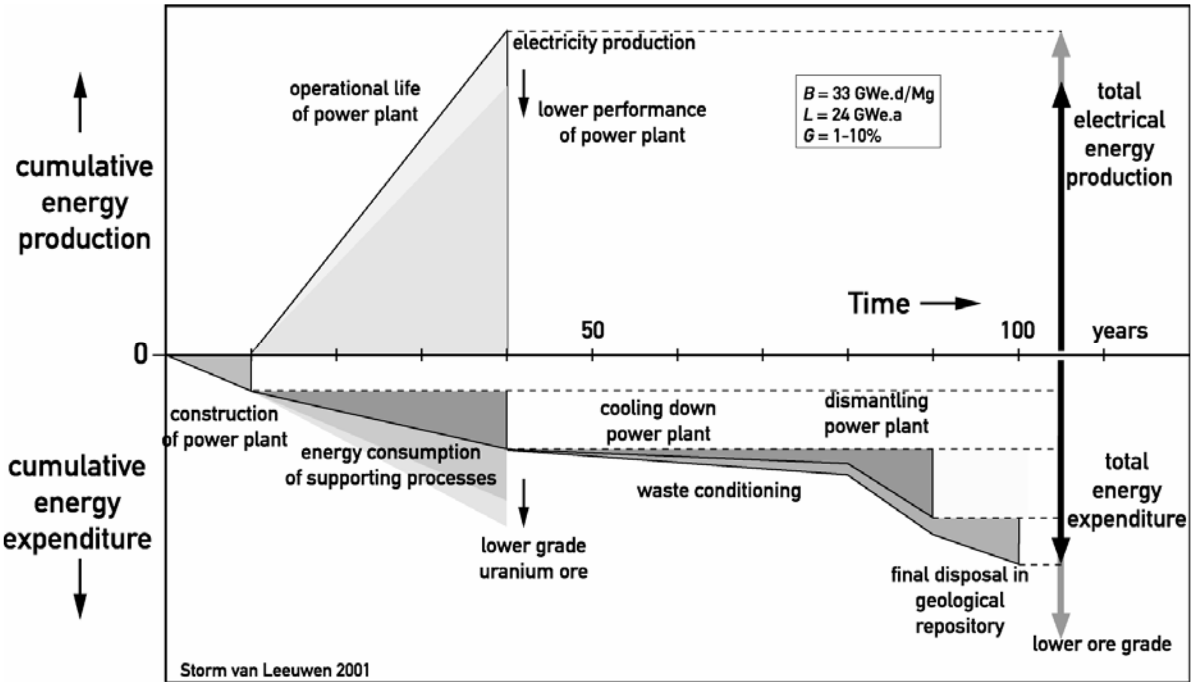
Nuclear Power: the Energy Balance

Introduction: General principles of sustainability; Summary of the costs of nuclear energy

Jan Willem Storm van Leeuwen and Philip Smith

Two debatable claims

The nuclear industry claims that nuclear power is a sustainable energy source and further that it produces negligible amounts of CO_2. These claims are 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 espoused by many in, and connected to, the nuclear industry. The main object of the five chapters comprising this document is to show that nuclear power not only leads to the production of far from a negligible amount of CO_2, but also, that it is most certainly not a sustainable energy source. This is underlined by the fact that if the known uranium resources were used to exhaustion, the total electrical energy produced would only amount to the present day world wide electrical energy use in less than a decade (this is shown quantitatively in Chapter 2). This limitation is masked at the present time by the fact that the electrical energy produced by nuclear reactors comprises only some two to three percent of the total useful energy consumption in the world, and there are still large deposits of uranium, with rich ore grades. If large numbers of nuclear reactors were to be built in order to satisfy the growing demand for electricity, the reserves of high grade ore would be rapidly exhausted, leaving immense amounts of low-grade ores over, most of which would cost more energy to utilize (if one includes all of steps of the fuel life cycle) than the reactors would deliver in the form of electricity.



