Can nuclear power provide energy for the future; would it solve the CO_2-emission problem?

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Summary

The industry claims that nuclear power is a sustainable energy source. This claim is highly debatable. Obviously, no source of energy that is derived from mining a resource in the earth's crust can be sustainable. Yet the sustainability of nuclear power is nonetheless accepted by many. The main object of this document and the accompanying technical documents is, therefore, to show that nuclear power, as now used, is not only not a sustainable energy source, but cannot provide even 1% of the energy predicted to be needed on the coming decennia. Another way of putting it is to say that **if** all of the electrical energy used **today** were to be obtained from nuclear power, all known useful reserves of uranium would be exhausted in less than three years. Other possibilities - fast-neutron breeders and even more exotic reactors, and getting essentially unlimited amounts of energy from the uranium in sea water, or obtaining useful energy from nuclear fusion will be discussed at the end of this paper.[1]

It is also untrue that the use of nuclear power does not result in CO_2-emission. The claim that nuclear power does not produce CO_2 may sound plausible because the operation of the reactor itself does not produce CO_2. This is true, but it is a misleading half-truth. We will show below that there are large hidden energy costs involved in producing electrical energy by nuclear power plants. Under present conditions that means burning fossil fuel, with the concomitant emission of CO_2. The details will be found below, and the total CO_2-emission will be compared with the emission that would be produced by an equal-sized gas-burning power plant. If all of the contributions are taken into account, the difference in the total amount of CO_2-emission is not very large. Nuclear power is not a solution to the CO_2-emission problem.

The reason is that it costs energy to produce nuclear energy, and more disturbing is that many of these energy costs will have to be paid many generations after a nuclear power station has stopped producing electricity. These are thus energy debts: debts incurred during its productive lifetime.

What are sustainable energy sources?

Physically speaking, the only sustainable energy source to which we have access on earth is the sun. Energy obtained from terrestrial sources will always be exhausted eventually. The sun, on a much larger time scale than we can imagine, will continue to provide a tremendous source of ultra-clean energy. But there is another aspect of sustainability that we must consider: environmental sustainability.

In any closed system, such as the biosphere, every conversion of energy from one form to another results in degradation of the environment. In scientific terms this is caused by the increase of entropy, which is the scientifically exact way of saying that it creates an increase in the degree of disorder. That this *must* occur follows from the second law of thermodynamics, a fundamental law of nature. So a sustainable source of energy must not only be inexhaustible, it must also not lead to an increase of entropy on earth.

We said above that the energy that comes from the sun is ultra-clean. Why is this so, in comparison with the dirty energy produced by burning fossil fuels, or nuclear power? It is ultra-clean because solar energy is produced by the conversion of gravitational energy into light and heat through nuclear processes in the interior of the sun. The increase of entropy resulting from this conversion occurs on the sun. Only the energy of light is exported to the earth. It is energy with an essentially zero entropy-content. It is important to recognize that it is just exactly this cleanness that was a necessary condition for the birth of life on earth. Taken individually, life processes also produce an increase of entropy, but over billions of years, due to its *self-organizing* capacity, life developed a closed cycle. All of its detriments are recycled, using the clean energy from the sun, and the total entropy in a closed natural life-cycle does not increase with time.

Physically unsustainable energy sources

Fossil fuel is not a sustainable source of energy. A finite amount was deposited in the earth's crust many millions of years ago, and will therefore be exhausted someday unless we stop burning the different forms in which it occurs. The same is true of nuclear energy, but even more so, since the total useable energy reserves of uranium are small compared to the energy reserves in fossil fuels. So, even leaving aside the multitude of other problems connected with the use of nuclear energy, it turns out that it can in no way be considered as the solution to the long-term energy problem. But even in the short term, as we will show below, except in the exceptional case that rich uranium ores are used, it hardly provides more energy than would be obtained from burning the fossil fuels directly. If low-grade ores are utilized, a nuclear power plant actually provides less useful (electrical) energy than one would get by just burning the fossil fuels themselves.

