Nuclear Power, The Energy Balance

Chapter 1
The CO_2-emission of the nuclear life-cycle

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Perhaps the hottest bone of contention in the current debate about the use in the future of nuclear energy, is whether its application would solve the CO_2-emission problem caused by the production of energy. In the figures on the following pages we compare the CO_2-emission of a nuclear energy system with that of a gas-burning plant.

As already remarked, the actual energy produced, and the CO_2, balance of a nuclear reactor depends on how rich the ores are that are used to obtain the uranium. To make this more easily understandable, we have converted, in Figures 4a, 4b, 5a and 5b and in summary in Figure 6, the cumulative energy production and deficits into the resulting CO_2-emission of a nuclear plant and compared these to a gas-burning plant. The (mass) percentage uranium (oxide) in the ore is called G. From Figure 4a we see that even with rich, soft, ores it takes seven years before a nuclear reactor (system) "overtakes" a gas-burning plant. With leaner ores the reactor system hardly overtakes a gas-burning plant in its The graphs in the Figures 4a and 4b take into account all energy expenditures, including the cost of dismantling the reactor, whereas the in Figures 5a and 5b the dismantling costs are left out of the calculation. The graphs in Figure 4a refer to "Soft ores" (mostly sandstone) and in Figure 4b to "Hard ores" (e.g. granitic).The equations of the lines are explained in detail in Chapter 5. Note that the lines in figures 4 and 5 end at 24 full-load years. It is shown in Chapter 3, that this is longest operating time that can be expected with the presently operating reactors.

