Life-cycle nuclear CO_2 emissions

Jan Willem Storm van Leeuwen
Independent consultant

member of the Nuclear Consulting Group

September 2019

storm@ceedata.nl

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.

Contents

Nuclear energy system

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.

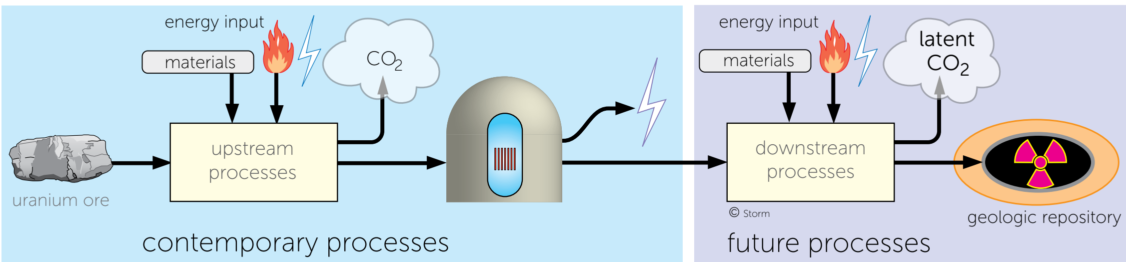

Figure 1
Outline of the nuclear energy system from cradle to grave, as analysed in this study. The query symbolises the uncertain future of the nuclear legacy.

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 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*.
This study compares the CO_2 emission of the reference advanced reactor with the official EPR design.

Assessment method

This study assesses by means of a physical/thermodynamic analysis the energy investments and CO_2 emissions of all processes needed to complete the processes of the nuclear chain from cradle to grave, assumed it will be finished in the safest possible way. The structure of the thermodynamic analysis is represented by Figure 2.

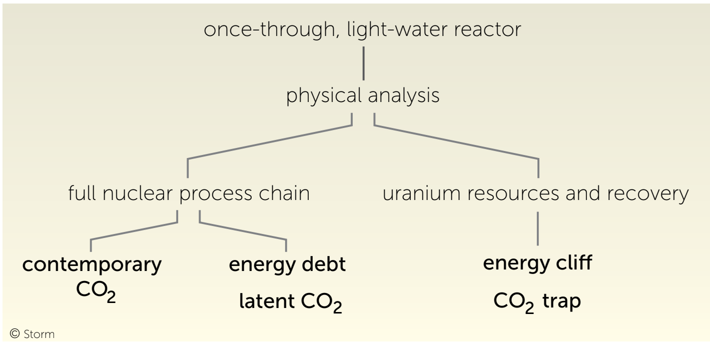

Figure 2
Outline of the physical assessment of nuclear power in this study.

Complete nuclear process chain

For estimation of the lifetime CO_2 emissions of nuclear power, the industrial processes comprising the nuclear process chain are divided into two categories: *contemporary processes*, occurring in advance of and during the operational lifetime of the nuclear power plant, and the *future processes*, occurring after final shutdown of the power plant. The contemporary processes encompass the upstream processes, needed to recover uranium from ore and to fabricate fuel elements for the reactor, in addition to construction of the nuclear power plant and operation, maintenance + refurbishments during the operational lifetime of the reactor. The future processes encompass the activities needed to manage all radioactive waste generated during operation of the nuclear power plant in the safest possible way and to isolate the radioactive waste from the biosphere.
Each process of the nuclear chain generates radioactive waste and non-radioactive waste. In this study the scope is limited to radioactive waste. The radioactive waste of the upstream processes, from ore to fuel, contain only naturally occurring radio-isotopes: uranium and thorium plus their decay products. During operation of the reactor the radioactivity of the involved materials rises a billionfold, caused by the generation of dozens of human-made radionuclides, in addition to uranium isotopes. This radioactivity is contained in spent fuel and in materials of the reactor plus associated installations.