Environmentally unsustainable energy sources

Nor from the viewpoint of environmental sustainability can we consider the burning of fossil fuel sustainable. Burning fossil fuels produces the "greenhouse gas" CO_2. This gas probably constitutes a danger for humankind on a much shorter, much more urgent, time scale than the exhaustion of the fuels themselves. Although it is not absolutely certain, as time passes it appears more and more likely that the immense amount of CO_2-emission in today's industrial society will lead to irreversible global warming. Only a few degrees of global warming would lead to unparalleled disruption of the climate and the disappearance of vast areas of habitable land under the sea. If we were to wait until it is proven beyond doubt that the CO_2 produced by human activities will lead to global warming, it would be too late to reverse the process. Proceeding on the basis of the best available scientific opinions it was agreed upon in the international conference in Kyoto in 1997 that the world must reduce the use of this source of energy as much as possible. The limits set at the time for the reduction of emissions were quite inadequate, it is true. But at least a beginning was made. The sequestration of CO_2 from the atmosphere in the form of coal, oil, calcareous rock, etc. was essential for the creation of the closed cycle of life on earth. Humanity has broken this cycle open by burning fossil fuels in immense amounts. *Caveat!*

The false claim is made that nuclear power is free from CO_2-emission, and therefore environmentally sustainable. If this were true it would then be eligible for classification as a CDM (Clean Development Mechanism), i.e. the transfer of low-CO_2-emission technology from North to South . This claim is based upon a distortion of the facts. It is true that the operation of a nuclear power plant does not in itself lead to CO_2-emission. However, large amounts of energy are needed in order to build the plant, in order to mine, refine, and enrich the uranium fuel, in order to condition and sequestrate the radioactive waste, and finally in order to dismantle the plant. Most of this energy must presently be obtained by burning fossil fuels. It should be noted that a great deal of this fossil-fuel energy will needed *after* the power plant has reached the end of its useful life.

But needed it will be if one is to classify nuclear energy as environmentally sustainable, and therefore it must be, from the beginning, chalked up to an *energy debt* inherent in the building and operation of a nuclear power plant. It is a distortion of the facts to pretend that this energy debt, that can at present only be paid by burning fossil fuels, does not exist. This will be shown in detail below. It must be understood that an energy debt is quite a different thing than a money debt. Money is only worth what people think it is worth. No amount of money placed in the bank can be used to "buy" energy when the sources are used up. The laws of physics are inexorable. Money can be made, but energy cannot be made. On the basis of calculations, using information from the nuclear industry, we can conclude that nuclear power, besides obviously not being a sustainable energy source, is not a solution to the problem of global warming.

Reducing the use of fossil fuels must be seen today as having the highest priority, and it is important to expose false solutions toward reaching this goal. We proceed below to show that nuclear power is not a viable way to substantially reduce CO_2-emission. It is no exaggeration to say that nuclear power can only exist because it is fueled by fossil fuels.

The CO_2-emission caused by the use of nuclear power

We treat here only the so-called *once through* use of enriched uranium in a water-moderated high-pressure nuclear power reactor. The uranium fuel used in such a reactor is slightly enriched in the fissionable isotope ^{235}U. When they are "burned up", the fuel elements are stored in water basins for some years, to permit the radioactivity to decline so that they can be transported. The final destination, after conditioning, is a stable geological stratum. The fuel is not reprocessed. This type of reactor, operated in this way, is by far the largest source of nuclear energy (outside of the former Soviet Union, and its satellites). Some fuel is reprocessed, but this is also an energy-consuming process that has yet to be shown to be safe and practicable. Other conceivable applications will be mentioned in our conclusions.