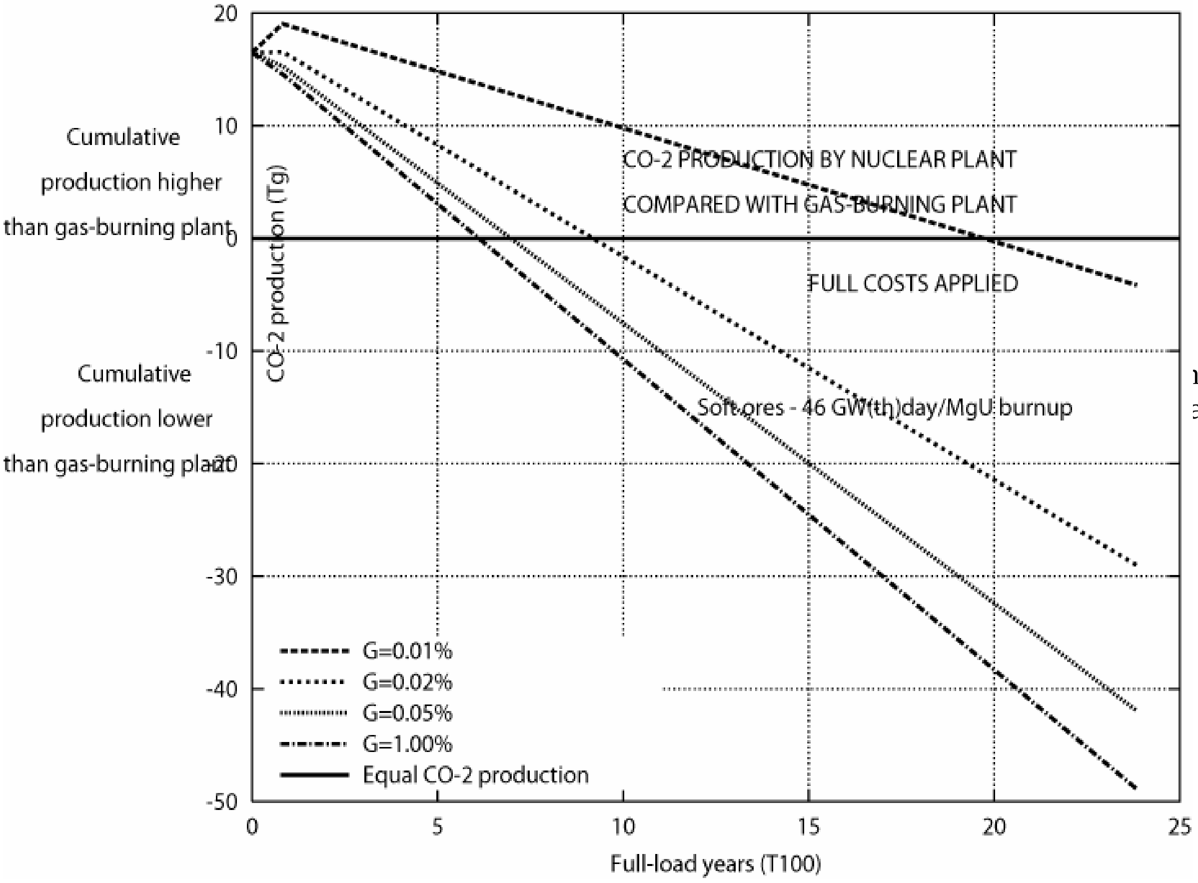

Figure 4a. In this figure the CO_2-emission of a nuclear system is compared to that of a gas-burning plant. The total costs are applied, including the debt of dismantling at the end of the reactor's useful life. It is assumed that the burnup is 46 GW(th)day/MgU.

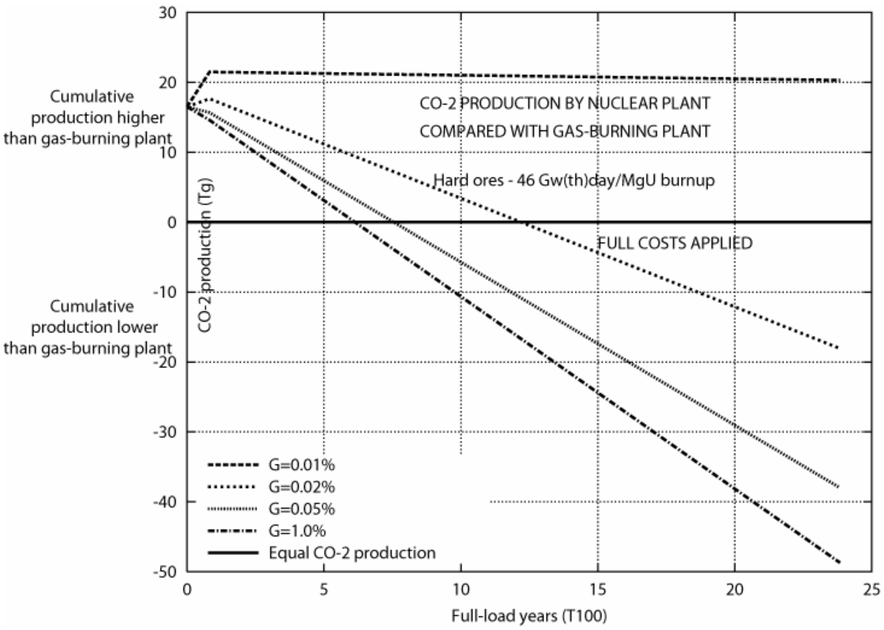

Figure 4b. The same as Figure 4a, but with the reactor supplied with uranium from hard ores

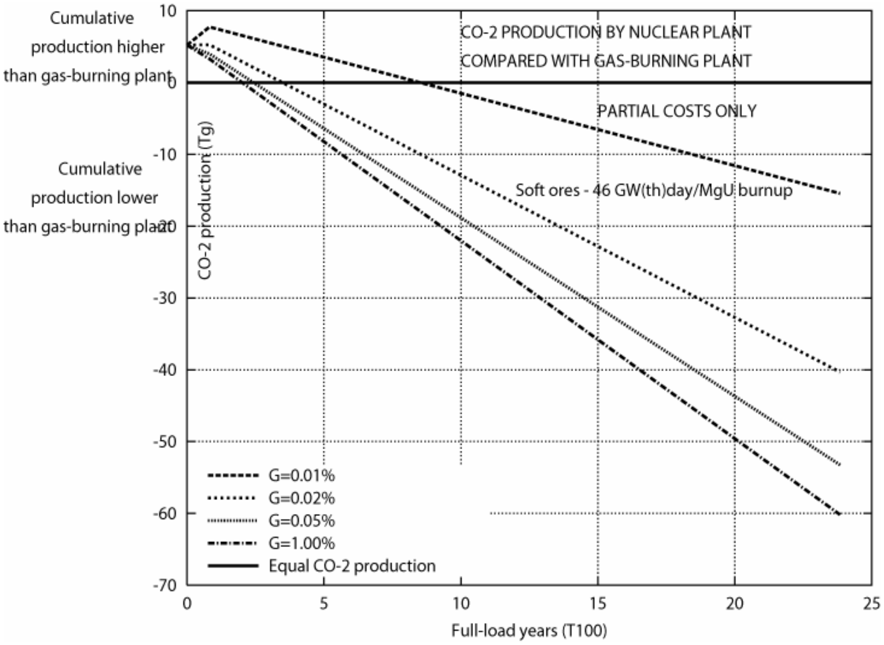

Figure 5a. The same as Figure 4a except that the dismantling costs of the reactor that were taken into account in Figures 4a and 4b are here neglected.

