicated in the diagram of Figure B7, the world average ore grade decreases with time. The most easily exploitable ore deposits with highest grades are mined first, because these offer the highest return on investment. During the past decades virtually no new rich ore deposits of significant size have been discovered. As a result the specific CO_2 emission of uranium recovery and consequently of nuclear

generated electricity rises with time, steeply at low grades. The larger a uranium resource, the lower its grade, a common geologic phenomenon. At a grade of 130-100 g U/Mg ore the specific CO_2 emission of nuclear power surpasses that of gas-fired electricity generation, this is called the *CO_2 trap*.

Table B2

Lifetime data on the specific CO_2 emission of uranium mining + milling.

quantity	unit	advanced reactor	EPR design
input mass of natural uranium, $m(U_{nat})$	Mg	5748	17880
gross electricity production, E_{gross}	kWh	$219 \cdot 10^9$	$780 * 10^9$
total CO_2 emission, soft ores G = 0.1-0.05% U_3O_8	Gg	1551 - 3283	4823 - 10214
total CO_2 emission, hard ores, G = 0.1-0.05% U_3O_8	Gg	5937 - 12527	18467 - 39106
specific CO_2 emission, soft ores, G = 0.1-0.05% U_3O_8	g CO_2/kWh	7.1 - 15.0	6.2 - 13.1
specific CO_2 emission, hard ores, G = 0.1-0.05% U_3O_8	g CO_2/kWh	27.1 - 57.4	23.7 - 50.1

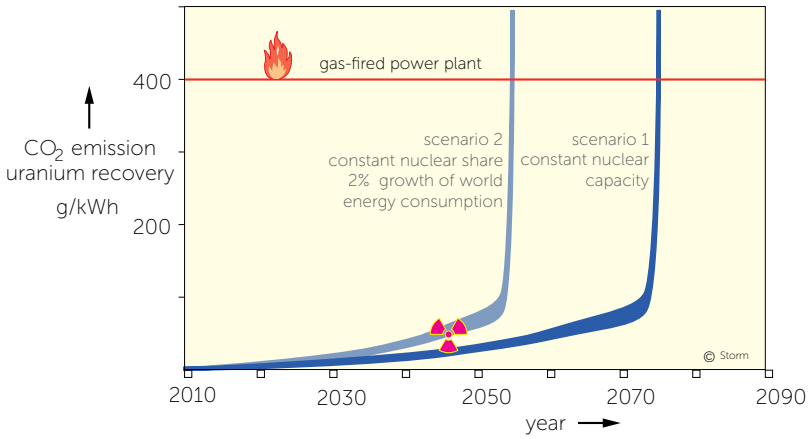

Figure B8

CO_2 trap: indication of the specific CO_2 emission by uranium mining + milling as function of the time, assuming that the richest available uranium ores are mined first. With time the mined ores are getting harder. In scenario 1 the nuclear capacity would remain at the current level (about 360 GWe). In scenario 2 the nuclear contribution to the global energy production would remain at the current level of 1.6%, implying an increasing global nuclear capacity.

ANNEX C

NUCLEAR FUEL PRODUCTION

Refining and conversion to UF_6

Yellowcake, the product of the uranium mine, has to be refined and converted into very pure uranium hexafluoride UF_6 , before enrichment is possible.
According to [ERDA-76-1] the specific energy consumption of this process is:

J_{conv} = 1.478 TJ/Mg U J_{th}/J_e = 27

The electric input has to be balanced with the gross electricity production of the nuclear power plant, the thermal energy input is the origin of the CO_2 emission. Specific CO_2 emission is:

$\gamma = 75*1.425 = 106.9$ $MgCO_2$/Mg U

Table C1
Lifetime data on refining and conversion of uranium for the reference advanced reactor and the EPR design.

quantity	unit	advanced reactor	EPR design
input mass of conversion process U_{nat}, m_3	Mg	5748	17880
thermal energy input E_{conv} (th)	PJ	8.191	25.48
electric energy input E_{conv} (e)	PJ	0.3035	0.9441
mCO_2	Gg	614.5	1911.4
specific CO_2 emission refining and conversion	gCO_2/kWh	2.81	2.45

Enrichment

Although enrichment by gas diffusion is still being applied, this assessment assumes all enrichment occurs by ultracentrifuge (UC).
Enrichment by UC has a lower direct energy use than gas diffusion, but costs of operation and maintenance are higher because of the relative short technical life of the centrifuges. The UC process produces more wastes [INFCE-2 1980], [INFCE-7 1980], [Crossley 1980] Becker *et al.* 1982]. The net difference in specific energy consumption - including construction, operation and maintenance - with the diffussion process is not large. According to [Crossley 1980] both processes cost roughly the same per SWU. US Department of Energy (DOE) expected that UC would prove more competitive in the future. Specific investment costs for both processes were about the same. This means that the operational costs, and thus the energy consumption, of the UC process must be higher than those of gas diffusion.
Energy requirements for operation and maintenance (O&M) are not included in the figures given by [Kolb *et al.* 1975], [Kistemaker 1975] and [Mortimer 1977]. This study uses the figure for UC from [Kistemaker 1975], which includes the energy consumption for construction of the plant:

J_{UC} = 1.342 GJ/SWU J_{th}/J_e = 0.78

Assumed that the energy consumption for O&M of a UC plant is twice that of a gas diffusion plant, as given by [Rotty *et al.* 1975] Q95:

$J_{o\&mUC}$ = 1.76 GJ/SWU J_{th}/J_e = 21

The total energy consumption for enrichment by UC is:

J_{UC} = 3.10 GJ/SWU J_{th}/J_e = 2.72

The electric input has to be balanced with the gross electricity production, the thermal energy input is the

origin of the CO_2 emission. Specific CO_2 emission is:

$\gamma = 75*2.267 = 170.0$ kgCO_2/SWU

Table C2

Enrichment data of the reference advanced reactor and the EPR design; see also Annex A.

quantity	unit	advanced reactor	EPR design
product mass U_{enrich} , P	Mg U_{enrich}	592.3	1529
enrichment assay x_p	% U-235	4.2	5.0
feed/product ratio F/P	–	9.51	11.46
specific separative work	SWU/kg U_{enrich}	5.66	7.20
lifetime separative work S	10^6 SWU	3.352	11.009
thermal enrichment energy input E_{enrich}(th)	PJ	7.600	24.96
electric enrichment energy input E_{enrich}(e)	PJ	2.792	9.170
mCO_2	Gg	569.8	1872
specific CO_2 emission enrichment	g CO_2/kWh	2.60	2.40

Fuel element fabrication

In the fuel fabrication plant the enriched uranium hexafluoride UF_6 is converted into uranium oxide UO_2. The pellets made from the UO_2 are packed in zircalloy tubes, which in turn are assembled with zircalloy spacers into fuel elements. The fuel elements can be placed into the reactor core. Zircaloy is the trade name of an alloy of zirconium with a few percents of another metal, e.g. tin; this study uses the name zircalloy

Zirconium for fabrication of nuclear fuel elements has to be extremely pure and free of hafnium. Purification is done by destillation of gaseous zirconium tetrachloride $ZrCl_4$. The destillation process plus the conversion of $ZrCl_4$ into metallic zirconium might consume a significant quantity of energy, in addition to the energy required for the production of zirconium from its ore.

This study starts from the figure of specific energy consumption of fuel fabrication from [ERDA-76-1]:

$J_e + J_{th} = 3.792$ GJ/kgU $\qquad J_{th}/J_e = 2.50$

$J_{th} = 2.709$ GJ/kgU

Specific CO_2 emission from the thermal energy input:

$\gamma = 75*2.709 = 203.2$ kgCO_2/kg U

According to [White 1998] p.126 the production of zirconium requires:

$J_{Zr} = 1.612$ GJ/kg Zr

$\gamma = 97.15$ kgCO_2/kg Zr

White's figure is based on refined copper, apparently not on a process analysis. Likely these figures do not include the production of zircaloy from zirconium. No data could be found on the specific energy consumption and CO_2 emission of the production of zircalloy from zirconium.

Assumed that 2 kg zircalloy is needed per kg enriched uranium in nuclear fuel, the energy input of the zirconium part of nuclear fuel would be:

$J_{Zr} = 3.2$ GJ/kg U

In view of the figure of [White 1998 it may be clear that the figure of [ERDA-76-1] does not include the production of zircalloy, consequently the total energy intensity may be:

$J_e + J_{th} = 7.0$ GJ/kgU $\qquad J_{th}/J_e = 2.50$

$J_{th} = 5.0$ GJ/kgU

$\gamma = 75*5.0 = 375$ kgCO_2/kg U

Data from practice on this issue are difficult to obtain from companies and in the open literature [Lundberg 2011]. Probably the energy consumption figures used in this study still mean an underestimation of the specific energy investments of this part of the nuclear process chain.
According to [Lundberg 2011] the production of zircalloy contributed 2.85 gCO_2eq/kWh to the total greenhouse gas emissions of the Forsmark nuclear power plant. Assuming that the performance and productive lifetime of the Forsmark NPP are similar to those of the advanced reference reactor, this study takes the same figure of the greenhouse gas emission of the zircalloy production in case of the reference reactor. For the EPR design the figure would be about 2.07 gCO_2eq/kWh, see also Table C4.