The energy costs and the energy debts of nuclear power

Our point of departure in the calculations, the results of which are sketched below and quantitatively proved in the following chapters, is that in order that nuclear power be classified as environmentally sustainable, no permanent environmental degradation may take place as the result of its use. This criterion has been applied to all phases of the "life cycle" of a nuclear reactor, with one exception: the tritium formed in the cooling water of a nuclear reactor by neutron capture in deuterium ("heavy" hydrogen). At present this is simply released into the biosphere. We do not know how serious this is as a hazard to life, nor do we have enough information to calculate the energy cost of sequestering it. What can be said is that tritium does not "belong" in the environment (except in minute amounts formed by cosmic rays in the atmosphere), but due to lack of information we cannot draw any conclusions about the damage caused by the release of large amounts to the biosphere.

The largest energy costs of a power plant itself, up to the end of its useful lifetime, are:

i the energy costs of building and operating the plant itself, and

ii the energy costs of mining, refining, and enriching the uranium in the ores.

The second of these depends sensitively on the richness of the ore, and for poor ores will, if the use of nuclear energy continues, become very high. In fact it will rise so high that nuclear power no longer produces more energy than is needed to keep it going (and pay its debts). In other words, the point is reached when ores become so poor that one would get more energy out of burning the fossil fuel directly than by following the roundabout path of using fossil fuels to build, operate, and fuel a nuclear power plant. This is an important fact, because by far the largest part of the uranium reserves are found in very poor ores.

The energy debts incurred by a nuclear power plant have to be paid after the plant has reached the end of its useful life. They are:

iii the energy costs of conditioning the extremely radioactive burned-up fuel elements so that they can be sequestered in a presumably stable geological stratum;

iv the energy costs of sequestration, and

v the energy costs of dismantling the plant itself.

Up to the present none of these debts, incurred in enormous amounts by the existing nuclear power plants, have been paid. For that reason we have had to estimate them. This is difficult because there are few precedents to use in the estimation of the costs of these highly dangerous and costly operations. Not only that, but in the case of the sequestration costs there is reason to doubt that it ever can be done safely. The proposals on how to do it are legion, ranging from the simple to the highly exotic. None may ever turn out to be satisfactory solutions. Here we will assume, nonetheless, that it can, somehow, be done. In Chapter 4 we calculate the energy costs, based on data from the industry, of sequestering this waste in a stable geologic repository.

