Novel notions

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October 2019
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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.

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Energy cliff

Recovery of uranium from the crust occurs by means of a sequence of physical and chemical separation processes. Actually these are conventional industrial processes, consuming energy and materials, and generating various wastes and effluents, including CO2 and other greenhouse gases.
Uranium resources in nature exhibit a great varietyof ore grades: the uranium content of the richest exploited resources is a factor of 2000 higher than that of the leanest ores. To recover 1 kg of uranium from the leanest ore at least 2000 times more rock has to be mined and processed than from the richest ore. This dilution factor is exacerbated by a decreasing recovery yield with declining ore grade, due to phenomena governed by the Second Law of thermodynamics.
The combination of a increasing dilution factor and decreasing recovery yield results in an exponential rise of the specific energy consumption per kg recovered uranium. This phenomenon in turn explains the existence of the energy cliff: the ore grade at which no net energy is extractable from the uranium mineral as found in nature. At ore grades below about 200-100 gram U3O8 per Mg rock no net energy can be generated from a uranium resource.
In addition to the ore grade and recovery yield other geologic and mineralogic factors are important for the specific energy consumption and CO2 emission of mining and milling. This assessment classifies uranium ore types into two classes: soft ores and hard ores. The figures valid for soft ores are based on a process analysis of the Ranger mine in Australia, one of the cheapest operating uranium mines in the world, due to its favourable conditions. The figures for hard ores are based on empirical data from mines in South Africa. Energy consumption and specific CO2 emission of recovery of uranium from hard ores are significantly higher than from soft ores. In practice the figures of the currently operational uranium mines will fall within the range between these two extreme curves.

The energy cliff sets a thermodynamic limit to the world uranium resources that can be considered net energy resources and could be reached within the lifetime of new nuclear power plants, provided that the global uranium consumption would remain at current rate. The chances for major new high-grade uranium resources discoveries during the next decades seem dim. This observation would imply that civil nuclear energy generation at the current global capacity, based on the present operational reactor technology, would be phased out as net energy source by about the year 2080.

For more details and physical background see reports:
- m35 *Energy cliff and CO_2 trap*
- m38 *Nuclear power and the Second Law*

For implications of the energy cliff see reports:
- m10 *Global context and prospects of nuclear power*
- m26 *Uranium mining + milling*
- m27 *Unconventional uranium resources*
- m28 *Uranium from seawater*
- m29 *Uranium for energy resources*

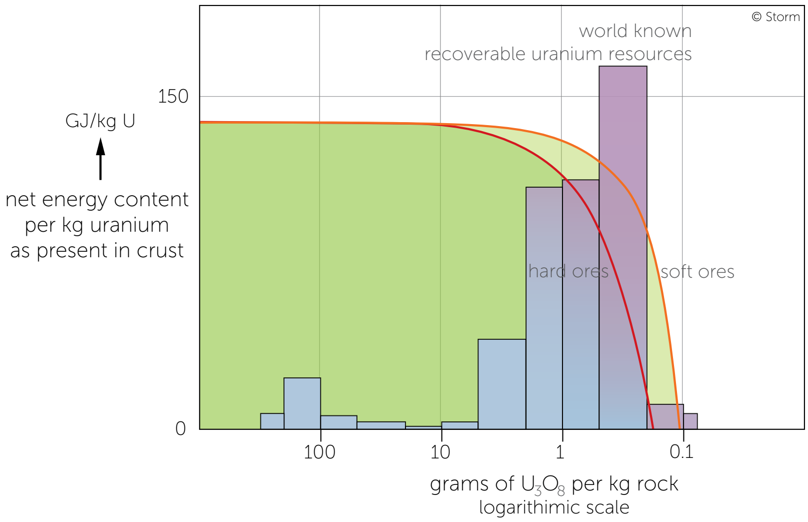

Figure 1

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. Below grades of about 0.2-0.1 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 is 1 to 0.5 g U/kg ore.