Purpose of the downstream processes is to avoid dispersion of these hazardous materials into the biosphere. This study starts from the viewpoint that all radioactive materials should be isolated from the biosphere. To that end the wastes are packed in appropiate containers that are disposed of in geologic repositories. In practice not all radioactive waste of the nuclear chain can be packed in containers, that are, mining waste and radioactive effluents (authorised and unintended discharges) from the nuclear power plant during its operational lifetime.

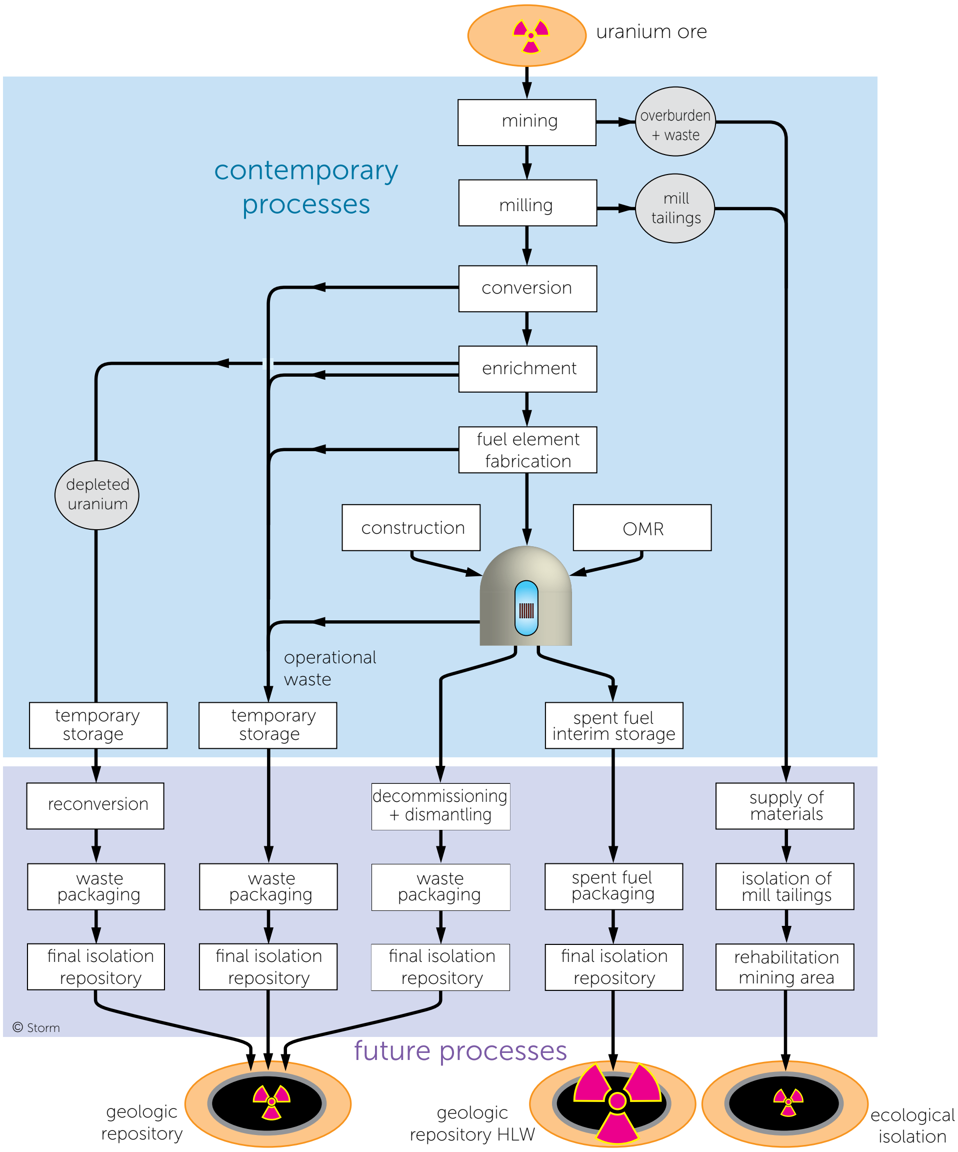

Figure 3

Complete nuclear process chain, divided into two subchains: the contemporary processes (front end or upstream processes) and the future processes (back end or downstream processes of the nuclear process chain). OMR = operation, maintenance and refurbishments. HLW = high-level waste.