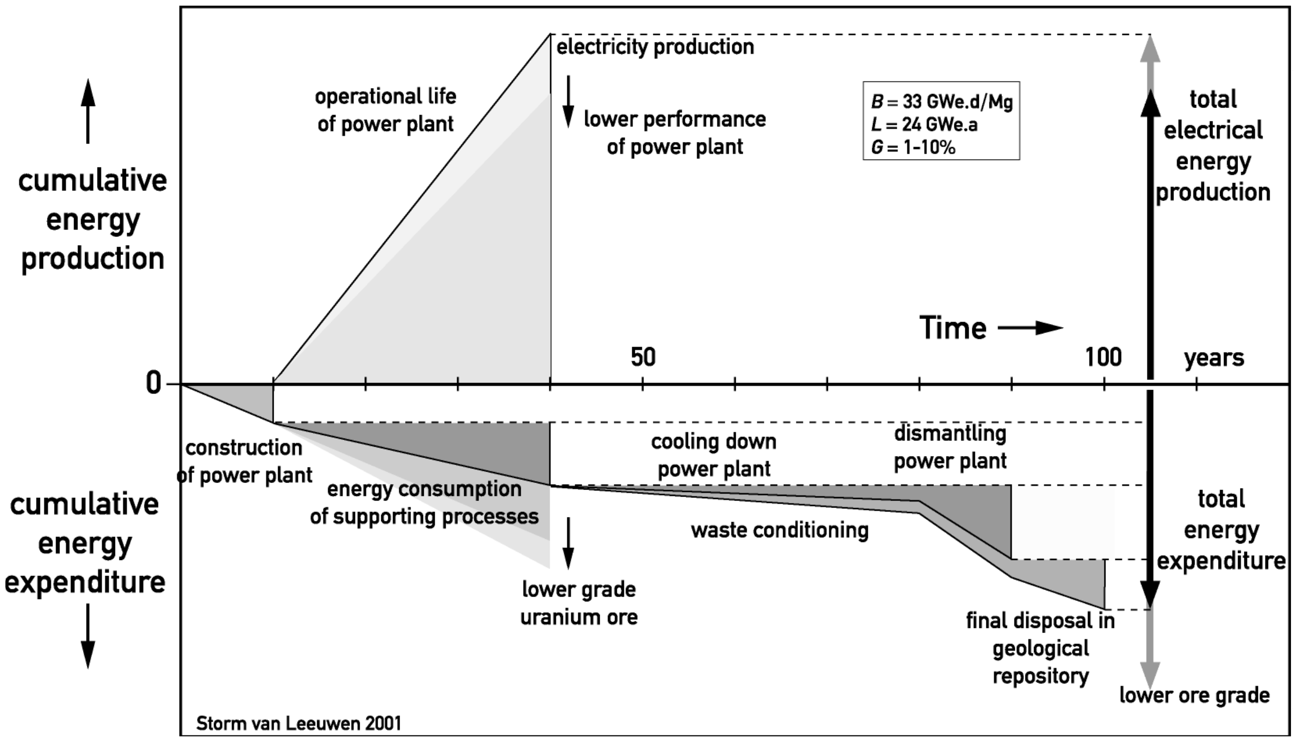

Figure 1. Schematic representation of the energy production and energy costs of nuclear power as a function of time.

Paying the costs of the first two categories and paying off the debts in the last three requires the burning of fossil fuels. The burning of the fossil fuel produces CO_2. It is therefore untrue to say that nuclear energy does not result in CO_2 emission.

Pretending that these debts do not exist does not make them go away. They are not like bad debts that can simply be written off as losses in the ledger. Mankind will have to pay them someday, or