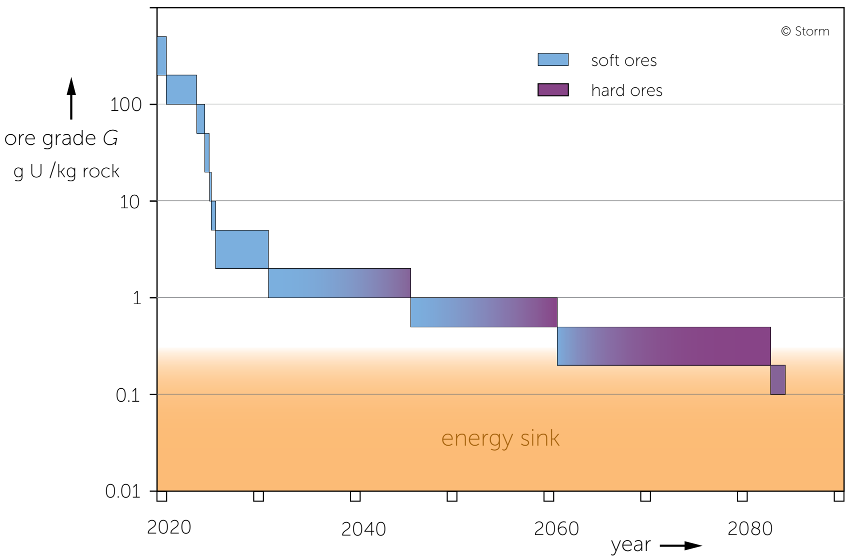

Figure 2

If the global nuclear generating capacity would remain constant at the present level, the energy cliff of the currently known uranium resources would be reached by about 2080; nuclear power would become an energy sink.

CO_2 trap

Mining of uranium ore occurs with diesel-powered equipment. The industrial processes needed to extract uranium from uranium-bearing rock (milling) are generally powered by fossil fuels, due to the remote locations of most uranium mines. For these reasons uranium mining + milling generates CO_2. In addition other greenhouse gases may be released by the extraction processes; these are left outside the scope of this study. As the energy consumed per kg recovered uranium increases exponentially with declining ore grade, the specific emission of CO_2 increases also exponentially. At a given low grade the specific CO2 emission of mining and milling per kilowatthour electricity produced from uranium from that ore surpasses the emission of fossil-fired electricity generation; this phenomenon is called the *CO_2 trap of nuclear power.*

Uranium mines of the world exhibit various conditions, such as ore grade, ore body size, overburden ratio, hauling distances, hardness of the rock to be mined, chemical composition and refractoriness of the ore. Consequently the specific CO2 emissions of recovery differ from mine to mine.
The easiest recoverable uranium deposits are mined first - and get first depleted - because these offer the highest return on investment. As a result the average ore grade of the remaining, yet to be exploited, resources declines over time, causing increasing specific energy consumption and CO2 emission. During the past three decades practically no new high-grade uranium resources are discovered and prospects for such discoveries are dim.
In addition to a declining average ore grade another factor contributes to a rising specific energy investment and CO_2 emission of uranium recovery: leaner ores tend to be harder. The shift from soft ores to hard ores causes an increase of the energy consumption and the CO_2 emission over time.

For more details and physical background see reports:
- m35 *Energy cliff and CO_2 trap.*
- m38 *Nuclear power and the Second Law*

For implications see reports:
- m03 *Contemporary CO_2 emissions of advanced nuclear power*
- m10 *Global context and prospects of nuclear power*
- m18 *Life-cycle nuclear CO_2 emissions*

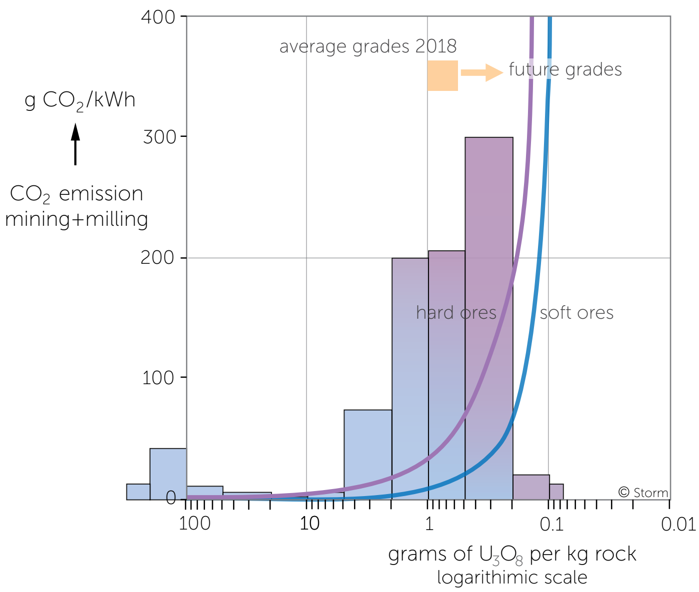

Figure 3

Specific CO_2 emission of uranium recovery vs ore grade.