We see from Figure 5a, where the costs of dismantling the reactor are left out of the calculations, and if rich, "soft" ores are available (i.e. G equal to 1% or higher), the nuclear power plant succeeds after about two full-load years causing the production, in total, of less than a gas-fired plant. If the ores are leaner, say 0.01%, this takes about 9 years. For poorer ores (i.e., ore grades lower than

0.01%) the nuclear power plant would be responsible for *more* CO_2-emission than if the same amount of (electrical) energy were to have been obtained from burning the fossil fuels directly.

The picture is less favourable, as is shown in Figure 5b, if hard ores must be used to supply the uranium. This difference come in good part from the much larger energy input needed to mill the ores (see Chapter 2 for the quantitative comparison). Another factor making the use of hard ores less favourable, that we have not tried to quantify, is that one can expect a considerably lower yield for hard ores because more difficult, and lower yield, purification procedures become necessary. The consequences of the first factor are large. For hard ores: the cumulative CO_2-emission for 0.02% ore grade only reaches equality with a gas-burning plant after five years of nuclear power plant operation, assuming, again for clarity, that costs of dismantling the nuclear reactor with extreme care to avoid the release of radioactivity are neglected.

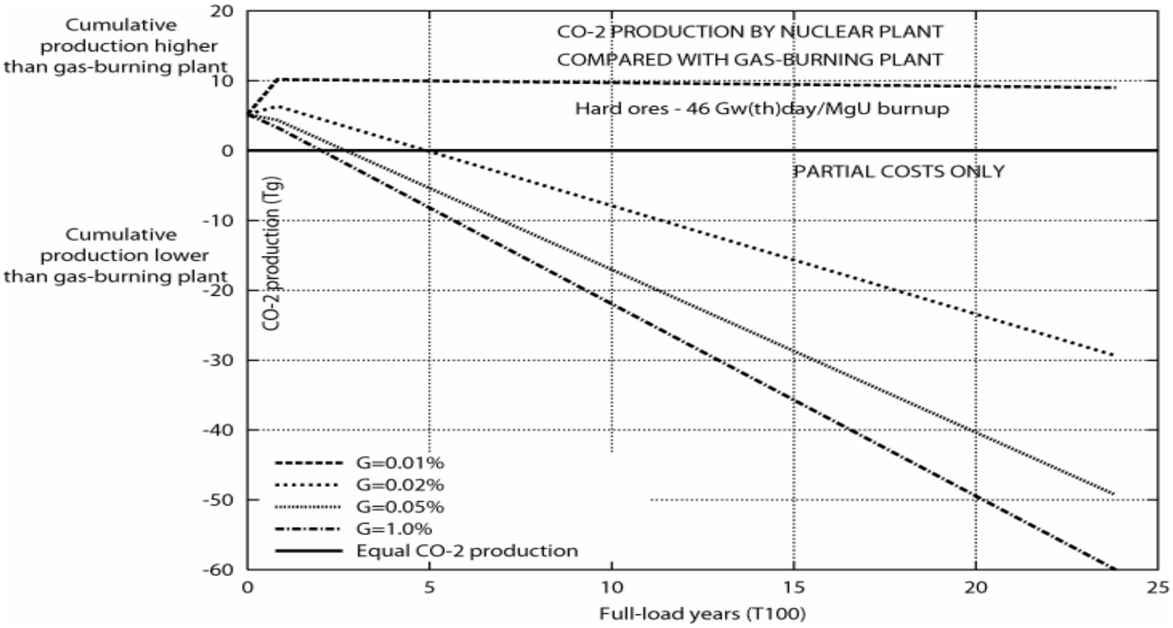

Figure 5b. The same as Figure 5a, but using hard ores as source of the uranium.