Table C3
Lifetime data on the fuel fabrication for the reference advanced reactor and the EPR design, excluding zircalloy production.

quantity	unit	advanced reactor	EPR design
input mass U_{enrich} , m_1 excluding zircalloy production	Mg	589.3	1521
thermal energy input E_{fuel}(th) excluding zircalloy production	PJ	1.596	4.120
electric energy input E_{fuel}(e) excluding zircalloy production	PJ	0.638	1.650
mCO_2 excluding zircalloy production	Gg	120	309

Table C4
Lifetime specific CO_2 emission of the fuel fabrication for the reference advanced reactor and the EPR design, including zircalloy production.

quantity	unit	advanced reactor	EPR design
fuel fabrication excluding zircalloy production	g CO_2/kWh	0.55	0.40
zircalloy production	g CO_2/kWh	2.85	2.07
sum fuel element fabrication (fuel + zircalloy)	g CO_2/kWh	3.40	2.47

Summary nuclear fuel production

TableC5 gives the summary of the lifetime energy inputs, CO_2 production and specific emission of the three front-end processes: refining + conversion, enrichment and fuel fabrication.

Table C5
Summary of thermal and electric energy inputs and specific CO_2 emission of the production of nuclear fuel from natural uranium for the reference advanced reactor and the EPR design.

process	unit	advanced reactor	EPR design
lifetime gross electricity production E_{gross}	kWh	$219 \cdot 10^9$	$780.5 \cdot 10^9$
sum thermal energy inputs, excluding zircalloy production	PJ	17.4	54.6
sum electric energy inputs, excluding zircalloy production	PJ	3.73	11.81
lifetime CO_2 production front end, excl. zircalloy production	Gg	1305	4092
sum specific emissions front end, excl. zircalloy production	g CO_2/kWh	5.96	5.24
zircalloy production	g CO_2/kWh	2.85	2.07
sum fuel production processes	g CO_2/kWh	8.81	7.31

ANNEX D

CONSTRUCTION AND OMR

Construction of the nuclear power plant

The CO_2 emission attributable to the construction of a nuclear power plant comprises not only the CO_2 emission of the construction acivities at the site, but also the embodied CO_2 emissions of the construction materials, such as concrete and steel, plus the CO_2 emissions of the production of all components and their transport to the construction site. The construction of a nuclear power plant is a very complicated sequence of activities involving high-quality materials and equipment.
The embodied energy and specific CO_2 emission of the steel and concrete of the nuclear power plant are calculated with the specific values of steel and concrete, taken from [IAEA-TecDoc-753 1994], [IPCC 2006] and [NRMCA 2012].

Table D1
Specific embodied energy and CO_2 emission of the construction materials concrete + steel

quantity	unit	steel	concrete	reference
specific energy input	MJ/kg	29.54	1.83	[IAEA-TecDoc-753 1994]
specific CO_2 emission	kg CO_2/Mg	2410	139 *	[IPCC 2006], [NRMCA 2012]

* Portland cement: 927 kgCO_2/Mg cement. Assumed the high quality concrete of an NPP contains 15% cement, then the chemical specific emission of concrete would be 139 kgCO_2/Mg concrete

Table D2
Embodied energy in the steel and concrete of the reference advanced reactor and the EPR design.
All energy units are primary energy units; Gg = gigagram = 10^9 g = 1000 metric tons.

reference	specific energy MJ/kg	advanced reactor			EPR design		
		mass Gg	energy PJ	$m(CO_2)$ Gg	mass Gg	energy PJ	$m(CO_2)$ Gg
steel	29.54	150	4.431	362	180	5.317	434
concrete	1.83	850	1.556	118	1020	1.867	142
sum steel + concrete		1000	6.0		1200	7.2	
total CO_2 emission				480			576

This study estimated the masses of these two construction materials of the reference advanced reactor and the EPR design, summarised in Table D2. The figures are based on a number of studies: [Rombough & Koen 1974], [ORNL-TM-4515 1974], [Shaw 1979], [Crowley&Smith 1982], [IAEA-293 1988], [Lako 1995], [Uchiyama 2002], [Ecoinvent 2003], [MPR-2776 2005]. Due to its double containment the construction mass of the EPR design is assumed to be higher than of the reference advanced reactor.

Table D3

Specific CO_2 emission of the construction concrete + steel of the reference advanced reactor and the EPR design.

quantity	unit	advanced reactor	EPR design
lifetime gross electricity production E_{gross}	kWh	$219 \cdot 10^9$	$780.5 \cdot 10^9$
mCO_2 (chemical, from steel + concrete)	Gg	480	567
specific CO_2 emission (chemical, from steel + concrete)	g CO_2/kWh	2.19	0.73

To the chemical contributions of steel and concrete should be added the chemical emissions of CO_2 and other greenhouse gases of the processing of numerous other materials, such as stainless steel, aluminium, copper, zirconium, other metals and synthetic materials.

The CO_2 emissions of construction could be estimated from the emissions coupled to the energy investments. In the past numerous studies were published with widely different results: figures found in 21 studies, dating from 1974 to 2011, vary from 0.7 to 26 PJ (many in primary energy units). Five of these studies were based on unknown data, four on data from 1980 and later, and twelve studies, including [WNA-*eroi* 2016], were based on LWR power plant designs from 1970-1974, not on actally built nuclear power plants. At that time the published specific costs and material requirements were lowest in history. This implies that the technical developments during the decades following the 1970s are not incorporated. Since 1970 the capacity of a generic LWR power plant evolved from 20-100 MW(e) to 1000-1600 MW(e) in 2018. The mass of construction materials evolved from some 100-200 Gg in 1970 to 800-1300 Gg in the 1990s. Construction mass further increased significantly for nuclear power plants built, and being built, after the Twin Tower attacks of 9/11 2001.

The wide range in the figures of energy investments point to different assessment methods, in addition to different data bases. Embodied energy in the materials is not always accounted for, some studies mention only the energy directy used at the construction site.

This study assumes that the direct plus indirect energy inputs and CO_2 emissions related to the construction of the nuclear power plant, such as: manufacturing, transport, construction, pipes, electric cables, electronic components, services, etcetera, are included in the figures found by the method used to estimate the overall energy investments and CO_2 emissions of construction. It seems unlikely that the chemical CO_2 emissions of the production of steel, concrete and other materials have been incorporated into the data, e.g. construction costs, used to estimate the construction energy, so these emissions should be added to the construction emissions.

Assessment of the construction of the reference nuclear power plant in the study [Storm 2007]resulted in an estimate of the construction energy investments of 80 PJ, with a large uncertainty range of ± 40 PJ. This study uses the average figure:

$$E_{construct} = E_{th} + E_e = 80 \text{ PJ} \qquad E_{th}/E_e = 4.8$$

Although this figure, originally published in [Storm&Smith 2005 & 2008], is criticized by some other studies, e.g. [Beerten *et al.* 2009] and [Lenzen *et al.* 2006], this study maintains it because no better assessment methods are reported and because of the uncertainty range in the used data.

The figure of $E_{construct}$ includes the direct energy consumption during construction at the construction site, according to [Vattenfall 2001a, 2001b, 2005], [WNA-*eroi* 2016] and [Setterwall 2005] (electric inputs are converted into thermal inputs):

$$E_{direct} = 4.1 \text{ PJ}$$

This would correspond with a total CO_2emission of:

$$mCO_2 = 75^*4.1 = 308 \text{ Gg}$$

Several of the published life cycle assessments of nuclear power used the Vattenfall figure as the total energy investment of construction.
For the EPR design this study assumes a construction energy investment of 1.2 times that of the advanced reactor, so:

$$E_{construct} = E_{th} + E_e = 96 \text{ PJ} \qquad E_{th}/E_e = 4.8$$

It should be noted that the EPR figures are based on hypothetical specifications of the EPR design. Especially the lifetime gross electricity production is questionable, because that figure is based on the improbably long productive lifetime of 55 FPY. Not one nuclear power plant in the world ever reached such a long effective lifetime. During the past years the world average remained nearly constant at 23-24 FPY.
In this study the electric components of the construction energy are assumed to be provided by nuclear power and are to be balanced with the gross electricity production of the nuclear power plant.