Uranium mining + milling

Process analysis of the first step in the nuclear process chain, the recovery of uranium from the earth's crust, proves that currently known uranium resources comprise ore bodies with widely divergent properties. These differences result in large uncertainty ranges in the figures of specific energy requirements and specific CO_2 emissions. of uranium mining + milling.

Table 1
Specific CO_2 emission (gCO_2/kWh) of the uranium recovery for 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

Related reports

Details and explanations can be found in a number of related reports:
m01 *Uranium-plutonium breeder systems*
from the Second Law of thermodynamics follows that closed-cycle reactor systems as net energy systems are infeasible
m03 *Contemporary CO_2 emissions of nuclear power*,
detailed analysis of upstream processes + construction + operation, maintenance, refurbishments.
m04 *Decommissioning and dismantling*
m06 *Energy analysis: the method*,
description of the methodology of thermodynamic energy analysis of energy systems.
m07 *Energy debt, latent CO_2, latent entropy*
m09 *Emission of other greenhouse gases by nuclear power*
m10 *Global context and prospects of nuclear power*
addresses the present nuclear contribution to the world energy supply (1.6%) and the future potential nuclear contribution to mitigation of the CO_2 emission
m19 *Characteristics of advanced reference reactor and EPR design*,
m24 *Thorium for fission power*
from the Second Law of thermodynamics follows that thorium reactor systems as net energy systems are infeasible
m26 *Uranium mining + milling*
detailed process analysis of the recovery of uranium from the earth's crust, energy cliff and CO_2 trap
m32 *Geologic repositories*
m35 *Energy cliff and CO_2 trap*
m38 *Nuclear power and the Second Law*
m39 *Construction and OMR of nuclear power plants*
m40 *Radioactive waste management*,
detailed analysis of the downstream processes, future energy investments and CO_2 emissions
m41 *Uranium mine rehabilitation*

Contemporary processes

Contemporary CO_2 emissions

Table 2

Lifetime CO_2 emissions of the contemporary processes, excluding waste management and final disposal. The uncertainty range of the uranium mining + milling figures is caused by different conditions at the operational uranium mines; the ore grade varies roughly from 0.1% to 0.05% U_3O_8 and the mineralogy varies widely, in this study simplified to 'soft ores' and 'hard ores'. 'Low' means: soft ores at a grade of 0.1% U_3O_8, and 'high' means hard ores at a grade of 0.05% U_3O_8.

process	g CO_2/kWh		total CO_2, Gg	
	advanced reactor	EPR design	advanced reactor	EPR design
uranium mining + milling, low	7.1	6.2	1.55	4.82
mean	32.3	28.2	7.04	21.97
high	57.4	50.1	12.53	39.11
refining + conversion	2.8	2.5	0.62	1.91
enrichment	2.6	2.4	0.57	1872
reconversion + fuel fabrication, incl zircalloy	3.4	2.5	0.74	1.93
construction	24.9	8.4	5.45	6.52
reactor OMR	24.4	18.1	5.34	14.10
sum contemporary processes - low	65	40	14	31
mean	90	62	20	48
high	116	84	25	65

.

The figure of the specific CO_2 emission of construction of the nuclear power plant has a considerable uncertainty range (± 50%), of similar magnitude as the range of the mining + milling values. In Table 2 the average value is shown, the uncertainty range is not indicated.