The presentation above of the relative (to a gas-burning plant) CO_2-emission brought about the nuclear fuel-cycle as given in Figures 4 and 5 does give the full picture but is tedious to follow and difficult to draw conclusions from. We present therefore a more convenient, and hopefully more easily understandable, picture in Figure 6. In this figure four curves are shown of the ratio of the total (i.e. cumulative) CO_2- production of a nuclear-energy system to that of a gas-burning plant producing the same amount of electricity for the four different conditions (i.e., soft and hard ores, and including and excluding the costs of dismantling, respectively). In this way the reader gets a quick view of the relative CO_2-emission of a nuclear reactor system and a gas-burning plant, for the several different operating conditions or assumptions.

One sees quickly, for example, the importance of taking, or not taking, the dismantling costs into account. Specifically, for rich ores, soft or hard, the relative, cumulative, CO_2-emission jumps from about 18% of the emission of a gas-burning plant when the dismantling costs are neglected to 33% when these are taken into account. The rapid growth of the CO_2-emission when the ore grade becomes less than 0.1% is also apparent.

The picture given in Figure 6 makes it clear that it is highly relevant to ask how much uranium is available in the richer ores (i.e., richer than 0.02% or 0.01% for hard or soft ores, respectively). It will be shown in Chapter 2, Figure 10, that this is surprisingly little. Specifically there is not even enough to provide the world's present yearly total electrical production of 55 EJ for a decade, even if the large amount of energy needed to properly dismantle the reactor is "saved" by leaving this problem for future generations. When these rich reserves are gone, the leaner ores will lead to more and more CO_2-emission until finally this emission will amount to more than if one were to burn the fossil fuels directly. The factor of 3.3 gain in CO_2-emission (compared to gas-burning plants) provided by nuclear energy, achieved with the presently available rich ores, is a very temporary gain and not a basis for policy decision concerning society's future energy supply. One wonders how it is possible, in the light of this, that plans are being actively made for a tremendous expansion of the nuclear energy option. Our conjecture is that the silent assumption behind this planning, illogical as it may be, that breeder reactors will someday become practical.