Storm van Leeuwen 2001

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

The claim that nuclear energy does not cause CO_2–emission 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 in this study that there are large energy costs involved in producing electrical energy by nuclear power plants. Under present conditions that means burning fossil fuel, with the resulting 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 a gas-burning power plant with the same output. If all of the contributions are taken into account, a nuclear plant fueled with high-grade ores causes the emission of between one-fifth and one-third of the CO_2 produced by a gas-burning plant. But this relatively favourable ratio only holds as long as there are rich uranium ores available. When these are exhausted, the use of leaner ores for the operation of nuclear plants will lead to the production of more CO_2 than gas-burning plants. In the long run, nuclear power is therefore not a solution to the CO_2-emission problem.

Energy debt

The cause of this little recognized problem of nuclear energy is that it costs energy from other sources (principally produced by burning fossil fuels) to produce nuclear energy. More disturbing is that many of these energy costs only become apparent after a nuclear power station has stopped producing electricity and, so these costs will have to be paid by unborn generations who have not profited from the nuclear-produced energy. These are thus energy debts: debts incurred during its productive lifetime, which our descendants will have to pay. We have made them visible in pictorial form in Figure 1. Here we have represented the cumulative gross electricity production as a triangular area above the base line. The five costs/debts are all shown as dark areas below the base line. 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. The effect of a less than ideal performance of the plant is also indicated. The time scale is probably not realistic. No large nuclear power plant has ever been dismantled.

Another point that is frequently overlooked, is that nuclear power can only produce electrical energy, whereas most of the energy used by mankind is thermal (heat). Electricity can also be used for this purpose, of course, (one need only think of electrical irons, and ovens, and space heating provided by the degradation of electrical energy to heat by ohmic conversion), one unit of electrical energy can be converted into one unit of thermal energy or one unit kinetic energy.

Methodology

In many industrial cost analyses, monetary units (almost always U.S. dollars) are used. We have chosen, as has been done in most of the analyses in which environmental values are considered, to use units of energy in this analysis because energy is a conserved quantity, whereas money is an arbitrary, and more importantly, a variable measure. Particularly in comparing costs and benefits of various processes the use of a money scale introduces the unpredictable effects of such factors as market prices, cartel price-forming and price regulations. Comparing the dollar costs of two processes is therefore frequently meaningless. But more important than these sources of inaccuracy, the use of monetary units is based on the illusion money is wealth and that compound interest creates wealth. This illusion leads to the use of *discounting* which gives the false impression that the future value of anything goes slowly to zero. This is certainly not true of the riches of the earth, but absolute nonsense when applied specifically to energy. One may counter that at any given moment, a company must choose its course on the basis of the current monetary prices of materials and the current market value of its products. This is not the occasion to enter into an ethical or philosophical discussion, but in our view it is clear enough that it is exactly because of this conventional way of doing business that the planet now stands on the brink of environmental catastrophe. Whether we like it or not, if our civilization to survive, it is imperative that policy choices with long-term consequences no longer be based on quarterly profit figures, but on an analysis of sustainability criteria. How this is to be brought about is not the issue here. The issue is that an honest evaluation of any system used to produce energy (this is the conventional wording - the correct term is to "convert" energy), energy units should be used, both for the production and for the costs.

In the detailed calculations of this document we have determined the energy costs of all of the important constituent steps of the nuclear-energy life cycle. This analysis method, the life-cycle analysis (LCA) is the accepted way of evaluating the performance of complex industrial systems.

Several LCA's of nuclear power plants have been published, particularly during the late 70's and early 80's, as quoted in Storm 1985. After a quiet decade, these LCA's have recently become topical again, e.g. Mortimer [1991a and 1991b], Lako 1995, Uitert 1995, Uchiyama 1995, Orita 1995, Mishra 1995, Bitkolov 1995, Tyner et al. 1988, Dilemma 1999, IAEA TecDoc-753 1994, Proops 2001, Dwarshuis 1992, WNA-11 2005, WNA-critique 2003 and WEC 2004. as a consequence of climate concerns. The nuclear industry claims that its products are CO_2-emission free. This claim is only correct for the nuclear reactor itself. All other processes in the nuclear chain, essential to operating nuclear reactors, do produce CO2. Recent publications claiming low CO_2-emissions for nuclear power as compared with other energy systems, e.g. the studies put together in [IAEA WM 1995], turn out to be oversimplified and incomplete. In order to assess the sustainability of nuclear power, a complete LCA is mandatory.

