CO2 emissions of nuclear power: the whole picture

Jan Willem Storm van Leeuwen

'Nuclear power is a clean means to generate electricity. At least, it causes no CO2 emissions.' Based on this view some environmental activists became proponents of nuclear power, for fear of the disastrous consequences of climate change. At first glance they seem to be right: nuclear power stations are silent, clean and (usually) operate reliably day and night, summer and winter. But alas, also in this case it's no free lunch. Nuclear power causes CO2 emissions indeed, and at a growing rate.

In a nuclear reactor enriched uranium is being fissioned, releasing heat. The heat is converted into electricity by means of steam turbines. Enriched uranium, the fuel for the nuclear reactor, is produced from uranium ore by means of a sequence of industrial processes. Uranium ore is recovered from the earth's crust at several places in the world.

When a certain portion of the uranium has been fissioned, the nuclear fuel has to be removed from the reactor, because the fuel is not suitable anymore for energy production. About once every year the spent fuel has to be replaced by fresh nuclear fuel. The question arises: what happens with the spent nuclear fuel?

Process chain

The technical system aimed at generating electricity from uranium has three components:

1. Upstream processes: needed to produce nuclear fuel from uranium ore in the earth's crust.
2. Mid-section: construction and operation of the nuclear power plant.
3. Downstream processes: needed for safe disposal of all radioactive wastes generated during the operational life of the nuclear power plant.

The three-component structure of a process chain – upstream processes, mid-section and downstream processes – is also valid for fossil-fueled power stations, actually for nearly all production processes.

Upstream part of the nuclear process chain

The upstream processes comprise the recovery of uranium from the earth's crust, transport, refining and conversion into a gaseous uranium compound, enrichment and fabrication of fuel elements that can be placed into the nuclear reactor. Without these upstream processes nuclear power would be impossible. Without nuclear power these processes would not exist. Each process consumes energy (electricity and fossil fuels) and emits CO2 into the atmosphere. Especially the recovery of uranium from the earth's crust consumes large amounts of fossil fuels and produces much CO2.

The average uranium content of the globally exploited ores decreases as more ore is mined, due to the fact that the easiest accessible and richest available ores are mined firstly. The richest ores offer the highest return on investment for the mining companies. The lower the uranium content, the more rock has to be mined and chemically treated and the more energy is consumed to extract one kilogram of uranium. Below a certain ore grade, the recovery of 1 kg uranium consumes as much energy as can be generated from 1 kg uranium in a nuclear power plant. This phenomenon is called the energy cliff of uranium ore. This conclusion is based on a physical analysis of data published by uranium mining companies during many years.

Construction

Construction of a modern nuclear power plant consumes about 850,000 tons of concrete and about 150,000 tons of steel, plus thousands of tons of other materials. The production of these construction materials and of the equipment of the plant consumes a lot of energy, accompanied by substantial CO2 emissions. The construction activities themselves contribute also to the CO2 emissions.

Operation, maintenance and refurbishments

The nuclear reactor is the sole component of the nuclear process chain that does not emit CO2. This fact may be the source of the incorrect view that nuclear power would be CO2 free. All other processes of the nuclear system, without which a nuclear power plant cannot produce electricity, do emit CO2.

During the fission process in the reactor, the radioactivity of the nuclear fuel and the surrounding materials increase a billion-fold. This increase is caused by the generation of fission products and activation products. Activation is the phenomenon that non-radioactive materials, such as concrete and steel, become radioactive by irradiation by neutrons from the fission process. It is impossible to artificially reduce the radioactivity of a material, or to make it less harmful. Radioactivity is harmful to all living organisms.

Numerous radioactive components of the power plant have to be replaced one or more times during the operational lifetime of the plant. In the end the reactor vessel may be one of the few original components that are not replaced. Operation, maintenance and refurbishments of a nuclear power plant consume considerable amounts of energy and emit CO2.

Downstream part of the nuclear process chain

An old Latin verb says: 'In cauda venenum', in the tail is the venom. This verb might apply to nuclear power. Due to the generation of large amounts of human-made radioactivity the spent nuclear fuel is strongly radioactive and remains so for long periods. The specific activity of spent fuel decreases with time due to natural decay of the radionuclides. After 1,000 years the specific activity of spent fuel is still a million times higher than the lethal level for human beings. An operating nuclear power plant generates each year an amount of artificial radioactivity corresponding to more than 1000 times the amount that is released by the explosion of one nuclear bomb of 15 kilotons (Hiroshima bomb).

The largest part of the human-made radioactivity is retained in the spent fuel elements at the moment of discharge from the reactor. In addition, a considerable amount of radioactivity is dispersed in thousands of tons of construction materials. These materials are released at the decommissioning and dismantling of the nuclear power plant after closedown. What should happen with these radioactive materials?

