Energy cliff and CO_2 trap

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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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Coal equivalence

Global nuclear generating capacity in the foreseeable future will depend on the availability of uranium resources of sufficiently high quality. 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 uranium-plutonium breeder systems 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. For more details see reports m01 *Uranium-plutonium breeder systems*, m20 *Reprocessing of spent fuel* and m24 *Thorium for fission power*.

Uranium occurs in many kinds of minerals in the earth's crust. The properties of the uranium-bearing rocks that are indicated as 'uranium ores' vary widely from mine to mine. An important parameter is the ore grade, usually measured as mass % U_3O_8. The ore grade of the currently known recoverable uranium resources vary from more than 20% to about 0.01%, a factor of more than 2000. Figure 1 shows the relative distribution of the known uranium resources, a common geological phenomenon is that the larger the resource the lower the ore grade. Due to phenomena governed by the Second Law of thermodynamics the percentage of uranium present in the ore that can actually be extracted (the extraction yield), declines exponentially with the ore grade. This results in an exponential rise of the mass of ore to be mined and processed per kilowatthour electricity produced by nuclear power plants: the coal equivalence.

Recovery of uranium from the earth's crust is achieved by means of a sequence of physical and chemical processes, requiring significant energy investments and emitting CO_2. For details of uranium recovery from the earth's crust see report m26 *Uranium mining + milling*.

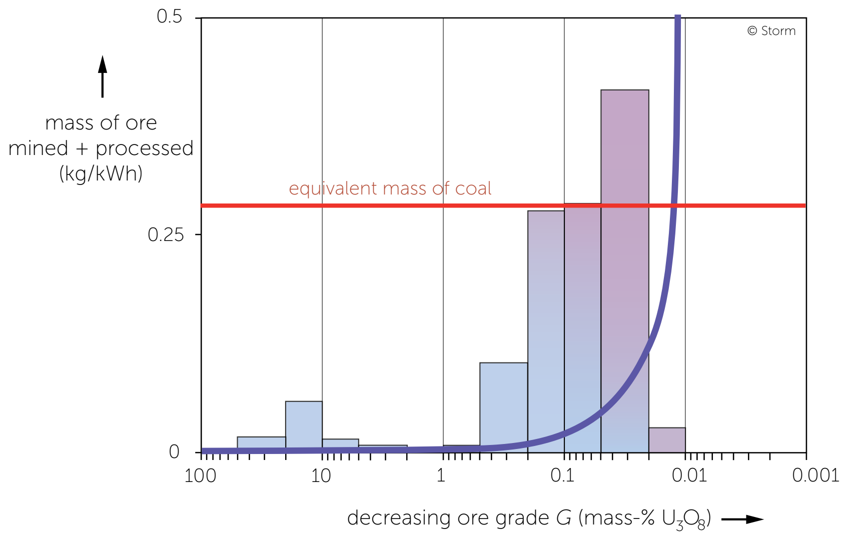

Figure 1
The mass of uranium ore to be processed to fuel one reactor for one year with uranium rises exponentially with decreasing ore grade. At a grade below 0.02% U_3O_8, 200 ppm, or 200 grams per Mg (metric ton) the mass of ore equals the mass of coal consumed by a coal-fired station to generate the same amount of electricity: this is the coal equivalence. The bar diagram as function of the ore grade represents the relative distribution of the known world uranium resources.

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.

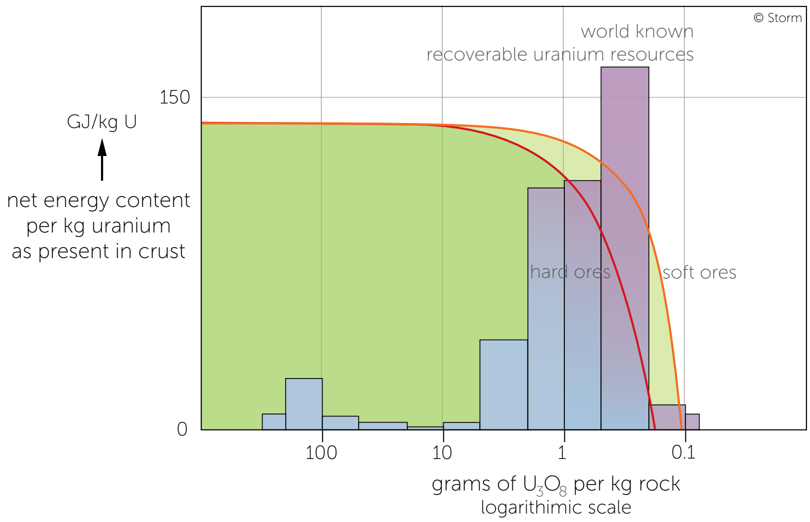

Figure 2

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 report m19 *Characteristics of the advanced reactor and EPR*). 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 2. 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.