Table D4
Specific energy investments and CO_2 emission of the construction of the reference advanced reactor and the the EPR design.

quantity	unit	advanced reactor	EPR design
gross electricity production E_{gross}	kWh	$219 \cdot 10^9$	$780.5 \cdot 10^9$
thermal energy input E_{constr}(th)	PJ	66.2	79.4
electric energy input E_{constr}(e)	PJ	13.8	16.6
mCO_2 (constr)	Gg	4965	5955
mCO_2 (chemical, from steel + concrete)	Gg	480	567
total mCO_2	Gg	5445	6522
specific emission	g CO_2/kWh	24.9	8.37

The study [ExternE 1998] is one of the few published analyses based on an existing nuclear power plant, the Sizewell B NPP in the UK (1188 MWe, load factor at that time 84.2%). According to this study the emissions due to the construction of the plant were: CO_2 10665, CH_4 20.6 and N_2O 0.66 t/TWh. Multiplying these figures by the global warming potentials (GWP) of CH_4 and N_2O results in:

CO_2 10665 t/TWh = 10.67 gCO_2/kWh
CH_4 20.6 t/TWh = 0.0206 gCH_4/kWh = 23*0.0206 = 0.47 gCO_2*eq*/kWh
N_2O 0.66 t/TWh = 0.00066 gN_2O/kWh = 296*0.00066 = 0.20 gCO_2*eq*/kWh

Based on these figures the greenhouse gas emissions due to the construction of Sizewell B becomes:

γ = 10.67 + 0.47 + 0.20 = 11.34 gCO_2*eq*/kWh.

[ExternE 1998] is found to be one of the very few studies mentioning the emission of greenhouse gases other than CO_2.
The ExternE study did not make clear how the emissions were calculated, the total mass of the emissions and the assumed operational lifetime in full-power years (FPY) were not given. Possibly the study assumed an operational lifetime of 40-50 calender years and an average lifetime load factor of 84%, resulting in an (unproven) effective lifetime of 34-42 FPY; such high figures are common in publications of the nuclear industry. Likely the ExternE method of calculation applied to the advanced reference reactor with an effective lifetime of 25 FPY might result in a higher emission figure of about 15 gCO_2*eq*/kWh.

Operation, maintenance and refurbishments (OMR)

Operation and maintenance costs during the active lifetime of a PWR power plant were about 100 M$ a year according to [Blok & Hendriks 1989], or about 138 M$ in 2000. This is about 2.1% of the average construction cost (6.5 G$(2000)/GWe) a year, or about 2.6% per full-power year. [Rotty *et al*. 1975] mentioned a value of 3.1% per year.
The study [Komanoff 1992] found a figure of 97 M$(1991) per year, about 122 M$(2000)/yr, for operation and maintenance of a 1 GWe plant. or 1.9% of the construction cost per year. At the moment of his study, the O&M costs were escalating at a rate of 4.7% per year, including inflation. Applying that rate, the O&M costs in 2000 would be about 147 M$(2000) per year, or 2.26% of the average construction costs. Assuming a load factor of 0.82, the O&M costs are about 2.8% of the average construction costs per full-power year (FPY), slightly lower than the value from [Rotty *et al.* 1975].
The average fixed O&M costs (excluding refurbishments) in the USA were 17.2 $/MWh according to [Thomas 2005] and [Thomas *et al.* 2007], or about 150 M$/GWe.a, 2.3% per FPY. In the UK the reported O&M costs were almost three times as high.
[MIT 2003 & 2009] reported fixed O&M costs in 1993 of 96 $/kW/yr with an escalation rate of 1% a year. This corresponds with some 149 M$(2000)/GWe.a, at an assumed load factor of 0.82, or 2.3% per year.
The study [Ecoinvent 2003] lists a large number of chemicals and auxiliary materials needed to operate a nuclear reactor, with a total mass of some 4000 Mg each year. This would correspond with 0.4% of the construction mass each year. The Ecoinvent study did not perform an energy analysis of these materials.
This study estimates the cost of operation and maintenance at 2.3% of the construction cost per year.
In addition, most NPPs need one or more large refurbishments during their active lifespan, for example replacing steam generators, implementation of new, updated control systems and updated safety measures. These replacements and updates may cost about 20-80% of the original construction costs. Assumed that the mean refurbishment costs are 50% of the mean construction costs and are to be spent over an operating period of 25 full-power years, the annual refurbishment cost are about 2% of the mean construction costs per full-power year.

Extensive refurbishments are required to reach an effective lifetime of 25 FPY. Extension of the operational lifetime beyond 25 FPY might require even more replacements: most parts of the nuclear power plants have to be replaced, except the reactor vessel. The reliability of the reactor vessel determines the operational lifetime of a NPP. The quality of the vessel deteriorates over time by stress, corrosion and neutron capture. In view of the operational experience it seems highly unlikely that the reactor vessel of the EPR design would reach the designed operational lifetime of 55 FPY.
It seems plausible to assume the refurbishment efforts will remain about constant, on the average, throughout the operational lifetime of a nuclear power plant, regardless the length of the operational lifetime. Consequently this study assumes that the average annual refurbishment cost will remain 2% of the construction cost, independently of the operational lifetime. The annual cost of OMR would then become 2.3% + 2% = 4.3% of the consrtruction cost .

If operation, maintenance and refurbishments together are taken as an average economic activity in de sector new construction, which may be an underestimate, the total energy requirements of this part of the nuclear chain can be approximated at 4.3% of the mean construction energy requirements per full-power year.
Table D5 summarises the energy investments and specific CO_2 emission of OMR.

Table D5

Lifetime energy investments, CO_2 production and specific emission of the operation + maintenance + refurbishments (OMR) of the reference advanced reactor and the EPR design.

quantity	unit	advanced reactor	EPR design
gross electricity production E_{gross}	kWh	$219 \cdot 10^9$	$780.5 \cdot 10^9$
thermal energy input E_{OMR}(th)	PJ	71.2	188
electric energy input E_{OMR}(e)	PJ	14.8	39.2
mCO_2 (OMR)	Gg	5340	14102
specific emission	g CO_2/kWh	24.4	18.07

ANNEX E

METHODOLOGY

Process analysis

During the 1970's and 1980's the methodology of energy analysis has been developed, maturing to a useful tool to estimate with reasonable accuracy the energy requirements of a good or economic activity and to assess the emission of CO_2 and other greenhouse gases (GHGs), see for example [IFIAS 1974], [IFIAS 1975], [Roberts 1975], [Chapman 1975], [Chapman 1976-1 and 1976-2, [Roberts PC 1976], [Reister 1977], [Bullard *et al*. 1978], [Roberts PC 1982], [Constanza & Herendeen 1984], [Spreng 1988]. Application of this methodology to assess the energy balance of nuclear power has been peer reviewed in 1985 [Storm 1985]. The same methodology is applied in this study.

Unambiguous definitions of the concepts used in energy analysis are formulated in [IFIAS 1974] and [IFIAS 1976]. In the energy analysis the quantity *enthalpy* ΔH is used, although *free energy* ΔG should be used. For fossil fuels and uranium, the numerical differences between enthalpy and free energy are not large, as shown in IFIAS 1974, so all energy analyses conveniently use ΔH, here called *useful energy*.

A generic industrial process is outlined in Figure E1. Each process has direct energy inputs and indirect energy inputs: the direct energy inputs are fossil fuels and/or electricity, the indirect inputs comprise the energy embodied in materials, equipment and services, including transport. Human labour and raw materials as found in nature, other than mineral energy sources, are considered to have zero embodied energy, according to the generally accepted conventions of the energy analysis method. Process analysis measures the energy directly consumed in the process plus the indirect energy inputs, embodied in the process chemicals and/or construction materials.

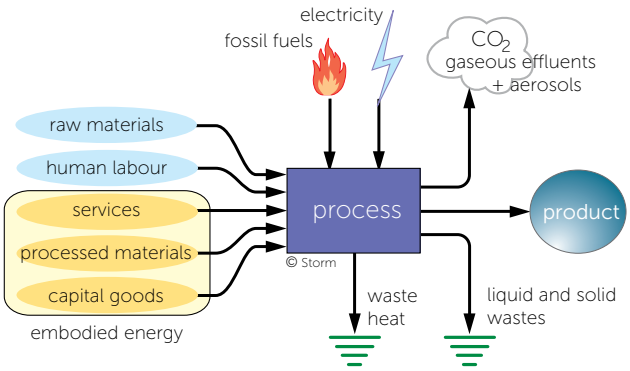

Figure E1

Mass flows and energy flows of a generic industrial process. A process has direct energy inputs, electricity and fossil fuels (e.g. diesel fuel) consumed in the process, and indirect energy inputs, which are embedded in the other inputs of the process. These flows are to be quantified by the energy analysis of the process.