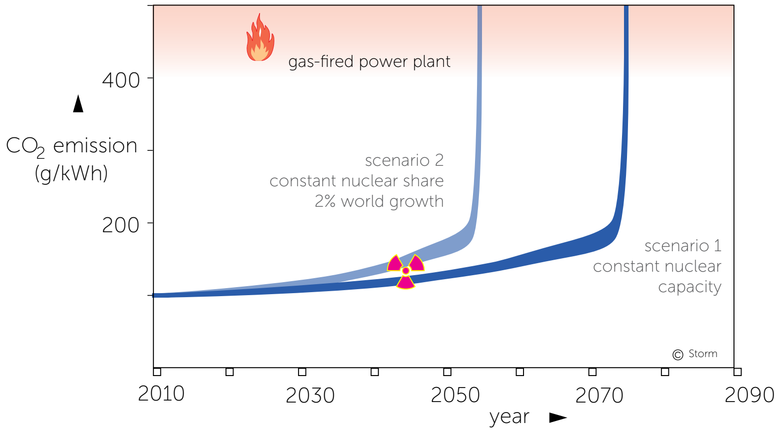

Figure 4

With time the richest available ore deposits will get depleted first, so with time nuclear power will rely on leaner ores. Consequently the CO_2 emission of uranium recovery and of nuclear power increases with time. If the global nuclear generating capacity would remain at the current level, the nuclear CO_2 emission would surpass that of fossil fuels after 2080: the CO_2 trap. If the nuclear capacity would grow according scenarios of the nuclear industry, the CO_2 trap would be reached much earlier.

Energy debt

A nuclear power plant 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 during one year at full power. The irreversible and harmful consequences of these disasters are noticeable on continental scales, affecting millions of people, costing hundreds of billions of euros, and will continue for undetermined time periods into the future.

Effective isolation of the nuclear legacy from the human environment for many thousands of years is a conditio sine qua non to avoid dispersion of the remaining 99.99% of the nuclear legacy into the biosphere. The main part of the nuclear legacy is temporarily stored at facilities with the potential development of powerful explosions when the cooling fails or something else goes wrong. In addition those facilities are vulnerable to terroristic activities. Adequate settlement of the legacy is required to keep vast areas on the Northern Hemisphere habitable, to keep rivers, lakes and seas uncontaminated by dangerous radionuclides, and to secure the lives of many billlions of people during the coming centuries.

Purpose of the downstream (back-end) processes of the nuclear chain must be to fulfil that condition as effective as possible. Basicly, the back-end processes are conventional industrial processes - no advanced technology is required - consuming materials and energy and consequently emitting CO2. Essentially the back-end processes are based on conventional industrial technology, but due to the radioactivity of the materials these processes will be more demanding than similar processes with non-radioactive materials, it's just a matter of investments of materials, energy and human effort. At the time of writing (2019) not one piece of the nuclear legacy from seven decades of civil nuclear power has been adequately isolated from the biosphere, the required activities are systematically postponed to the future.

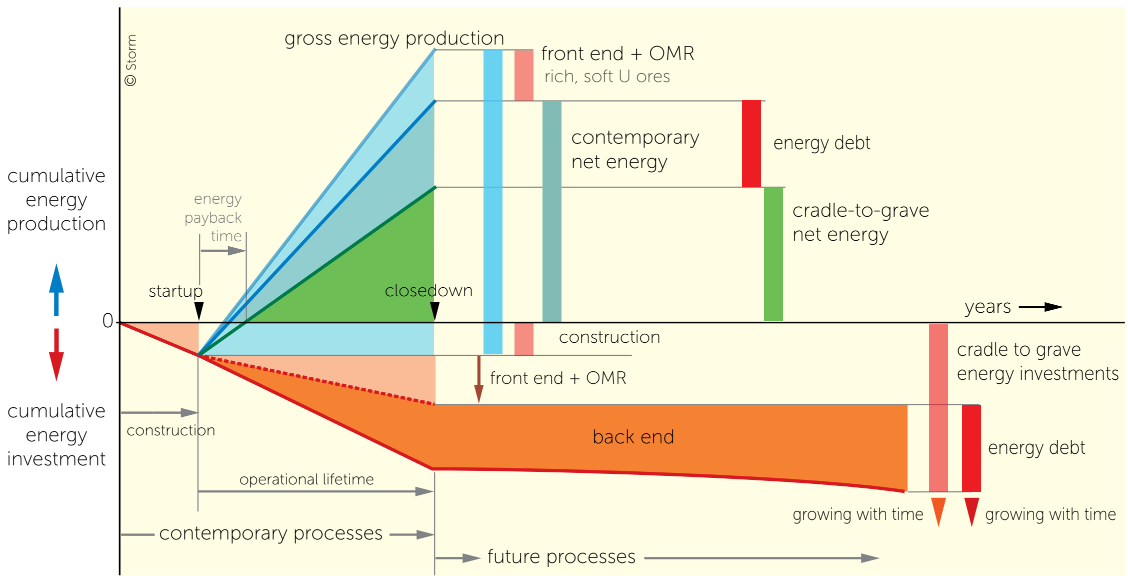

Figure 5

Dynamic energy balance of the nuclear energy system. Current estimates by the International Atomic Energy Agency (IAEA) and World Nuclear Association (WNA) point to cradle-to-grave periods of 100-150 years or even more.