Our choice of nuclear reactor system and fuel cycle

We have considered in this study only the so-called *once through* use of enriched uranium in a light-water-moderated high-pressure nuclear power reactor (LWR). In this process 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 period, to permit the radioactivity to decline so that they can be transported. The final destination, after conditioning, is an assumed stable geological stratum. The fuel is not reprocessed. The LWR in the once through mode is by far the largest source of nuclear energy, 88% of the power reactors of the world in 2002 (see atw-5 2003 and WNAinfo 2003) are LWR’s.

One may ask why we have not chosen to consider the option of fuel reprocessing. In principal, more of the energy of uranium could then be made available. There are some reasons for our choice.

Advantages of recycling nuclear fuel in LWR’s are questionable, see e.g. WNAinf13 2003, WNAinf15 2002 and NEA ppr 2003.

Breeder reactors, in fact the breeder cycle, will not become available for large-scale power generation within the next three decades (MIT 2003), see also Chapter 2.

Sustainability criteria

The First Law of Thermodynamics

No source of stored energy obtained from the earth's crust (such as coal, oil, uranium) can correctly be considered sustainable. This is because the First Law of Thermodynamics, i.e. energy cannot be created or destroyed, puts an absolute limit on the energy production. The internal energy in such fuels can be converted to kinetic energy (energy of motion) or electricity. These forms of energy, when used, are converted into heat. Once this has occurred, the heat energy will be dissipated into the environment where it cannot do any more useful work (work is used here in the technical sense of causing something physical to happen). The energy has not disappeared, but it has become degraded to uselessness. Therefore all such “sources” of stored energy will be exhausted eventually. In evaluating the use of such resources it is also important to realize that it costs energy to obtain and use them. At a certain point in the exhaustion of reserves, it will cost more energy to make the remaining part available than is delivered when it is used. Uranium and highly dispersed sources of carbon are examples. The only inexhaustible source of energy, from the point of view of the earth, is light from the sun, which comes from outside the system earth.

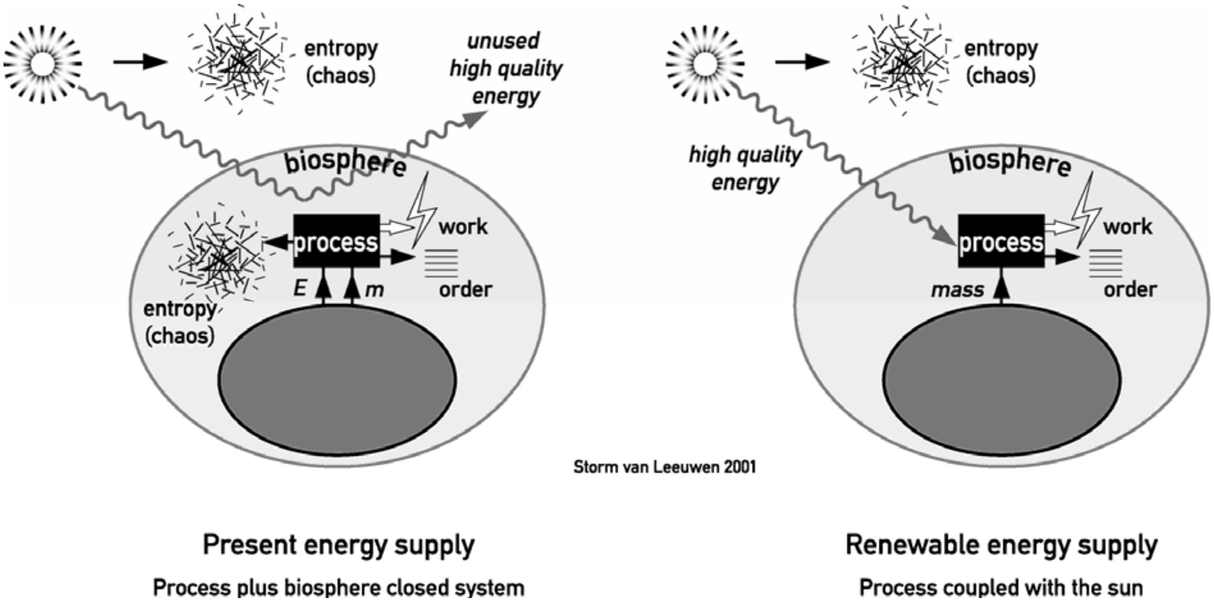
More than 90% of the present world energy supply is based on mineral resources and is consequently limited. Substitution of the mineral energy systems by renewable systems based on flow energy, will take decades. So, the basic question is: what role can nuclear power play in the forthcoming decades? This is a First Law problem: how much usable energy can be generated from the known uranium resources?