A process analysis starts with mapping out all inputs of the process per unit product and all output flows. The simplified diagram of Figure E1 is based on the assumption that the wastes released into the biosphere are relatively harmless; the qualification 'relatively harmless' is an economic notion. Strictly the harmful wastes are the input of a following, separate process. The waste managing process(es) may occur at another place and at another time than the production process itself.
The input of processed materials, such as steel and concrete, are the products of one or more preceding

industrial processes, each of which with their own direct and indirect energy inputs and GHG emissions. The input of capital goods, for example the reactor vessel, pumps and control equipment, are the products of other industrial processes in the economic system. The process flows of these fabrication processes have the same generic outline as presented by Figure E1. Obviously a full process analysis of the construction of a nuclear power plant becomes rather complicated in this way, so a simple shortcut would be welcome. Usually this done by means of an input/output analysis, which is applied in cases of complex industrial activities.

Energy systems

The sole purpose of an energy system is to convert the potential energy in a raw mineral energy resource (fossil fuels, uranium) into a useful energy form, which can be distributed and used for any energy service. The product of an energy conversion system is useful energy made available to users other than the conversion system itself. The nuclear energy system is no exception to the generic energy system, in fact it is the most complex energy system ever designed and comprises a large number of industrial processes. The raw energy resource is uranium ore and the sole product is electricity. The potential energy in uranium, primary input E_o, is system-dependent and is in practice not more than the fission heat released by fission of 5 g nuclei per kg natural uranium.

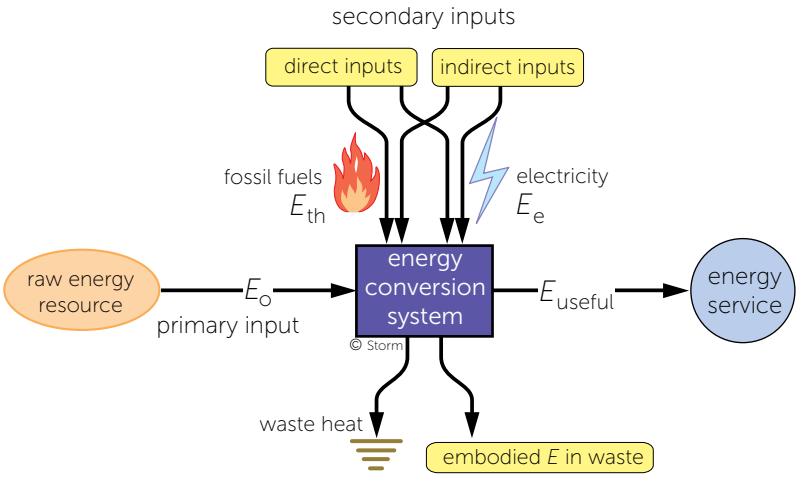

Figure E2

Outline of a generic energy system. The energy system itself comprises a number of industrial processes. The secondary inputs are required for the construction and operation of the system, and for waste handling. Energy services are, among other, transport, work, process heat, electricity. The raw energy resource can be a mineral resource in the earth's crust.

Thermal and electric energy inputs

World energy statistics are usually given in primary energy units, such as (metric) tonne oil equivalent (TOE). In that case the calorific equivalents (heat of combustion) of fossil fuels and other fuels are expressed in TOE, e.g. [BP 2017]. BP uses the conversion factor: 1 TOE = 42 GJ. Electricity is converted into primary energy units by multiplying the amount of electricity by a factor f and the result is added to the combustion heat from directly used fossil fuels, see equation E1.

In the 2006 BP statistics and later the value $f = 2.6$ is used for nuclear energy and for hydroelectricity, based on a conversion efficiency of 0.38 of thermal energy into electricity. The BP statistics before 2001 used the values $f = 3$ for nuclear and $f = 1$ for hydroelectric energy.

From a thermodynamic viewpoint any factor $f \neq 1$ for nuclear energy is incorrect. One joule of electricity, from

whatever source, can be converted into not more than one joule heat. The sole usable output of nuclear power plants is electricity, as is of hydro, PV and wind.
In fact the use of 'primary energy units' in this way conflicts with the First Law of thermodynamics: energy cannot be produced, nor destroyed, only converted from one kind into another. Quality cannot be added to quantity.

$$E_{prim} = E_{th} + f \cdot E_e$$

E_{prim} = primary energy J
E_{th} = thermal energy J
E_e = electric energy J
f = conversion factor

eq E1

In most energy analyses, e.g. [ISA 2006] and [Ecoinvent 2003], the electric inputs of the nuclear system are converted into 'primary energy units'. This method introduces ambiguities and confusion, due to the application of variables which are not physical constants, but depend on assumptions, usually implicit, which change by time and other factors.
Electric and thermal energy (fossil fuels) inputs of industrial processes are kept separated in this study. The total energy input of a process, $E_{process}$, is defined as the sum of the electric and thermal inputs, at a thermal/electric ratio R that depends on sector or process, see equation E2. Note that the energy inputs of the nuclear process chain are part of the final energy consumption of the economic system.

$$E_{process} = E_{th} + E_e \qquad R = \frac{E_{th}}{E_e}$$

$E_{process}$ = total energy input of a process J
E_{th} = thermal energy input J
E_e = electric energy input J
R = thermal/electric ratio

eq E2

Input/output analysis

Energy embodied in capital goods and services, sometimes also in processed materials, is difficult to estimate with process analysis and requires a second method: the input/output (I/O) analysis This method has been developed in economics. By the I/O method the embodied energy of a material is approximated by multiplying the price of a material in year *i* by the energy intensity in year *i* of the economic sector which produced the material. Methodological apects of I/O and process analysis are discussed in the above mentioned publications and also, for example, in IAEA [TecDoc-753 1994].
The concept of the energy/gdp ratio is based on the notion that in a given year the economy consumes a measured amount of energy units and produces a measured amount of units of economic transactions or changes by human action, quantified by the gross domestic product (GDP). The energy input is measured in joules J and the GDP is often measured in US dollars (USD).
The average energy intensity of one unit of economic transactions e_i in a given year *i* is:

$$e_i = \frac{E_{gross(i)}}{GDP_i}$$

e_i = energy/GDP ratio of year i J/$_i$
$E_{gross(i)}$ = gross energy production in year i J
= $E_{e(gross)} + E_{th(gross)}$
GDP_i = gross domestic product of year i $_i$

eq E3

Activities involving nuclear technology likely require more usable energy per mass unit product than the average activity, as a consequence of the high quality specifications. So, this method may understate the energy invested in the nuclear system.

Process analysis, see previous section, may lead to a large underestimation of the total construction energy requirements, when services and supporting activities of the construction are discounted, according to e.g. [Rombough & Koen 1975] and [Bullard *et al.* 1978]. This is the case in a number of energy analyses published in the past. Input/output analysis is well suited to large aggregated activities, like the construction of a nuclear power plant. [Chapman 1975] concluded:

> "In principle this is an unsatisfactory procedure since the inputs to nuclear systems are likely to be uncharacteristic products of the sectors documented in the input-output tables. However there are grounds for believing that, provided a product has a large vector of inputs, i.e. requires inputs from many other sectors of the economy, then the average energy intensity derived from the input-output table is fairly reliable."

The I/O analysis may be simplified by using the general energy/gdp ratio of a particular year in a particular country to calculate the net energy requirement of a complex activity. The general energy/gdp ratio (or energy intensity) *e* is defined as the quotient of the total primary energy consumption of a country (in joules) and gross domestic product GDP (often in US dollars) of a given year *i*. Usually primary energy units are applied, which introduces ambiguities, as pointed out in the previous section.
In case of the construction of a nuclear power plant, estimation of the construction energy using the energy intensity *e* from the monetary costs in the same year, according to equation E4, does not introduce a large error. The range in the reported capital costs of nuclear power plants (in the USA ±50%) is larger than the uncertainty introduced by this simplification.

$$E_{constr} = C_{constr(i)} \bullet e_i \bullet a_i$$

E_{constr}	=	primary energy requirements of construction	J
$C_{constr(i)}$	=	construction cost in year i	$\$_i$
e_i	=	energy/GDP ratio of year i	$J/\$_i$
a_i	=	multiplier in year i	

eq E4

This simplification gives a fairly reliable value of the energy embodied in that activity, including energy costs of craft labour, services, subsidies, etcetera, according to [Tyner, Constanza & Fowler 1988]. This conclusion endorses the conclusions of other studies, e.g. [Rombough & Koen 1978], [Roberts PC 1982], [Bullard *et al.* 1978], [Constanza & Herendeen 1984]. As Constanza & Herendeen put it:

> "Embodied energy (calculated the way we suggest) is a good, non-trivial static correlate of the economic value of the relatively large aggregates of goods and services that make up the entries in the I/O tables."