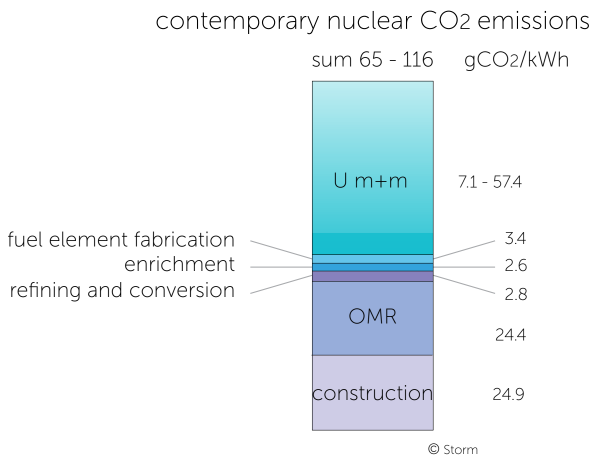

Figure 4

Contemporary CO_2 emissions of the advanced reference reactor. OMR = operation, maintenance and refurbishments of the nuclear power plant. U m+m = uranium mining + milling

Comtemporary energy investments

Table 3

Lifetime energy investments of the contemporary processes, excluding waste management and final disposal. The uncertainty range of the uranium mining + milling figures is caused by different conditions at the operational uranium mines; the ore grade varies roughly from 0.1% to 0.05% U_3O_8 and the mineralogy varies widely, in this study simplified to 'soft ores' and 'hard ores'. 'Low' means: soft ores at a grade of 0.1% U_3O_8, and 'high' means hard ores at a grade of 0.05% U_3O_8.

process	advanced reactor		EPR design	
	*E*e + *E*th PJ	*E*th PJ	*E*e + *E*th PJ	*E*th PJ
uranium mining + milling, low	20.7	20.7	64.3	64.3
mean	94.4	94.4	293	293
high	168	168	521	521
refining + conversion	8.5	8.2	26.4	25.5
enrichment	10.4	7.6	27.8	25.0
reconversion + fuel fabrication	2.2	1.6	5.8	4.1
construction	80	66.2	96	79.4
reactor OMR	86	71	227	188
sum contemporary processes - low	208	175	447	386
mean	282	249	676	615
high	355	323	904	843

Future processes

Future (latent) CO_2 emission

Table 4

Lifetime CO_2 emissions of the future processes, including waste packaging and final waste disposal of the upstream processes.

	process	g CO_2/kWh		total CO_2, Gg	
		advanced reactor	EPR design	advanced reactor	EPR design
1	refining + conversion waste managem. + disposal	0.65	0.40	0.14	0.31
2	enrichment waste management + disposal	0.37	0.34	0.08	0.27
3	reconv. + fuel fabr. waste managem. +disposal	0.90	0.56	020	0.44
4	reactor OMR waste management + disposal	12.06	7.44	2.64	5.81
	sum waste managem.. + disp. upstream processes 1-4	14.0	8.74	3.06	6.83
5	depleted uranium conditioning + waste man. + disp.	5.7	5.1	1.255	3.95
6	decommissioning + dismantling + waste man. + disp.	40.9	13.6	8.95	10.63
7	spent fuel handing + final disposal	8.2	5.9	1.80	4.64
8	mine rehabilitation	4.8	4.2	1.06	3.30
	sum downstream processes 5-8	60	29	13	23
	sum future processes	74	58	16	29

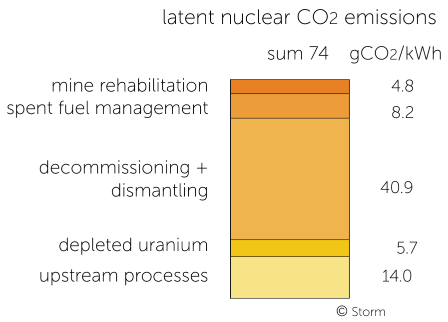

Figure 5

Future (latent) CO_2 emissions of the advanced reference reactor. The future processes include conditioning and final disposal of all radioactive wastes, including the waste of the upstream processes.