During the past decades various concepts have been proposed for definitive disposal of radioactive materials. According to the nuclear industry the radioactive waste issue is not a problem. However, a fact is that after 70 years of civil nuclear power, all human-made radioactive materials are still stored at vulnerable temporary storage facilities.

The sole way to prevent more dispersal of radioactive materials into the human environment is to isolate the materials from the biosphere for periods of hundreds of thousands of years. There are designs of definitive disposal facilities in galleries deep in geologically stable formations. Nowhere on earth is such a geologic repository operational for high-level nuclear wastes. Sweden and Finland are the farthest with the construction of geologic repositories for spent fuel and for other radioactive wastes. Construction of a geologic repository and sequestering the radioactive wastes are energy-intensive and produce large amounts of CO2.

Another important part of the downstream processes is the decommissioning and dismantling of the nuclear power plant at the end of its operational lifetime. Globally some 600 nuclear power plants are to be dismantled some day. The mass of radioactive debris and scrap released from one nuclear power station may amount to some 100,000 tons at various levels of radioactivity. The radioactivity is caused by neutron irradiation and contamination with radionuclides during the operational life of the plant. Some 10,000 tons are expected to be classified as high-level waste.

In addition, many thousands of cubic meters of contaminated soil are to be considered radioactive waste, due to leaks and small accidents. First estimates of dismantling nuclear power plants in the UK and in Switzerland point to a cost as high as the construction cost, or even higher. It is not clear if these estimates include cleanup of the plant site and final disposal of the radioactive debris and scrap.

According to the nuclear industry, dismantling should occur many decades after final shutdown and will take a period of at least 10 years. How much energy and human effort will be needed? Who will pay these activities some 60–100 years after final shutdown?

No new technology is needed to adequately finish the downstream processes. Geologic repositories are similar to deep underground mines. Energy consumption and CO2 emissions of other downstream processes can reliably be estimated based on similar industrial processes without radioactive materials. Energy consumption and CO2 emission of all downstream processes together prove to be about as large as those of the upstream processes including construction and operation of the nuclear power plant.

Contemporary CO2 emissions and latent CO2 emissions of nuclear power

The CO2 emissions of the upstream processes, construction and operation are called the contemporary CO2 emissions, because they occur before and during the operation of the nuclear power plant. By means of a physical analysis of all processes and activities separately it is possible to reliably estimate the contemporary CO2 emission of nuclear power. The methodology was developed during the 1970s and 1980s and has been peer reviewed extensively by international peer groups. The used data originate exclusively from the nuclear industry. The model nuclear power plant in this analysis corresponds with the newest nuclear power plants presently operating. The assumed lifetime electricity production is higher than the current global average. Energy consumption and CO2 emission of uranium mining plus milling is calculated based on data published by the mining industry.

The CO2 emission of the downstream processes, that is inextricably coupled to the present application of nuclear power, will occur in the future, long after closure of the nuclear power plant. For that reason these postponed emissions are called the latent CO2 emissions of nuclear power. The latent emissions are hidden in the future and are usually not taken into account.

A physical analysis of the complete nuclear process chain comes to estimates of the contemporary CO2 emission of 65–116 grams CO2 per kilowatt-hour delivered electricity, and of the latent emission of 74 g CO2/kWh. The spread of the figures of the contemporary emissions is caused by differences of the presently operational uranium mines. The differences result from different properties of the mined uranium ore, such as the ore grade and the chemical composition of the ore. The CO2 emissions of the uranium mining plus milling increase as more ore is mined, because the richest ores are mined first, so the remaining ores are leaner.

Table 1. Contemporary CO2 emissions of nuclear power

PROCESS	g CO2/kWh
uranium mining + milling, low, rich ores	7.1
average	32.3
high, lean ores	57.4
refining + conversion	2.8
enichment (ultracentrifuge)	2.6
conversion + fuel element fabrication, including zircalloy production	3.4
construction of the nuclear power plant	24.9
operation + maintenance + refurbishments of the power plant	24.4
sum emissions of contemporary processes – low	*65*
average	*90*
high	*116*

Table 2. Latent (future) CO2 emissions of nuclear power

PROCESS	g CO2/kWh
definitive isolation of the radioactive waste of the upstream processes	14,0
conversion and definitive isolation of depleted uranium	5.7
dismantling of the nuclear power plant, inclusief definitive isolation of the debris	40.9
interim storage and definitive isolation of the spent fuel	8.2
rehabilitation of a proportional part of the uranium mine	4.8
sum emissions of future processes	*74*