For more details see reports:

m07 *Energy debt, latent CO_2 emissions, latent entropy*

m18 *Life-cycle nucleae CO_2 emissions*

Related reports:

m04 *Decommissioning and dismantling*

m40 *Radioactive waste management*

m41 *Uranium mine rehabilitation*

Latent CO_2 emissions

Operation of the contemporary parts of the nuclear process chain - construction, front-end processes and OMR (operation + maintenance + refurbishments) - emit CO_2 during the operational lifetime of the nuclear power plant: the contemporary CO_2 emissions of nuclear power. To keep the nuclear legacy controllable, massive investments of energy, materials and human effeort are required, as explained under 'Energy debt'. Realization of the activities comprising the energy debt are unavoidably coupled to CO_2 emissions. These CO_2 emissions are directly related to the nuclear electricity generated and consumed today, and are therefore called the latent CO_2 emissions of the currently operating nuclear power plants.

At the moment of electricity generation by a given nuclear power plant the latent CO_2 is not yet formed, but will come into existence decades after the nuclear power plant is permanently closed down, when the back-end activities are started.

Even if all nuclear reactors in the world were to be closed down today, the energy debt, and consequently also the latent CO2 emissions, would increase over time due to a number of factors: accidents, human (mis) behaviour, natural disasters, and phenomena governed by the Second Law of thermodynamics, such as deterioration of the materials used for temporary storage, resulting in unintended dispersion of radioactive materials. The longer the back-end processes are postponed, the more energy would be required to achieve the same safe situation, and the more CO_2 would be generated.

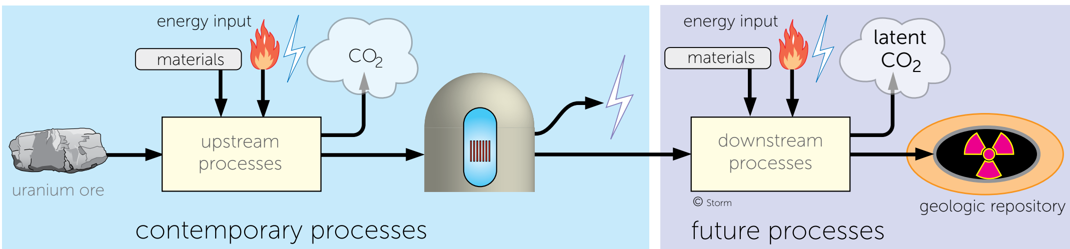

Figure 6

Simplified outline of the nuclear energy system

or more details see reports:

- m07 *Latent CO_2 and energy debt*
- m18 *Life-cycle CO_2 emissions*
- m38 *Nuclear power and the Second Law*

Related reports:

- m04 *Decommissioning and dismantling*
- m40 *Radioactive waste management*
- m41 *Uranium mine rehabilitation*

Latent entropy and delayed entropy: legacy of nuclear power

The conversion of potential energy into useful energy is inevitably coupled to the generation of entropy. Entropy is a measure of disorder: a measure of random dispersion of matter, energy and directed flow. Higher entropy of a system means less quality and less usefulness. Enhancing the quality of a system by lowering its entropy requires investments of useful energy and dedicated human effort.