To answer this question, the net energy obtainable in a nuclear reactor from one kilogram of uranium has to be calculated, and corrected for all of the costs incurred in the life cycle. The total contribution of fission power to the world energy supply can be then calculated from the known uranium resources. This is done in Chapter 2. Evidently, it is too simple to take the theoretical energy content of uranium, which is based on the fission of all atoms in natural uranium: ^{235}U and ^{238}U, or even on the fission of all atoms of ^{235}U (a more modest degree of technological optimism), and on zero energy use of the system needed to convert the fission energy into electricity, from ore body through all of the steps ending in waste disposal. Visions of an unlimited energy supply by fission power ("too cheap to meter") stem from these naive assumptions. But even with breeder systems, only a part of the uranium can be fissioned.

As mentioned, the usable energy content of uranium can only be correctly calculated in an elaborate life-cycle-analysis (LCA), as is done in this report. As it turns out, even if all known uranium reserves are exhausted, the total energy produced (i.e. converted to a usable form) amounts to only a negligible part of the energy which forecasts predict will be needed in the coming decades.

The Second Law of Thermodynamics

A second, and more rigorous, sustainability criterion is provided by the Second Law of Thermodynamics, which states that any conversion of energy in a closed system such as the biosphere, causes an increase of disorder, or chaos. This is illustrated in Figure 2.



Storm van Leeuwen 2001

Figure 2. In this figure the fundamental difference between a renewable energy source and one using materials in the crust of the earth s shown schematically. See the text for further explanation.

The drawings in Figure 2 illustrate how the unavoidable entropy (disorder) increase caused by the conversion in the sun of the potential energy of nuclear forces into heat and light remains on the sun. If, however, energy conversion (of resources from the earth's crust) takes place in the biosphere of the earth there must result degradation of the environment. In order to make an honest evaluation of energy conversion under the constraint of environmental sustainability we require in this study that, besides the bare energy costs needed to obtain the energy in the first place, the (energy) costs of repairing this degradation are chalked up as debts against the positive energy made available by the conversion. The costs of nuclear energy in this report are calculated on the basis of this criterion, i.e., that the process itself must provide the extra energy needed to "repair the damage". In particular, it is found that when the richness of available ores drops below a certain critical value, there is no energy surplus to satisfy this criterion. This will occur long before the inevitable exhaustion (prescribed by the First Law) has occurred.

The type of process shown on the right in Figure 2 can, if properly done, provide a truly sustainable stream of useful energy. That is why we stated above that the sustainability criterion prescribed by the Second Law is more rigorous than the criterion of availability of energy sources, laid down by the First Law. The increase of entropy resulting from this conversion occurs on the sun. Only the energy of light is exported to the earth. This 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 on the planet developed a closed cycle. All of its detriments are recycled (or rather *were*, before fossil fuels entered the picture) using the clean energy from the sun, and the total entropy in a closed natural life-cycle does not increase with time.