CO_2 trap

Coupled to a rising energy consumption with decreasing ore grade appears a rising CO_2 emission per kg recovered uranium. Figure 3 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*.

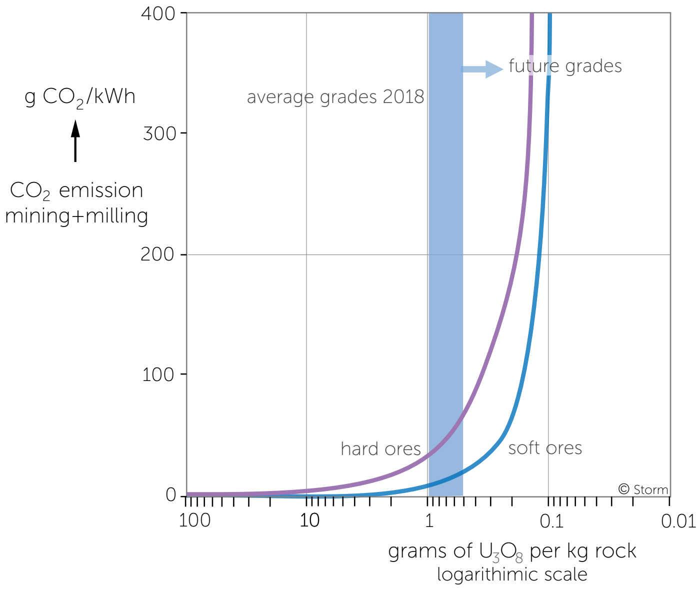

Figure 3

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.

Consequences

As indicated in the diagram of Figure 3, 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 4 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.

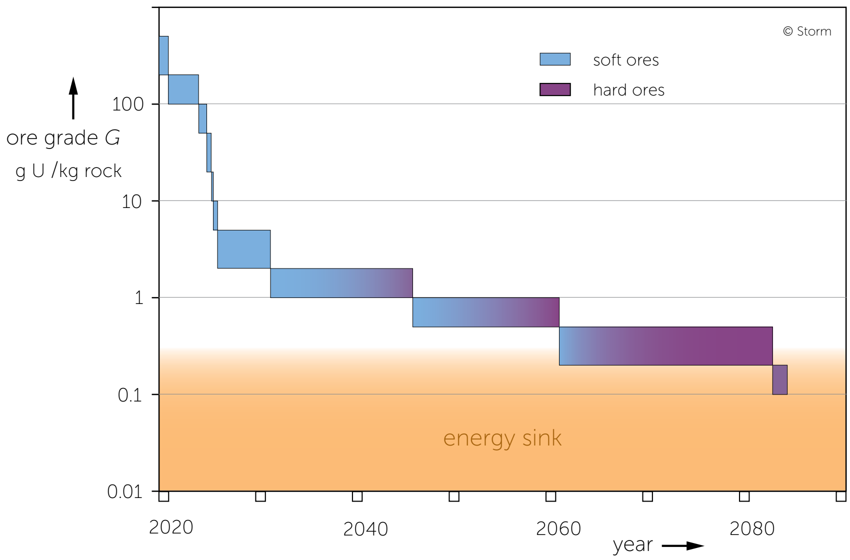

Figure 4

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.

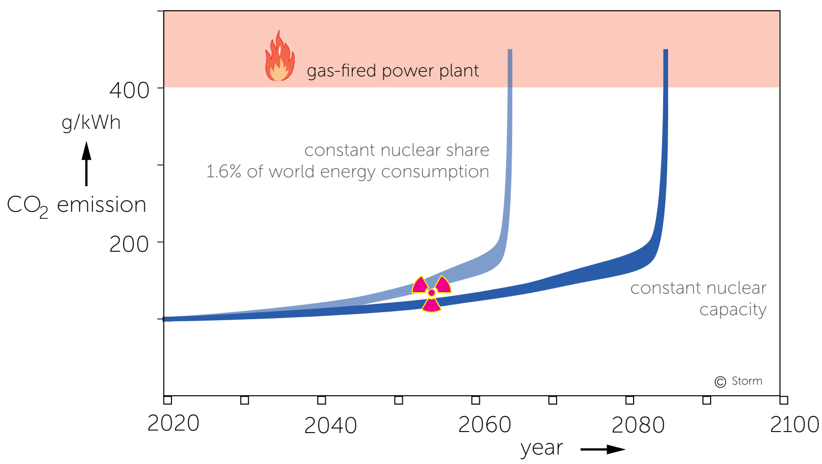

Figure 5

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.