Certainly, the construction of a nuclear power plant is a large aggregate of goods and services. Nuclear technology may considered being high-tech, on top of an extensive industrial and economic infrastructure of other high-tech production processes. The studies of [Rombough & Koen 1975] and [Bullard *et al.* 1978] showed that the value calculated via a detailed I/O analysis is somewhat higher than the value found via the simplified method. Both studies concluded that construction of a (coal-fired) power plant is more energy-intensive than the average economic activity. Likely the construction of a nuclear power plant would be even more energy-internsive, in view of the large amounts of materials with high quality specifications incorporated in the plant.

A more accurate estimation of the construction energy can be found by multiplying the construction costs of a plant (in year *i*) with the energy/cost ratio (in J/$) of the sector 'new construction of utilities', in the same year *i*. This can be done by multiplying the result by a factor *a*, derived from the publication of [Bullard *et al.* 1978]. In this study a constant value of $a = 1.16$ is assumed (valid for the year 1967), although factor *a* is

slightly increasing with time and getting more electricity-intensive. In view of the high-tech character of the nuclear industry the multiplicator might by higher for nuclear power plant construction.

Input-output analysis is playing an increasingly important role in assessements of the environmental effects of energy systems [IPCC-*ar5* 2014].

Origin of the nuclear CO_2 emission

The CO_2 emissions by the nuclear system result from burning fossil fuel to provide the thermal energy inputs of the process chain and from chemical reactions (e.g. in the cement and steel production), directly related to the operation of the nuclear energy system.
This study assumes the electric inputs of the contemporary processes, as represented in Figure 1 in the introduction, to be produced by the nuclear system itself. Consequently these inputs are to be balanced with the electricity delivered to the grid E_{grid}. The net electricity delivered to the economic system (consumer) is indicated by E_{net} (see Figure E3). The front-end processes refining + conversion, enrichment, fuel fabrication and construction of the nuclear power plant may be considered to occur contemporarily with the operation of the power plant. Because of the remote locations of the mines the electric inputs of the recovery of uranium (mining + milling) are generally generated at the site by oil-fuelled generators. For that reason the electric inputs of mining + milling are converted into thermal energy, assuming that the generators at the mines have a thermal conversion efficiency of 40%.
The operating plants would provide the electrical energy inputs needed for the front-end processes and for construction and OMR of new power plants, and are balanced with the gross electricity output. Strictly these inputs are not CO_2 free, if the CO_2 emission of the complete nuclear system is calculated on basis of the gross output, as is done in this study. This difference is ignored, in view of the range in the values.

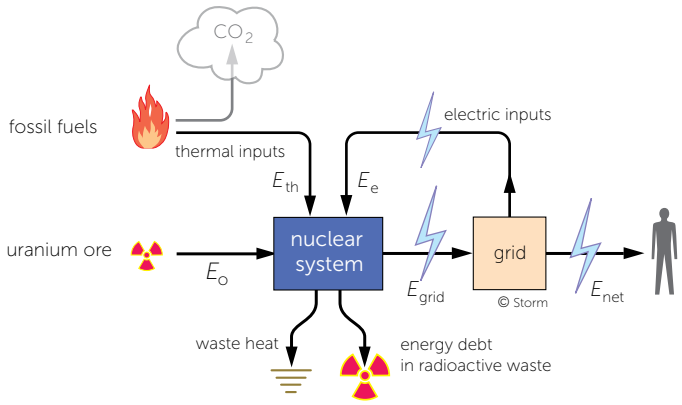

Figure E3
Energy flows of the nuclear energy system. The electrical inputs are assumed to be provided by the system itself (see text). The CO_2 emission by the nuclear system comes from the burning of fossil fuels in the nuclear process chain and from chemical reactions.

A methodological issue arises concerning the back-end processes of a given nuclear power plant, because these could be fulfilled only after closedown of the power plant, as pointed out in the first section. No advanced technology is needed to complete the back end. Like other industrial processes the back-end processes require inputs of materials and energy and emit CO_2 and possibly also other GHGs. The consumption of energy and the emission of CO_2 by the back-end processes are to occur during periods of decades to more than a century after the closedown of a particular nuclear power plant: the cause of the *energy debt* and *latent CO_2 emission*. The energy inputs are to be provided in the future by the then

operating energy systems.

This study assumes the specific CO_2 emission (CO_2 intensity γ) of all thermal energy inputs (fossil fuels) of the nuclear energy system to have a mean value of:

$$\gamma = 75 \text{ g}(CO_2)/\text{MJ(th)} .$$

Many thermal inputs of the industrial processes of the nuclear system are fossil fuels. Above value might be not overestimated as the average CO_2 emission of fossil fuels.

REFERENCES

Ahlswede et al. 2012
Ahlswede J, Hebel S, Ole Ross J, Schoetter & Kalinowski M B,
Update and improvement of the global krypton-85 emission inventory,
‹ 1-s2.0-S0265931X12001816-main.pdf ›
http://www.sciencedirect.com/science/article/pii/S0265931X12001816?np=y
retrieved Oct 2015

Areva 2012
The EPR reactor. The reference for New Build,
Areva, December 2012.
‹ Areva-8p-EPR-09112012-16.pdf ›
(brochure, 8 pages)
http://www.epr-reactor.co.uk/scripts/ssmod/publigen/content/templates/show.asp?P=198&L=EN
download 20180119

Becker et al. 1982
Becker EW, Bier W, Bley P, Ehrfeld W, Schubert K & Seidel D,
Development and technical implementation of the separation nozzle process for enrichment of uranium-235. Kernforschungszentrum Karlsruhe GmbH,
March 2, 1982,
KfK 3310

Beerten et al. 2009
Beerten J, Laes E, Meskens G & D'haeseleer W,
Greenhouse gas emissions in the nuclear life cycle: A balanced appraisal,
Energy Policy, 37, 2009.

Blanchard et al. 1982
Blanchard RL, Fowler TW, Horton TR & Smith JM,
Potential health effects of radioactive emissions from active surface and underground uranium mines,
Nuclear Safety, Vol 23 no 4, July-August 1982.

Blasing & Jones 2003
Blasing TJ & Jones S,
Name that compound: the game for CFCs, HFCs, HCFCs and halons,
CDIAC, August 2003,
http://cdiac.ornl.gov/pns/cfcinfo.html

Blasing & Smith 2006
Blasing TJ & Smith K,
Recent greenhouse gas concentrations,
CDIAC, July 2006,
http://cdiac.ornl.gov/pns/current_ghg.html

Blok & Hendriks 1989
Blok K & Hendriks C A,
Elektriciteitsproduktietechnieken voor de komende twintig jaar. Vergelijking van Milieu effecten,
Rapport W 90006 (in Dutch),
Vakgroep Natuurwetenschap en Samenleving, University of Utrecht, November 1989.

BP 2017
BP Statistical Review of World Energy, June 2017
‹bp-statistical-review-of-world-energy-2017-full-report.pdf ›
https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-full-report.pdf

Bruckner et al. 2014
Chapter 7, Energy Systems, in:
Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,
Cambridge University Press, 2014,
ISBN 978-1-107-65481-5,
‹ ipcc_wg3_ar5_full.pdf ›
http://mitigation2014.org/report/publications/
accessed Sep 2015, 24 December 2018.

Bullard et al. 1978
Bullard C W, Penner P S & Pilati D A,
'Net energy analysis, Handbook for combining process and input/output analysis',
Resources and Energy, vol. 1, 1978, pp.267-313.

Burnham et al. 1974,
Burnham JB, Brown RE, Enderlin W, Hanson MS, Hartley JN, Hendrickson PL, Paasch RK, Rickard WH, Schrenkhise RG & Watts RL,
Assessment of uranium and thorium resources in the United States and the effect of policy alternatives,
PN-238-658,
Battelle Pacific Northwest Laboratories, Richland, Washington: December 1974.

Chapman 1975
Chapman P F,
'Energy Analysis of Nuclear Power Stations',
Energy Policy, December 1975, pp 285-298.

Chapman 1976a
Chapman P F,
Methods of energy analysis,
part of: Aspects of Energy Conversion,
Proceedings of a Summer School held at Lincoln College, Oxford, UK,
14-15 July 1975, pp 739-758.

Chapman 1976b
Chapman P F,
Principles of energy analysis,
part of: Aspects of Energy Conversion,
Proceedings of a Summer School held at Lincoln College, Oxford, UK,
14-15 July 1975, pp 715-737.

Constanza & Herendeen 1984
Constanza R & Herendeen RA,
'Embodied energy and economic value in the United States economy, 1963, 1967 and 1972',
Resources and Energy, vol.6, June 1984, pp. 129-163.

Crossley 1980
Crossley P S,
Centrifuges help match supply and demand
Nuclear Engineering International, October 1980, p.45-48

Crowley & Griffith 1982
Crowley J H & Griffith J D,
US construction cost rise threatens nuclear option,
Nuclear Engineering International, June 1982, pp 25-28.