As stated, the existence of life on earth was only possible because of the immense stream of low-entropy energy from the sun, and its evolution up to today probably could not have taken place if were not for the sequestration, by life processes themselves during eons in the past, of a vast amount of carbon in calcareous rocks and burnable carbon and hydrocarbons. This sequestration removed almost all of the CO_2 from the atmosphere, and led to its present composition in which existing life forms can live. In Kyoto, almost ten years ago (1997) this was, to a certain extent, recognized. Disregard of the agreements reached there could have disastrous consequences. Mankind is literally "playing with fire."

An idealized picture of a process taking place on earth, but using the clean energy from the sun, is as shown in Figure 3, and compared with the use of nuclear energy. The basic difference in the environmental effects between the present means of energy production and a sustainable one, using energy from the sun is illustrated.

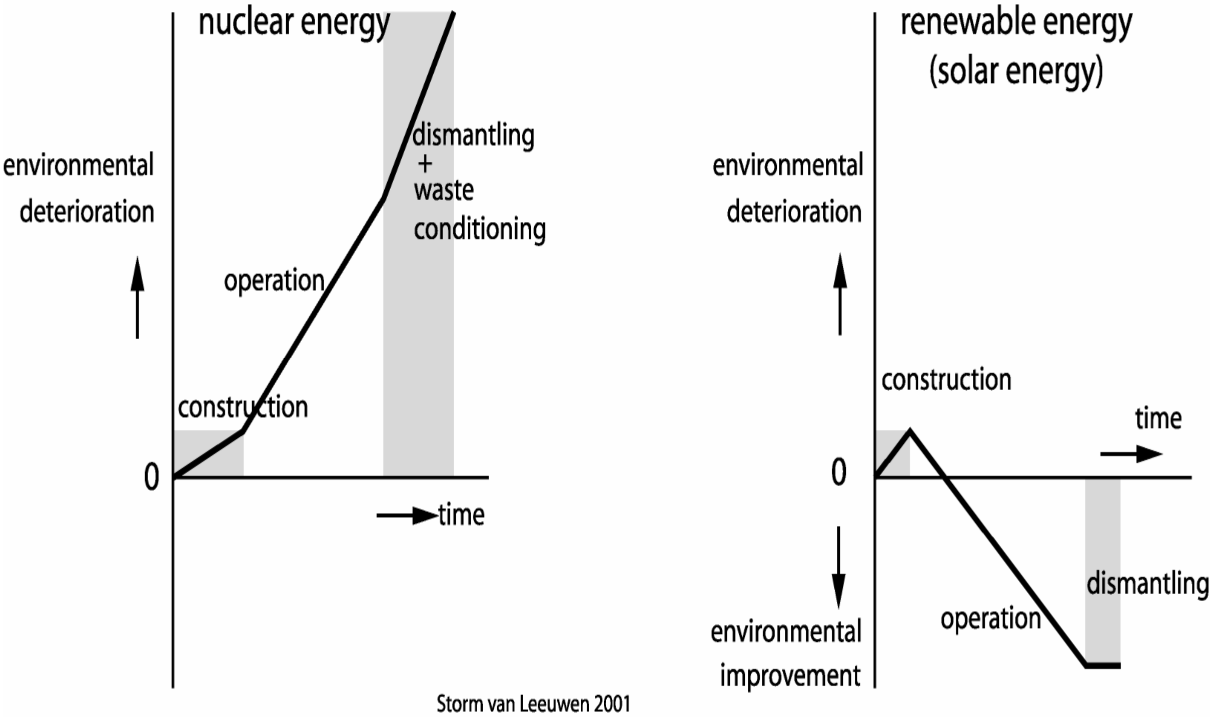


Figure 3. In this figure the difference in the environmental effects of nuclear power and an energy system operating on solar energy is shown. Nuclear energy is generated from resources within the biosphere, so all entropy of the conversion process flows into the biosphere. More entropy means deterioration of the environment. In case of solar energy systems, the entropy of the energy generating process remains on the sun. Solar electricity can be used to lower the entropy of the biosphere and thus improving the quality of the environment**.**