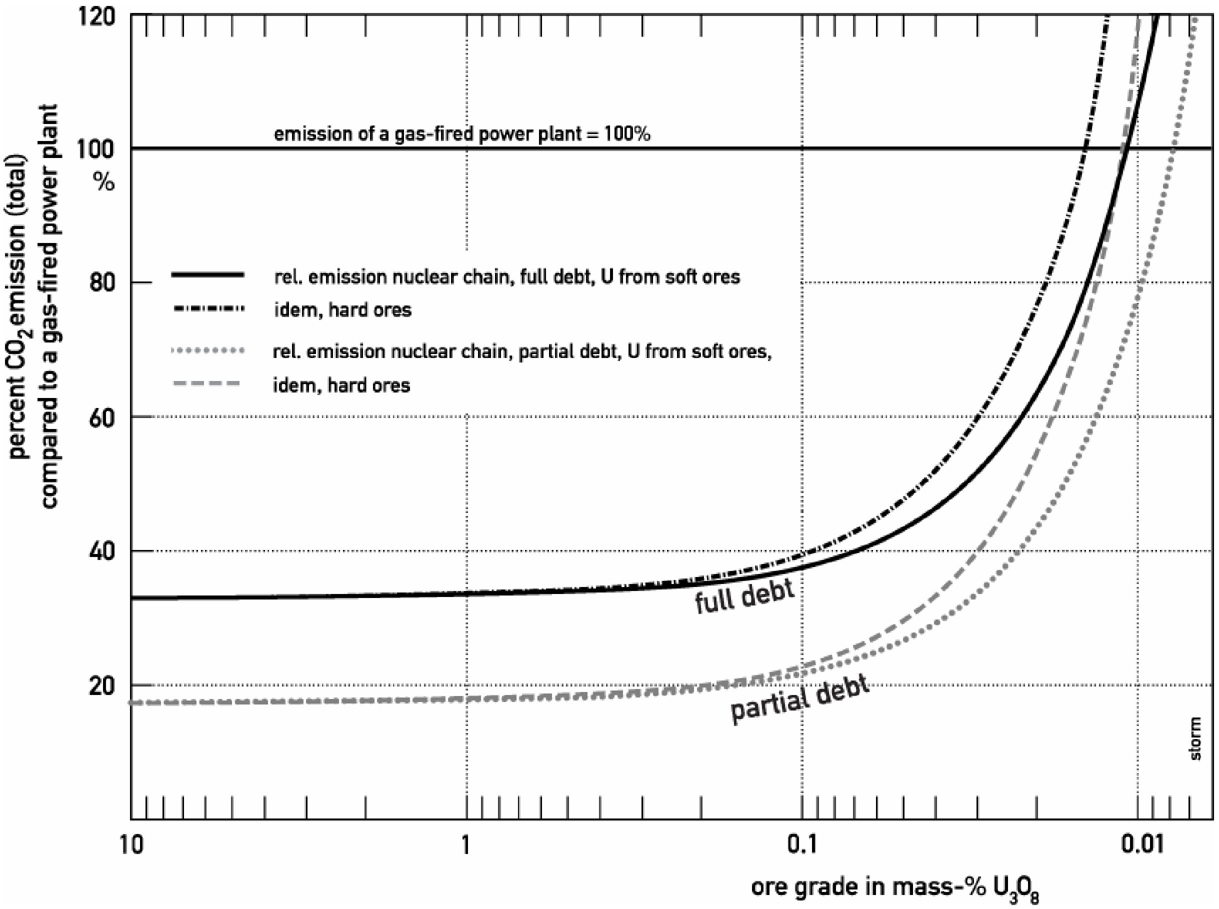

Figure 6. The cumulative ratio of CO_2-emission of a nuclear-energy system to that of a gas-burning system producing the same net electricity output as the nuclear system, for different conditions, as a function of the grade of the ore used to supply the reactor with uranium. The curves for full debt assume that the reactor is dismantled with meticulous care for the environment, while those for partial debt assume that this is not done. The ratios for soft and hard ores are both shown. The details of the calculations are given in the text.

Calculation of the curves in Figure 6.

For a given ore grade the ordinate of a curve in Figure 6 for the assumptions and ore type given on that curve is found from:

$$\frac{\mathbf{CO2TOT}}{\mathbf{ENGF}\times\mathbf{NETEL}},$$

where ***CO2TOT*** is the total (lifetime) CO_2 emission of the nuclear system, ***NETEL*** is the net electricity output of the nuclear system (the gross electrical output minus the sum of the electrical component all of the cost items, which are assumed provided for by the nuclear system itself), and ***ENGF***= 0.1011Tg is the CO_2 emission per PJ electricity delivered by a gas-burning plant.

CO2TOT is the sum of three thermal energy expenditure terms multiplied by ***CO2F***=0.075 Tg CO_2/PJ to get the amount of CO_2 emitted by burning oil (the most likely source of thermal energy in an industrial system) to provide the thermal energy needed. The three energy terms of which we need the thermal component are: (i) the debt term, either 240 PJ or 80 PJ, as explained heretofore, (ii) the energy cost of the initial reactor load, and (iii) the energy cost of one reload times the number of reloads in the reactor lifetime. The energy cost of the initial load and the reloads are each made up of thirteen items, as listed at the end of the Introduction. The thermal energy cost of the j_{th} item is found from the calculated total cost of that item, $\mathbf{E_j}$, using the ratio, $\boldsymbol{R_j}$, of thermal to electric costs (also listed in the table) for that item with the relation:

$\dfrac{\mathbf{E_j \times R_j}}{\mathbf{R_j + 1}}$. The thermal energy cost of the debt is found using the same equation, but with the value of R appropriate to the debt.

In Chapter 2 we treat the cost and availability of uranium fuel, but we also review the various possibilities of extending the usefulness of the nuclear option. We show there that it is out of the question to produce electrical energy through the utilization in nuclear reactors of the uranium in the granitic rock of the earth's crust or of the uranium in the oceans. We also summarily discuss unproven, technical developments such as the fast-neutron breeder, nuclear fusion, and exotic new developments in nuclear reactors. It is obviously impossible to rule out *a priori* that any of these options might be practical. But arguments are presented to show that the practicability of any of them is improbable.

Unpleasant as it is, we must face the fact that there is no "magic bullet" that will give us unlimited energy. One must conclude that the future of our civilization depends critically on reducing the use of energy drastically and rapidly. The dream of a society built on endlessly expanding energy use is a pipe-dream. It may also be remarked that from an ethical, human viewpoint a societal choice for a drastic reduction in energy use would lead to a more peaceful, contented society than the one in which we live, continually searching, as it is for more energy.