CSIRO 2004
Taylor G, Farrington V, Woods P, Ring R & Molloy R,
Review of environmental impatcs of the acid in-situ leach uranium mining process,
CSIRO Land and Water Client Report, August 2004,
CSIRO Land and Water, Clayton South, Vic 3169, Australia,
www.epa.sa.gov.au/pdfs/isl_review.pdf

DOE/EIA 1997
Nuclear power generation and fuel cycle report 1997,
DOE/EIA 0436(97),
Energy Information Administration, September 1997.

Dones 2007
Dones R,
Critical note on the estmation by Storm van Leeuwen J.W. and Smith P. of the energy uses and corresponding CO2 emissions from the complete nuclear energy chain,
Paul Scherrer Institut PSI, 10 April 2007,
http://gabe.web.psi.ch/pdfs/Critical%20note%20GHG%20PSI.pdf
16 Sept 2014: no longer available on the above website, available on:
http://www.researchgate.net/publication/237409163_Critical_note_on_the_estimation_by_Storm_van_Leeuwen_J.W._and_Smith_P._of_the_energy_uses_and_corresponding_CO2_emissions_from_the_complete_nuclear_energy_chain
27 Dec 2018: no longer available on the above site, downloadable from:
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.190.5849&rep=rep1&type=pdf
rertrieved 27 Dec 2018

Ecoinvent 2003
Dones R,
Kernenergie
ecoinvent-Bericht no.6 – Teil VII
In: Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz (ed. Dones R.).
Final report ecoinvent 2000 No. 6-VII,
Paul Scherrer Institut Villigen,
Swiss Centre for Life Cycle Inventories, Duebendorf, CH,
www.ecoinvent.ch

EIA-G 2001
Global Warming Potentials,
Appendix G, Emissions of greenhouse gases in the United States, 2001,
www.eia.doe.gov/oiaf/1605
downloaded 20070815

EPA 2002
Greenhouse gases and global warming potential values,
Excerpt from the Inventory of US greenhouse emissions and sinks,
US Greenhouse Gas Inventory Program,
EPA 430-R-02-003,
US Environmental Protection Agency, April 2002,
www.epa.gov/globalwarming/publications/

ERA 2006
Energy Resources of Australia Ltd (ERA),
Ranger Operation,
2006,
http://www.energyres.com.au

ERA-AR 2005
Energy Resources of Australia Ltd (ERA),
ERA 2005 Annual Report,
Chairman's and Chief Executive Report,
2006
http://www.energyres.com.au

ERDA-76-1
A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future,
Volume 1, The Plan. p. 111-116, Appendix B: Net energy analysis of nuclear power production,
Washington DC: Energy Research and Development Administration, 1976.

ExternE-UK 1998
Power Generation and the Environment – a UK Perspective,
Volume 1, June 1998
AEAT 3776
‹ Memoire_CCVK_81_Externe_UnitedKingdom.pdf ›
http://www.regie-energie.qc.ca/audiences/3526-04/MemoiresParticip3526/Memoire_CCVK_81_Externe_UnitedKingdom.pdf
retrieved May 2016

Franklin et al. 1971
Franklin W D, Mutsakis M & Ort R G,
Total energy analysis of nuclear and fossil fueled power plants,
ORNL-MIT-138,
Oak Ridge National Laboratories and Massachusetts Institute of Technology, 23 November 1971.

GJO-100 1980
Statistical data of the Uranium Industry
GJO-100 (80)
Department of Energy, Grand Junction Office, Colorado, USA, 1980.

Huwyler et al. 1975
Huwyler S, Rybach L and Taube M,
Extraction of uranium and thorium and other metals from granite,
EIR-289, Technical Communications 123,
Eidgenössische Technische Hochschule, Zürich,
September 1975
Translated by Los Alamos Scientific Laboratory, LA-TR-77-42, 1977.

IAEA-293 1988,
Factors relevant to the recycling or reuse of components

arising from the decommissioning and refurbishment of nuclear facilities,
Technical Report Series No 293,
International Atomic Energy Agency (IAEA), Vienna, 1988,
ISBN 92-0-125888-7.

IAEA-ccnap 2014
Climate Change and Nuclear Power 2014,
International Atomic Energy Agency, Vienna, 2014,
‹ccanp2014web-14869824.pdf›
http://www.iaea.org/books/IAEABooks/10771/Climate-Change-and-Nuclear-Power

IAEA-npss 2017
Nuclear power for Sustainable Development,
International Atomic Energy Agency IAEA
November 2017
‹ np-sustainable-development.pdf ›
https://www.iaea.org/sites/default/files/np-sustainable-development.pdf
retrieved 26 Dec 2018

IAEA TecDoc-753 1994
Net energy analysis of different electricity generation systems,
IAEA TecDoc-753
IAEA, Vienna, 1994.

IFIAS 1974
Energy analysis workshop on methodology and convention,
IFIAS, International Federation of Institutes for Advanced Study,
Guldsmedshyttan, Sweden, August 1974. Stockholm.

IFIAS 1975
Workshop on energy analysis and economics,
IFIAS, International Federation of Institutes for Advanced Study,
Lidengo, Sweden, June 1975. Stockholm.

INFCE-2 1980
Enrichment availability
Reprot of the INFCE Working Group 2
IAEA, Vienna, 1980
STI/PUB/534

INFCE-7 1980
Waste management and disposal,
Report of the INFCE Working Group 7,
International Nuclear Fuel Cycle Evaluation,
IAEA, Vienna, 1980.
STI/PUB/534

IPCC 2006
2006 IPCC Guidelines for National Greenhouse Gas Inventories,
Chapter 4: Metal Industry Emissions,
‹V3_4_Ch4_Metal_Industry.pdf›
www.ipcc-nggip.iges.or.jp/public/2006gL/pdf/3_volume3/

IPCC-ar5 2014
Climate Change 2014: Mitigation of Climate Change.
Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,
Cambridge University Press, 2014,
ISBN 978-1-107-65481-5,
‹ ipcc_wg3_ar5_full.pdf ›
http://mitigation2014.org/report/publications/
accessed Sep 2015, 24 December 2018.

ISA 2006
Life-Cycle Energy Balance and Greenhouse Gas Emissions of Nuclear Energy in Australia,
A study undertaken for the Department of Prime Minister and Cabinet of the Australian Government,
ISA, The University of Sydney, 3 November 2006,
www.isa.org.usyd.edu.au/publications/reports.shtml

James & Simonson 1978
James HE & Simonson HA,
Ore-processing technology and the uranium supply outlook,
Paper in:
Uranium, supply and demand
Proceedings Third International Symposium by The Uranium Institute, London, July 12-14, 1978, pp 107-181.

James et al. 1978
James HE, Boydell DW & Simonson HA.
South African uranium industry plans for expansion
Nuclear Engineering International, November 1978, pp 42-45.

Jan & Krug 1995
Jan R von & Krug H,
'Brennelemente für den weltweiten Einsatze', (in German),
ATW 40. Jg (1995), Heft 3, März, pp 164 166.

Kistemaker 1975
Kistemaker J,
Energie-analyse van de totale kernenergie cyclus gebaseerd op licht water reactoren,
FOM Instituut voor Atoom- en Molecuulfysica, Amsterdam,1975, (in Dutch)
prepared for Landelijke Stuurgroep Energieonderzoek (LSEO)
LSEO 682

Kistemaker 1976
Kistemaker J,
Aanvulling op: Energie-analyse van de totale kernenergiecyclus gebaseerd op lichtwater reactoren,
LSEO 818, juli 1976 (in Dutch).

Kolb et al. 1975
Kolb G, Niehaus F, Rath-Nagel St & Voss A,
Der Energieaufwand für Bau und Betrieb von Kernkraftwerken, (in German),
Bericht Jül-1230, Jülich: Kernforschungsanlage Jülich GmbH, August 1975.

Komanoff & Roelofs 1992
Komanoff Ch & Roelofs C,
Fiscal fission: the economic failure of nuclear power,
Komanoff Energy Associates, for Greeenpeace USA and Greenpeace International, December 1992.

Kunakemakorn et al. 2011

Kunakemakorn J, Wongsuchoto P, Pavasant P & Laosiripojana,
Greenhouse emission of European Pressurized Reactor (EPR) nuclear power plant terchnology: a life cycle approach,
Journal of Sustainable Energy and environment, vol 2, no 2 (April-June 2011), p 45-50,
‹ 96-190-1-SM.pdf ›
http://journal.jgsee.org/index.php/JSEE/

Lako 1995
Lako P,
'Greenhouse gas emissions from nuclear power plant construction',
Part of: Assessment of greenhouse gas emissions from the full energy chain for nuclear power and other sources',
Working material, International Atomic Energy Agency, Vienna, Austria, 26 28 September 1995.