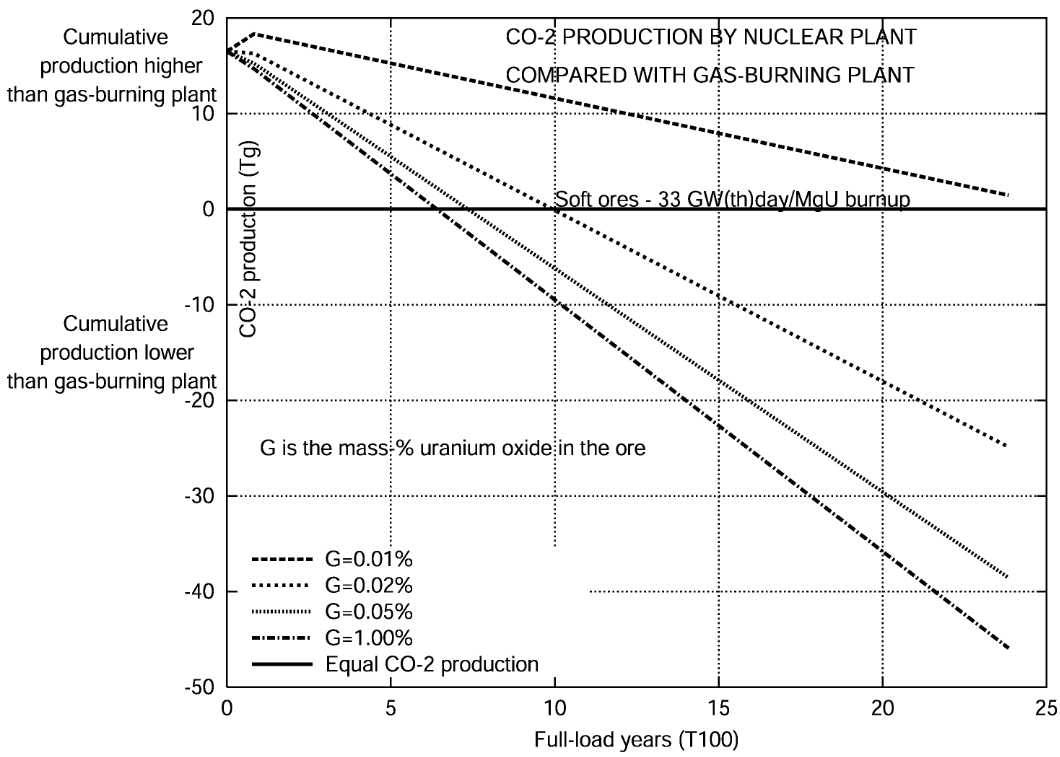

Figure 2a. A comparison between the cumulative CO_2 emission of a gas-burning plant and a nuclear plant. See the text for the meaning of "Soft ores" and 33 GW(th)day/MgU

pay the consequences of a poisoned environment. We have made them visible in pictorial form in Figure 1. Here we have represented the cumulative electricity production as a triangular area above the baseline. The five costs/debts are all shown as dark areas below the baseline. These areas are roughly to scale. The actual calculations were made for a rich ore (uranium content = 1%). The area that changes as the ore becomes poorer is indicated in the diagram, as is the effect of less than ideal performance of the power plant. The time scale is, of course approximate. No large scale power plant has ever been dismantled and we may not forget that finding a safe, permanent, storage for the radioactive waste is still an unsolved problem.

When does a nuclear power plant produce more CO_2 than a gas-fired plant?

As already remarked, the actual energy, and thus CO_2 balance, depends on how rich the ores are from which the uranium is obtained. To make this more easily understandable, we have converted, in Figures 2a, 2b and 2c the cumulative energy production and deficits into the resulting CO_2 emission, and compared these to a gas-fired plant. The percentage uranium in the ore is named G. The CO_2 emission is given in units of Tg, which is equal to a million metric tonnes. The equations of the lines are detailed in Chapter 5.

The graphs in Figure 2a refer to "Soft ores", mostly sandstone and in Figure 2b to "Hard ores" (e.g. granitic). In Figure 2c we show the ratio in CO_2 emission at the end of the life of a nuclear power plant, i.e., 24 full-load years.

We see from Figure 2a that if rich, "soft" ores are available (i.e. G equal to 1% or higher), the nuclear power plant succeeds after about seven full-load years causing the production, in total, of