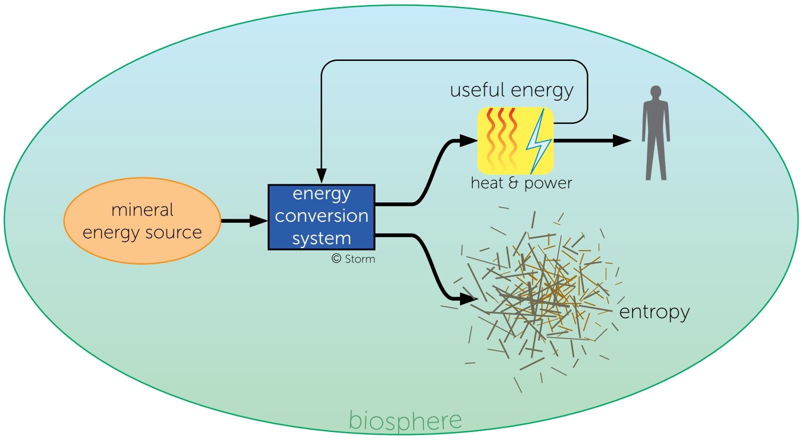

Figure 7

Conversion of potential energy embodied in mineral energy sources into useful energy is unavoidably accompanied by the generation of an amount entropy larger than the amount of entropy that could be compensated for by the the generated amount of useful energy. A part of the generated useful energy is required to construct and operate the energy conversion system, and to manage the wastes produced by the system.

The Second Law of thermodynamics reads:

by every change the entropy of the universe increases.

From the Second Law follows that the amount of entropy generated during the production of a given quantity of useful energy is larger than could theoretically be compensated for by that quantity of useful energy. In other words: it takes more useful energy than the produced quantity to reverse the entropy generation and to restore the original condition of the system in which the energy conversion took place.

All human activities occur within the biosphere. From a thermodynamic viewpoint the biosphere may be regarded as a closed system, without (notable) mass exchange with its surroundings, outer space. Conversion of potential energy into useful energy from any mineral energy source within the biosphere increases the entropy of the biosphere, also in case of nuclear power then. Consequently, the question is not: if nuclear power generates entropy, the question is: what shape takes that nuclear entropy?

Conversion of potential energy embodied in uranium into heat (and subsequently into electricity) is possible by means of a complex system of industrial processes, each generating entropy that has to be attributed to the produced electric energy. The entropy generation of the fission process, converting potential energy into heat and radiation, occurs within the casing of the reactor and the fuel elements. Unavoidably a part of the fission entropy escapes into the environment by heat, nuclear radiation and leakages of radioactive matter. As long as the spent fuel elements remain intact, the main part of the fission entropy remains enclosed in a small volume, that part is called the *latent entropy of nuclear power*.

If left unattended the fuel elements will loose their integrity as result from phenomena following from the Second Law. Consequently the contents will get dispersed into the biosphere and the latent entropy will become unretained (mixing) entropy of the biosphere. This process will happen spontaneously, if no work is done to prevent it.

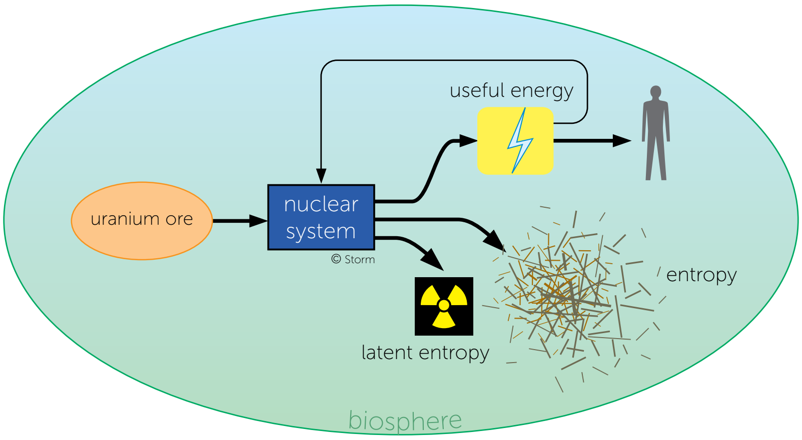

Figure 8

Nuclear power is generated by an energy system, based on uranium as mineral energy source. An important difference of the nuclear energy system with other mineral energy systems is the generation of latent entropy, in addition to the directly observable increase of the entropy of the biosphere. Without investments of useful energy and human effort the latent entropy will develop into a huge and irreversible increase of the entropy of the biosphere.

During the disaster of Chernobyl an amount of latent fission entropy equivalent to less than the annual entropy generation of one nuclear power plant of 1 GWe turned into unretained entropy of the biosphere; this amount corresponded with less than 0.01% of the world inventory of latent fission entropy.

After the fission process stops, the nuclear entropy production goes on. By radioactive decay of the fission products new nuclides come into being, and radiation and heat is generated. This kind of on-going spontaneous entropy generation, inextricably bound up with the fission entropy generation, is called the *delayed entropy* generated by nuclear power.

Latent fission entropy and delayed nuclear entropy form the nucleus of the nuclear legacy.

For more details and physical background see reports

m07 *Energy debt, latent CO_2, latent entropy*

m38 *Nuclear power and the Second Law*