Lenzen et al. 2006
Lenzen M, Dey C, Hardy C & Bliek M,
Life-Cycle Energy Balance and Greenhouse Gas Emissions of Nuclear Energy in Australia,
A study undertaken for the Department of Prime Minister and Cabinet of the Australian Government,
ISA, The University of Sydney, 3 November 2006,
www.isa.org.usyd.edu.au/publicatiobs
www.isa.org.usyd.edu.au/publications/documents/ISA_Nuclear_Report.pdf

Lenzen 2008
Lenzen M,
Life cycle energy and greenhouse gas emissions of nuclear energy: A review,
Energy Conversion & Management 49 (2008) 2178-2199,
http://energiasostenible.org/mm/file/GCT2008%20Doc_ML-LCE%26Emissions.pdf

Lundberg 2011
Lundberg M,
Environmental analysis of zirconium alloy production,
Uppsala University, December 2011, ISSN 1401-5757,
UPTEC-F11061.
‹ FULLTEXT01.pdf ›
https://uu.diva-portal.org/smash/get/diva2:475527/FULLTEXT01.pdf
retrieved 19 Jan 2019

MIT 2003 + 2009
Deutch J et al.,
The Future of Nuclear Power. An Interdisciplinary MIT Study,
Massachusetts Institute of Technology, Cambridge MA, USA, 2003
ISBN 0-615-12420-8
http://www.mit.edu/afs/athena/org/n/nuclearpower/pdf
Update 2009
http://web.mit.edu/nuclearpower/

Mortimer 1977
Mortimer N D,
The Energy Analysis of Burner Reactor Power Systems,
PhD dissertation, Milton-Keynes Open University, UK,
December 1977.

MPR-2776 2005
Bubb J, Carroll D, D'Ollier R, Elwell L & Markel A,
DOE NP2010 Nuclear power plant construction infrastructure assessment,
prepared for Department of Energy, Washington DC,
MPR-2776,
21 October 2005,
www.ne.doe.gov/

Mudd 1998
Mudd G,
An environmental critique of in situ leach mining: The case against uranium solution mining,
A research report for Friends of the Earth (Fitzroy) with The Australian Conservation Foundation, July 1998,
www.sea-us.org.au/scifacts.html

Mudd 2000
Mudd G M,
Acid in-situ leach uranium mining: 2 - Soviet Block and Asia,
paper for: Tailings and Mine Waste '00,
Fort Collins, CO, USA, January 23-26 2000,
proceedings AA Balkema, Rotterdam, pp.527-536.
‹2000-TMW-AcidISL-FSU-Asia.pdf›
http://users.monash.edu.au/

Mudd 2011
Mudd G,
Uranium mining & CO2 accounting,
AusIMM Uranium Conference, Perth, 8 June 2011
file: 2011-06-08-AusIMM-U-Mining-v-Grade-v-CO2.ppt
www.ausimm.com.au/uranium2011/

Mudd & Diesendorf 2007
Mudd GM & Diesendorf M,
Sustainability Aspects of Uranium Mining: Towards Accurate Accounting?
2nd International Conference on Sustainability Engineering and Science,
Auckland, New Zealand, 20-23 February 2007.
www.nzsses.auckland.ac.nz/

Mutschler et al. 1976
Mutschler PH, Hill JJ, & Williams BB,
Uranium from the Chatanooga shale, Some problems involved in development,
PB-251-986,
Bureau of Mines, Pittsburg, USA, February 1976.

NREL 2013a
Life cycle greenhouse gas emissions from electricity generation,
National Renewable Energy Laboratory,
NREL/FS-6A20-57187, Januari 2013,
https://www.nrel.gov/docs/fy13osti/57187.pdf
retrieved 26 Dec 2018
see also webpage:
https://www.nrel.gov/analysis/life-cycle-assessment.html
retrieved 29 Dec 2018

NREL 2013b
Life Cycle Assessment Harmonization,
not dated, probably 2013 or later: refers to Q790 (2012) and Q798 [NREL 2013a][IPPV-AR5

https://www.nrel.gov/analysis/life-cycle-assessment.html
accessed 29 December 2018

NRMCA 2012
Concrete CO2 Fact Sheet,
NRMCA Publication Number 2PCO2, February 2012,
‹concrete CO2 fact sheet feb 2012.pdf›
www.nrmca.org/sustainability/
retrieved 17-12-2014

Odeh, Hill & Forster 2013
Odeh N, Hill N & Forster D,
Current and Future Lifecycle Emissions of Key 'Low Carbon' Technologies and Alternatives,
Final report, 17 April 2013
Ricardo-AEA, Ref ED58386
‹ Ricardo-AEA-lifecycle-emissions-low-carbon-technologies-April-2013.pdf ›
https://www.theccc.org.uk/wp-content/uploads/2013/04/Ricardo-AEA-lifecycle-emissions-low-carbon-technologies-April-2013.pdf

Orita 1995
Orita Y,
'Preliminary assessment on nuclear fuel cycle and energy consumption',
Part of: Assessment of greenhouse gas emissions from the full energy chain for nuclear power and other sources,
Working material, International Atomic Energy Agency, Vienna, Austria, 26 28 September 1995.

ORNL-TM-4515 1974
Bryan RH & Dudley IT,
Estimated quantities of materials contained in a 1000-MW(e) PWR power plant,
ORNL-TM-4515
Oak Ridge National Laboratory, June 1974.

Pehl et al. 2017,
Pehl M, Arvesen A, Humpenöder F, Popp A, Hertwich E G & Luderer G,
Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling,
Nature Energy, vol 2, December 2017, p.939-945.

Reister 1977
Reister, D.B.,
The energy embodied in goods,
ORAU/IEA(M)-77-6,
Institute for Energy Analysis, Oak Ridge Associated Universities, February 1977.

ResourcefulPaths 2016
What drives GHG emissions from copper production?
Resourceful Paths, November 2016.
http://www.resourcefulpaths.com/blog/2016/11/23/what-drives-ghg-emissions-from-copper-production
retrieved 19 Jan 2019

Roberts 1975
Roberts F,
'The convention conventions',
Energy Policy, December 1975, pp.345-347.

Roberts PC 1976
Roberts P C,
Energy analysis in modelling,
part of: Aspects of Energy Conversion,
Proceedings of a Summer School held at Lincoln College, Oxford, UK,
14-15 July 1975, pp 759-771.

Roberts PC 1982
Roberts, P.C.,
'Energy and value',
Energy Policy, September 1982, pp.171-180.

Rombough & Koen 1974
Rombough C T & Koen B V,
The total energy investment in nuclear power plants,
Technical Report ESL-31
Energy Systems Laboratories, College of Engineering, The University of Texas at Austin, November 1974.

Rombough & Koen 1975
Rombough C T & Koen B V,
Total energy investment in nuclear power plants,
Nuclear Technology, Vol 26 May 1975, pp 5-11.

Ross & Guglielmin 1968
Ross AH & Guglielmin LG,
Milling technology of uranium ores
Nuclear Applications, vol 5, nr 11, November 1968, pp 311-318.

Rotty et al. 1975
Rotty R M, Perry A M & Reister D B,
Net energy from nuclear power,
ORAU-IEA-75-3,
Institute for Energy Analysis, Oak Ridge Associated Universities, November 1975.

Scheidt 1995
Scheidt S vom,
'Kohärenz zwischen Brennstoff Auslegung und – Fertigung',
ATW 40, Heft 3, März, pp. 167 169, Jg 1995.

SDC 2006
The role of nuclear power in a low carbon economy – Paper 2: Reducing CO2 emissions – nuclear and the alternatives,
Sustainable Development Commission, March 2006,
http://www.sd-commission.org.uk/data/files/publications/Nuclear-paper2-reducingCO2emissions.pdf
retrieved 31 Dec 2018

Seneca 2015,
Krypton-85: How nuclear power plants cause climate change,
The Seneca Effect, 2015
https://thesenecaeffect.wordpress.com/2015/07/01/krypton-85-how-nuclear-power-plants-cause-climate-change/
retrieved Oct 2015

Setterwall 2005
Caroline Setterwall 051124 (Vattenfall AB)
Energy_per_lifecycle_phase_Ian_Martin_051124.xls

Forsmark NPP (nuclear power plant), reference year 2002
downloaded from: www.nuclearinfo.net

Shaw 1979
Shaw K R,
Capital cost escalation and the choice of power stations,
Energy Policy, December 1979, pp 321-328.

Simonson et al. 1980
Simonson HA, Boydell DW & James HE,
The impact of new technology on the economics of uranium production from low-grade ores
paper in:
Uranium and nuclear energy
Proceedings Fifth International Symposium by The Uranium Institute, London, July 2-4, 1978, pp 92-180.