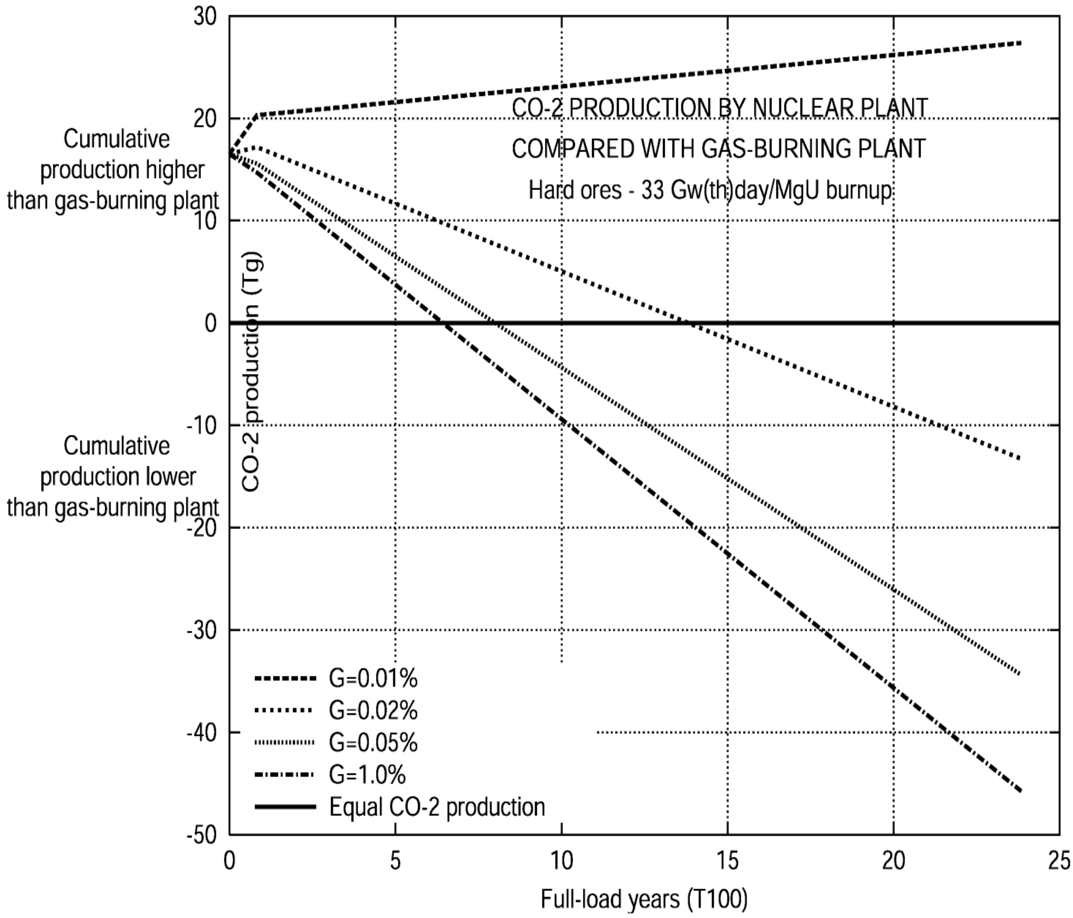

Figure 2b. The same as Figure 2a, but for "hard" ores.

less than a gas-fired plant. If the ores are leaner, say 0.02%, this takes about 13 years. For poorer ores (e.g. 0.01%) the nuclear power plant is 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. If the present-day practice of using a 33 GW(th)day/Mg HM "burnup" of the fuel elements were to be replaced with the more modern value of 46 GW(th)day/Mg HM a slight advantage would accrue. This difference is too small to show in the graph.

The picture at the "end of the road" for both hard and soft ores, i.e. the total CO_2 emission of a nuclear plant compared to a gas-fired plant during the 24 full-load years lifetime of a nuclear plant (which is the maximum that can be expected; see Chapter 3 for the data on which this conclusion is based) is shown in Figure 2c. We see from this figure that for rich ores, hard or soft, the use of nuclear power would produce 30% of the total CO_2 emission of a gas-fired plant. But once the ore grade falls below 0.02% for hard ores, or 0.01% for soft ores, the use of nuclear energy leads to the