Future energy investments (energy debt)

Table 5
Lifetime energy investments of the future processes, including waste packaging and final waste disposal of the upstream processes.

	process	advanced reactor		EPR design	
		*E*e + *E*th PJ	*E*th PJ	*E*e + *E*th PJ	*E*th PJ
1	refining + conversion waste managem. + disposal	2.1	1.9	4.7	4.2
2	enrichment waste management + disposal	1.2	1.1	4.0	3.6
3	reconv. + fuel fabr. waste managem. +disposal	3.0	2.6	6.5	5.8
4	reactor OMR waste management + disposal	40.0	35.3	87.0	77.7
	sum waste managem + disposal processes 1-4	45.8	40.9	102.2	91.3
5	depleted uranium conditioning + waste man. + disp.	18.0	16.6	57.1	52.6
6	decommissioning + dismantling + waste man. + disp.	140.0	119.3	166.3	141.6
7	spent fuel handing + final disposal	26.9	21.2	69.4	51.8
8	mine rehabilitation	14.7	14.1	45.6	43.9
	sum downstream processes 5-8	200	171	338	290
	sum future processes 1-8	245	212	441	381

Summary cradle-to-grave CO_2 emissions

Table 6

Summary lifetime CO_2 emissions of the complete nuclear process chain from cradle to grave

process	g CO_2/kWh		total CO_2, Gg	
	advanced reactor	EPR design	advanced reactor	EPR design
sum contemporary processes - low	65	40	14.27	31.16
mean	90	62	19.75	48.30
high	116	84	25.24	65.44
sum future processes	74	38	16112	29.34
total nuclear process chain from cradle to grave low	139	78	30.38	60.50
mean	164	100	35.87	77.64
high	190	122	41.35	94.78

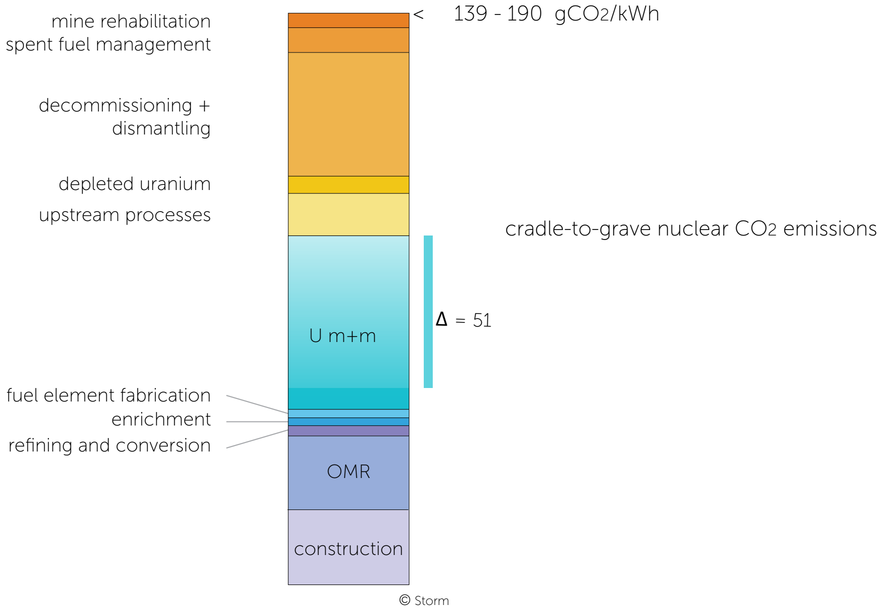

Figure 6

Lifetime CO_2 emission of nuclear power, based on the advanced reference reactor: contemporary + latent CO_2. OMR = operation, maintenance + refurbishments of the nuclear power plant. U m+m = uranium mining + milling; the large value range (Δ = 51 gCO_2/kWh) is caused by widely diverging conditions at the currently operational uranium mines.