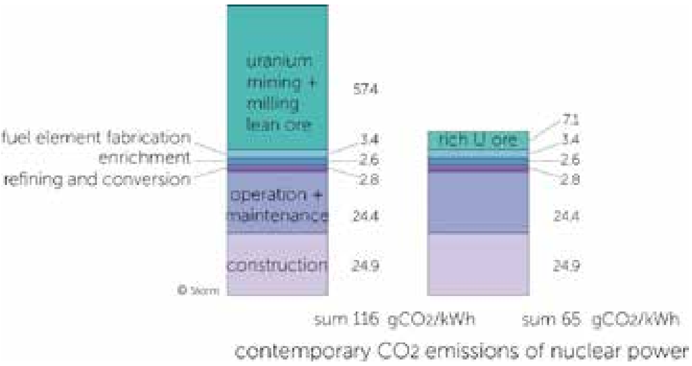

Figure 1: Contemporary CO2 emissions of nuclear power

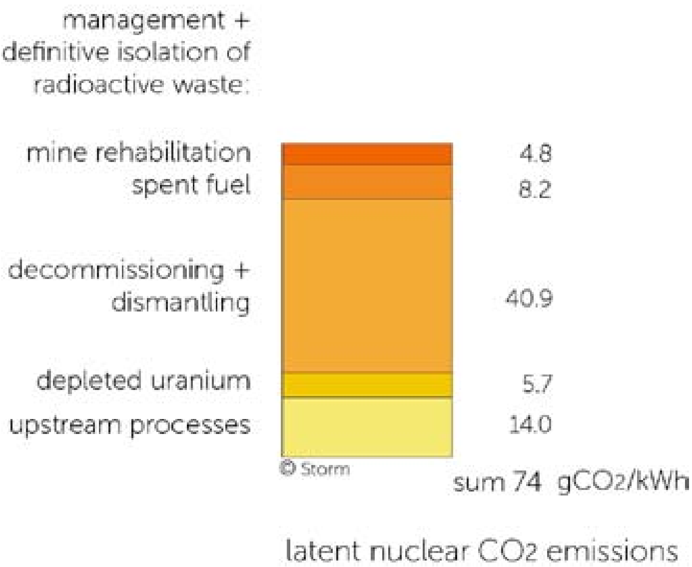

Figure 2: Latent CO2 emissions of nuclear power

CO2 trap of nuclear power

To keep the global nuclear capacity constant at the present level, about 370 GWe, each year until 2060 nine new nuclear power plants should be connected to the grid. The present construction rate is far lower than nine plants a year for a period of 40 years. During the coming four decades nearly all currently operating nuclear power plants would reach the end of their technical lifetime and have to be closed down.

Assumed that the global nuclear capacity would remain constant, the average CO2 emissions of nuclear power would become higher than 400 g CO2/kWh after the year 2070. With this figure nuclear power comes into the same emission range as fossil fuelled power stations. This phenomenon is called the CO2 trap of nuclear power. The chance is dim of discovery of major new rich uranium ore deposits, by which the CO2 trap could be postponed to a later year. During the past four decades no such deposits have been discovered, despite extensive exploration.

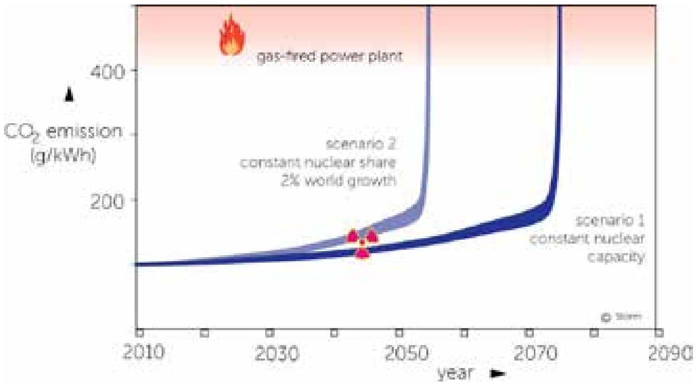

Figure 3: The nuclear CO2 emissions are rising with time, because the richest uranium ores get depleted and the available ores become leaner. Consequently the energy investments for recovery of uranium from the crust are rising with time. During the past 3-4 decades no new large rich uranium deposits have been discovered.

Visibility of upstream and downstream activities

The downstream processes of the nuclear energy system are usually invisible to the public, because they occur at other places far from the nuclear power plant, often on different continents. Moreover, large time differences may play a part: downstream processes can be invisible because they have not yet taken place.

These facts may contribute to the incorrect view that a nuclear power plant is a stand-alone system, and consequently that for calculation of the CO2 emissions of nuclear power only the power plant itself has to be taken into account. Usually construction, operation and maintenance of the power plant are also left outside the scope. Actually the specific CO2 emissions of nuclear power is identical to the emissions of the whole cradle-to-grave sequence of processes that makes nuclear power generation possible.