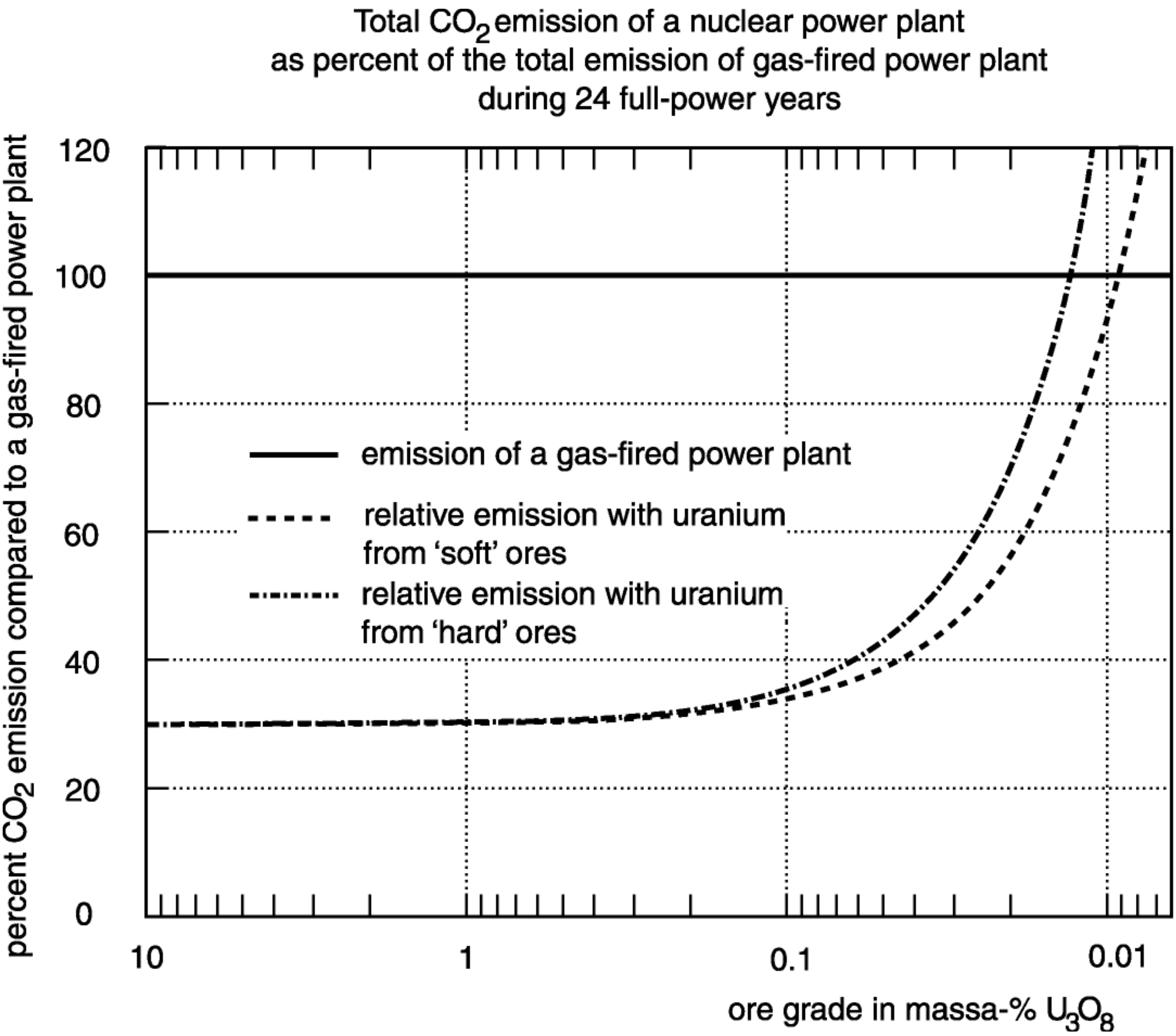

Figure 2c. A comparison between the total CO-2 emission of a nuclear plant at the end of its life (24 full-load years) and a gas-fired plant, for both hard and soft ores.

emission of more CO_2 than just burning the fossil fuels directly.

This picture makes it clear that it is highly relevant to ask how much uranium is available in the richer ores (above about 0.1% uranium content). It will be shown in Chapter 2 that this is not very much. Specifically there is not even enough to provide the world's yearly total electrical production of 60 EJ for even a full three years. And when this is gone, the leaner ores would produce more CO_2 than if one were to burn the fossil fuels directly. What it amounts to is that the factor of 3.3 gain in CO_2 emission provided by nuclear energy is a very temporary gain and not a basis for future energy supply.

Unpleasant as it is, we must face the fact that nuclear energy is not the "magic bullet" that will give us unlimited energy. The future of our civilization depends critically on reducing the use of energy drastically and rapidly.

Other possibilities of utilizing energy from nuclear reactions

(i) *The fast breeder.* If fast-neutron breeder reactors were a viable alternative to the "once-through" use of uranium, one could prolong the date of exhaustion of uranium, and perhaps considerably reduce the concomitant CO_2-emission. But the claims that such breeders would provide energy for essentially infinite time are no longer heard. In addition they would have to use, and produce, large amounts of plutonium, the ideal explosive for nuclear weapons. In this article we do not go into the very cogent objections to nuclear energy arising out of the danger to civilization that nuclear weapons represent, because this document is only concerned with energy costs and production.