Sovacool 2008
Sovacool B K,
Valuing the greenhouse gas emissions from nuclear power: A critical survey,
Energy Policy 36 (2008), p.2940-2953.
www.sciencedirect.com/science/article/pii/S0301421508001997

Spreng 1988
Spreng D T,
Net-energy analysis and the energy requirements of energy systems,
Oak Ridge Associated Universities (ORAU)
Praeger Publishers, New York NY, 1988
ISBN: 0-275-92796-2.

SRI 1975
Manpower, materials, equipment and utilities required to operate and maintain energy facilities,
PB 255 438,
Stanford Research Institute (SRI), Menlo Park, CA, March 1975,
prepared for Bechtel Corporation, San Francisco CA and National Science Foundation.

Storm 1985
Storm van Leeuwen JW,
'Nuclear Uncertainties. Energy Loans for fission power',
Energy Policy, pp. 253-266, June 1985.

Storm & Smith 2005 & 2008
Storm van Leeuwen J W & Smith Ph B,
Nuclear power - the energy balance
Ceedata, Chaam (Netherlands), 2005, update 2008
www.stormsmith.nl

Storm 2007
Storm van Leeuwen J W,
Nuclear power - the energy balance,
Part F. Reactor construction, operation, maintenance, refurbishments, decommissioning and dismantling,
December 2007
www.stormsmith.nl/reports

Storm 2015
Storm van Leeuwen J W,
Can nuclear power slow down climate change?
commissioned by the World Information Service on Energy (WISE), November 2015,
supported by 7 international NGOs,
report for tge United Nations Climate Change Conference CoP 21,
Paris, 30 november - 12 december 2015
sponsored by The Greens in the European Parliament,
ISBN 978-90-71947-50-6
https://www.wiseinternational.org/sites/default/files/u93/F4%201nuclGHGshare-ED.pdf
https://www.wiseinternational.org/sites/default/files/u93/SummaryJWSvL%20Nov15.pdf
https://rationalwiki.org/wiki/Krypton-85_and_climate_change

Storm 2017
Storm van Leeuwen J W,
Climate change and nuclear power,
commissioned by the World Information Service on Energy (WISE), October 2017,
supported by 8 international NGOs,
report for the United Nations Climate Change Conference CoP 23, Bonn, 6-17 november 2017
ISBN 978-90-71947-54-4
https://wiseinternational.org/sites/default/files/u93/climatenuclear.pdf
http://www.dont-nuke-the-climate.org/wp-content/uploads/2017/05/climatenuclear.pdf
indirectly:
http://www.nonuclear.se/en/climate-nuclear-storm-van-leeuwen2017

Thomas 2005
Thomas, Stephen,
The Economics of Nuclear Power,
Nuclear Issues Papers, No. 5,
Heinrich Böll Foundation 2005,
co-published by WISE,
www.boell.de

Thomas et al. 2007
Thomas S, Bradford P, Froggatt A & Milborrow D,
The economics of nuclear power,
Report prepared for Greenpeace International,
Amsterdam, May 2007,
www.greenpeace.org

Tyner et al. 1988
Tyner Sr G, Constanza R & Fowler R G,
'Net energy yield of nuclear power',
Energy, vol.13, no.1, 1988, pp.73-81.

Uchiyama 2002
Uchiyama Y,
LCA information, personal communication, fax dated 8 Febr 2002.

UK-EPR 2007
UK-EPR. Fundamental safety overview. Volume 1: Head Document. Chapter A: EPR design description.
AREVA NP & EDF, 2007
‹ 1.A - EPR Design Description - v3.pdf ›
http://www.epr-reactor.co.uk/ssmod/liblocal/docs/V3/Volume%201%20-%20Overview/1.A%20-%20EPR%20Design%20Description/1.A%20-%20EPR%20Design%20Description%20-%20v3.pdf
accessed 20 Jan 2018

UK-EPR-Dsum 2007
UK-EPR. Fundamental safety overview. Volume 2: Design and safety. Chapter D: Reactor and core. Sub-chapter D-1 Summary description of the core and fuel assemblies.
not dated, presumably 2007
‹ 2.D.1- Summary Description - v2.pdf ›
http://epr-reactor.co.uk/ssmod/liblocal/docs/V3/Volume%202%20-%20Design%20and%20Safety/2.D%20-%20Reactor%20and%20Core/2.D.1%20-%20Summary%20Description%20-%20v2.pdf
accessed 20 Jan 2018

UNEP 2016
Green energy choices: the benefits, risks and trade-offs of low-carbon technologies for electricity production,
United Nations Environment Programme, 2016,
ISBN 978-92-807-3490-4
The full report should be referenced as follows:
UNEP (2016) Green Energy Choices: The benefits, risks and trade-offs of low-carbon technologies for electricity production. Report of the International Resource Panel. E.G. Hertwich, J.Aloisi de Larderel, A.Arvesen, P.Bayer, J.Bergesen, E.Bouman, T.Gibon, G.Heath, C. Peña, P.Purohit, A.Ramirez, S.Suh, (eds.).
http://www.resourcepanel.org/reports/green-energy-choices-benefits-risks-and-trade-offs-low-carbon-technologies-electricity
also:
https://www.uncclearn.org/sites/default/files/inventory/-green_energy_choices_the_benefits_risks_and_trade-offs_of_low-carbon_technologies_for_electricity_production-2016unep_gec_web.pdf_1.pdf
retrieved 28 Dec 2018

Vattenfall 2001a
Vattenfall AB Generation Nordic Countries,
The Nuclear Fuel Cycle,
Executive Summary of:
Vattenfall Generation's Certified Environmental Product Declaration of Eelectricity from Forsmarks Kraftgrupp AB (FKA),, pdf
www.environdec.com

Vattenfall 2001b
Vattenfall AB Generation Nordic Countries,
Appendix to:
EPD: Certified Environmental Product Declaration of Eelectricity from Forsmarks Kraftgrupp AB (FKA),
S-P-00021
June 2004, updated 2005.
www.environdec.com

Vattenfall 2005
Vattenfall AB Generation Nordic Countries,
EPD: Certified Environmental Product Declaration of Eelectricity from Forsmarks Kraftgrupp AB (FKA),
S-P-00021
June 2004, updated 2005.
www.environdec.com

Voorspools et al. 2000
Voorspools K R, Brouwers E A, D'haeseleer W,
Energy content and indirect greenhouse gas emissions embedded in 'emission-free' power plants: results for the Low Countries,
Applied Energy, vol 67, no 3, 1 November 2000, pp. 307-330.
‹ Voorspools-Brouwers-D'haeseleer-AE 67(2000)307-330.pdf ›
not free on web, purchase:
https://www.sciencedirect.com/science/article/pii/S0306261900000167

Warner & Heath 2012
Warner E S & Heath G A,
Life Cycle Greenhouse Gas Emissions of Nuclear Eelectricity Generation. Systematic Review and Harmonization,
NREL/JA-6A20-48514
Journal of Industrial Ecology, vol 16 (Supplement 1) April 2012, pp. S73 -S92.
www.wileyonlinelibrary.com/journal/jie
https://www.nrel.gov/research/garvin-heath.html

White 1998
White SW,
"The energy payback and CO2 gas emissions from helium-3 fusion and wind electrical power plants,
Ph.D. Thesis, at the University of Wisconsin, Madison, December 1998,
UWFDM-1093
Fusion Technology Institute, University of Wisconsin, Madison, Wisconsin,
‹ fdm1093.pdf ›
http://fti.neep.wisc.edu/

WISE-Ua 2015
Impacts of uranium in-situ leaching
WISE Uranium Project,
updated 9 Jan 2015
‹ Impacts of uranium in-situ leaching ›
http://www.wise-uranium.org/uisl.html
retrieved Sept 2018

WMO 2000,
Global Atmosphere Watch Measurements Guide,
World Meteorological OrganizationGlobal Atmosphere Watch,
WMO TD No. 1073,
not dated, presumable 2000,
‹ 7530.pdf ›
http://www.empa.ch/plugin/template/empa/*/7530
retrieved Oct 2015

WNA-CO2 2016
CO2 implications of electricity generation,
World Nuclear Association, November 2016
‹ CO2 implications of electriciry generation - World Nuclear Association.pdf›
http://www.world-nuclear.org/information-library/energy-and-the-environment/co2-implications-of-electricity-generation.aspx
retrieved December 2018

WNA-eroi 2016
Energy return on investment,
World Nuclear Association, updated November 2016
http://www.world-nuclear.org/information-library/energy-and-the-environment/energy-analysis-of-power-systems.aspx
retrieved June 2017

WNA-mining 2016
Uranium mining overview,
World Nuclear Association, uodated February 2016
‹ Uranium mining overview - World Nuclear Association.pdf ›
http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview.aspx
retrieved 11 April 2018

WNA-Ugeol 2015
Geology of uranium deposits,
World Nuclear Association, February 2015
‹ Geology of uranium deposits - World Nuclear Association.pdf ›
http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/geology-of-uranium-deposits.aspx
retrieved 11 April 2018