Nuclear legacy

The downstream part of the nuclear chain involves a nuclear legacy for future generations. During the disasters of Chernobyl and Fukushima jointly an amount of artificial radioactivity has been globally dispersed about equal to the production of one nuclear power plant during one year. This amount corresponds with only 0.01% of the amount of human-made radioactivity that is temporarily stored within the biosphere at vulnerable temporary storage facilities. Further dispersion of the human-made radioactive materials will certainly occur,

potentially causing disasters that may dwarf Chernobyl and Fukushima, if man does not invest adequate amounts of energy and human effort to prevent that.
The Second Law of thermodynamics is relentless.

Prospects of nuclear power

In 2018, the global gross energy production of all energy sources jointly was 585 exajoule. The share of nuclear power was 10 exajoule, not more than 1.7%. From these figures it follows that globally the nuclear contribution to CO_2 reductions is minor, even if nuclear power was free of CO_2 emissions.

How are the prospects for nuclear power? The most advanced types of currently operational nuclear power plants cannot fission more than 0.5% of the uranium nuclei present in natural uranium as found in nature. Since the dawn of civil nuclear power in the 1950s, the nuclear industry is working on nuclear energy systems, based on a uranium-plutonium cycle, that would be able to fission 30-50% of the nuclei in natural uranium.

However, an operating nuclear power plant that could fulfil this promise has never been realized in practice. After seven decades of research in seven countries and investments of hundreds of billions of dollars, this type of nuclear power plant is fading off the scene. This failure can be explained by reason of technical problems and limitations arising from phenomena governed by the Second Law of thermodynamics.

Research on the use of thorium as a net energy source, based on a thorium-uranium cycle, started also in 1950s. Thorium is not fissionable and has to be converted into fissionable uranium in a nuclear reactor The technical problems and limitations arising from the Second Law of thermodynamics apply all the more so to nuclear power plants based on thorium. Development of thorium-based energy systems was halted during the 1970s.

From the above observations it follows that nuclear power in the future has to rely exclusively on the currently operational nuclear reactor technology.

Conclusions

The view that nuclear power is free of CO_2 emissions turns out to be a fallacy, originating from disregarding construction, operation, maintenance, upstream processes and downstream processes of a nuclear power plant.

Actually, the specific CO_2 emission of nuclear power is the same as the joint emission of all processes without which nuclear power would be impossible.

The cradle-to-grave CO_2 emission of nuclear power is 139-190 g CO_2/kWh, the sum of the contemporary emissions (65-116 g CO_2/kWh) and the latent emissions (74 g CO_2/kWh). These figures are the result of a comprehensive physical analysis of data on all involved processes published by the nuclear industry during the past years.

CO_2 trap. The CO_2 emission of nuclear power will rise in the future, due to depletion of rich uranium ores. If the world nuclear capacity would remain constant at the present level, the nuclear CO_2 emission will surpass the emission of gas-fired power plants after the year 2070.

Nuclear legacy. The downstream processes of nuclear power plants must be performed in such an effective way that nuclear disasters will be prevented that may dwarf the disasters at Chernobyl and Fukushima.

Energy debt. The present use of nuclear power leaves behind a substantial energy debt for the future generations. It comprises the future energy investments required to complete the downstream processes adequately.

In 2018 the world energy supply of all energy sources jointly was 585 exajoule. The share of nuclear power was 10 exajoule, not more than 1.7%.

The most advanced types of nuclear power plants that are currently operational, or will become operational, cannot fission more than 0.5% of the uranium nuclei present in natural uranium.

Net energy production by reactor systems that, according to the nuclear industry, could fission 30-50% of the uranium nuclei in natural uranium proved to be infeasible.

Thorium-based nuclear power plants proved to be infeasible as well.

Failures of both the uranium-plutonium and the thorium-uranium systems can be attributed to phenomena governed by the Second Law of thermodynamics.

Also in the future nuclear power has to based solely on the present reactor technology.

Background documents

Descriptions of the processes, calculations, methodology and references to used publications can be found in the following reports which can be downloaded from www.stormsmith.nl/reports.html. It should be emphasized that all data used in this analysis originate from publications of the nuclear industry and associated official institutions and from uranium mining companies.

Global context and prospects of nuclear power
Uranium-plutonium breeder systems
Thorium for fission power
Contemporary CO2 emissions of advanced nuclear power
Decommissioning and dismantling
Methodology of energy analysis
Energy debt, latent CO2 emissions, latent entropy
Emission of non-CO2 greenhouse gases
Life-cycle nuclear CO2 emissions
Advanced reference reactor and EPR
Uranium mining + milling
Uranium for energy resources
Unconventional uranium resources
Uranium from seawater
Energy cliff and CO2 trap
Industrial views on radioactive waste
Geologic repositories and waste conditioning
Problems for the future – message to the future
Construction and OMR of nuclear power plants
Radioactive waste management – future CO2 emissions
Uranium mine rehabilitation