Programs to develop fast-neutron breeders, programs demanding tremendous investments (not only of money, but also of fossil fuels), in the United States, the United Kingdom, France, and Germany have turned out to be failures. It would be unwise and unscientific if we were to claim that breeders can never be a viable energy source. No one can possibly prove that. But after a half a century of failed attempts the dreams of the fast-neutron breeder appear to be pipe dreams.

(ii) *Nuclear fusion.* Another pipe dream in the nuclear realm is that of fusion, i.e. the "melting" together of isotopes of the lightest element, hydrogen. This is the process that converts gravitational energy to heat and light in the interior of the sun. The primary energy-producing nuclear reaction in the sun is the fusion of (ordinary or light) hydrogen nuclei. It has always been clear that the temperatures and pressures necessary for this reaction are unattainable on earth. Until recently, however, energy production through the fusion of nuclei of deuterium (the D-D reaction), the next heavier hydrogen isotope, was thought to be possible. It was conceived that this could be done in a self-sustaining *plasma*, an almost totally ionized gas constrained by magnetic fields. The fusion of the deuterium nuclei releases energy which, the idea was, could amount to more than the tremendous energy necessary to produce and maintain the plasma.

The attractiveness of this option is that ordinary water contains deuterium (in the form of "heavy" water). It constitutes only 0.015% of water, but in the totality of the oceans there is an unimaginably large amount. In recent years it has become doubtful, however, whether a self-sustaining plasma is realizable. But what really seals the fate of fusion energy is that the D-D reaction, for fundamental physical reasons, cannot provide a net production of energy in a plasma. There are losses that cannot, even theoretically, be eliminated. The only reaction that could theoretically achieve net energy production is the deuterium-tritium (D-T) reaction. But tritium, the heaviest isotope of hydrogen, only exists in nature in the minute amounts formed by cosmic rays (see above in the section on energy costs and energy debts). End of the dream of an effectively infinite source of energy.

Not quite, perhaps. Fusion advocates believe that a "breeder" system could provide the necessary tritium. But even the most optimistic advocates do not expect the gigantic technical problems to be conquered in the coming fifty years. We have seen what has happened to the dreams of "breeders" before, and are therefore sceptical.

(iii) *Uranium from sea water.* If unlimited amounts of uranium were available one might possibly speak of nuclear power as a sustainable energy source. There is, in fact, an immense amount of uranium dissolved in the water of the oceans, although it is exceedingly dilute (a few parts per billion). There are advocates of nuclear energy who claim that this can be extracted in such a way that there is, theoretically, an energy gain (i.e., that the energy needed to perform the extraction is less than the energy which the uranium could produce in a nuclear reactor). The only attempt to prove that this is realistic resulted in an exorbitantly high cost of uranium.

(iv) *Exotic nuclear reactors*. A half a century of attempts to design and then build a functioning fast-neutron breeder reactor or to show the feasibility of producing energy from nuclear fusion, both at gigantic cost, have culminated in failure. Recently a new type of nuclear reactor has been conceived that differs fundamentally from all previous designs in that it is not "critical", i.e. it only amplifies the energy that is applied to it. This has the obvious charm that it cannot explode - cutting off the flow of input energy stops its working, immediately. The design differs in almost every detail from the present day reactor. It uses thorium, not uranium, of which there is more in the earth's crust. But its input energy must be supplied by a particle accelerator. If this can be done is an unanswered question.

We leave these possibilities, and probably many others still to come, to the future. What is important is that we are certain that today the claim is false that nuclear power is a sustainable energy source free of CO_2-emission. The operation of nuclear power plants on the *once-through* basis leads to the production, under the most favourable circumstances, of less CO_2 than fossil-fuel fired plants. The difference is not large, however, which means that nuclear power certainly cannot be considered a Clean Development Mechanism (CDM). Even more important is the fact that even if exploited to exhaustion in the coming fifty years, existing uranium ores could only provide an insignificant fraction of the energy predicted to be needed.

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The data and calculations on which our conclusions are based can be downloaded from the website: http://www.oprit.rug.nl/deenen