The factual foundations of these calculations

The calculations of this report are based on the data to be found in the references. Since an elaborate study in 1982 [Storm, 1982], few new data have become available on most parts of the nuclear process chain, especially the head of the chain. More recent studies, see above, use partly the same references as [Storm, 1982]; hardly any more recent data are used. In this revised version we only refer to the primary references. Evidently, the specific energy uses of the processes in the nuclear chain have not changed significantly since 1982. The present study differs from many other studies in that the energy expenditure and net energy production of the full nuclear process chain are calculated as a function of the operating time (T_{100}), measured in full-power years. In other studies a fixed operating time is assumed, mostly an optimistic high estimate of 30 to 40 years with high load factors of 0.7 - 0.8. These high values are not substantiated by the statistics of the present nuclear power plants in the world. The actual performance of the ~400 operating reactors is treated in details in Chapter 3, where it is shown empirically that 24 full-power years is the longest lifetime that may be expected as an average for all reactors of the world.

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. Up to the time when the burning of fossil fuels began, mankind (as well as all life on earth) was entirely dependant upon this solar energy. What are the criteria that an energy source must satisfy in order to be labelled as sustainable? There are two. One must know how much energy is available (physical sustainability) from a source as well as the effects of its use on the environment (environmental sustainability).

Physically unsustainable energy sources

Fossil fuel is obviously not a sustainable source of energy. As mentioned, 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, as was argued above, 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 available, it hardly provides more energy than would be obtained from burning the fossil fuels directly. If low-grade ores were to be utilized, a nuclear power plant would actually provide 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 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, as stated above, 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. As we have remarked, the sequestration of CO_2 from the atmosphere in the form of coal, oil, calcareous rock, etc. was probably 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!*

Based upon the false claim that nuclear power is free from CO_2-emission, and therefore environmentally sustainable, the nuclear industry claims that nuclear power should be classified as a Clean Development Mechanism (CDM). It would then be eligible for the transfer of low-CO_2-emission technology from North to South. As we have argued, this claim is based upon a distortion of the facts. As explained, 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 as well as the depleted uranium, and finally in order to dismantle the plant. Most of this energy must be obtained by burning fossil fuels, and, as we have noted, a great deal of this fossil-fuel energy will be 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 (in the sense of "weak" sustainability, by which we mean that as long as the raw materials are not exhausted, the process does not permanently damage the environment) 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 exhausted. 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 in this study that nuclear power is not a viable way to substantially reduce CO_2-emission except in the very short term, i.e. as long as very rich uranium ores are not exhausted. It is no exaggeration to say that nuclear power can only exist because it is fueled by fossil fuels. If the fossil fuels are gone, nuclear energy will also have to disappear.

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 calculated in the following chapters, is that 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.[1] This is no small matter, and we hasten to explain our choice. We are quite aware of the fact that in practically all modern technological processes the environment is to some extent adversely affected. So why do we take such a strict view, and how would the conclusions we reach be affected if we were to take a more tolerant attitude? One reason for strictness is that between that and a total abandonment of any protection of the environment there are myriad levels of protection that one could demand, and that for each step one would have to justify the particular choice made. Our strict choice leads to the easiest conceptual picture. We have made one exception to this policy, and that is in the dismantling of the reactor. We present both the results of including and of neglecting this very large energy cost, i.e. debt. It is conceivable that society will decide to leave no longer useful reactors intact, but simply totally isolated from the environment, instead of painstakingly dismantling them and sequestering the radioactive detritus in stable geological strata, a course that would show responsibility toward future generation. A policy of simply abandoning them would lead to an apparent substantial lowering of the energy debts of nuclear energy. Apparent, because the costs will reappear later, in a time in which there are no fossil fuels are available to provide environmental protection. This poisoning of the environment would indeed result in more "efficient" nuclear power, in the sense that the present cost items would be lower, the momentary energy efficiency higher.

---

[1] 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 same holds true on radioactive carbon C-14.

Summary of the cost items of nuclear energy

The most important 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 ;
ii the energy costs of mining and refining the uranium in the ores, and
iii the energy costs of enrichment of the uranium and fabrication of the fuel elements;
iv operating and maintenance costs (including refurbishment of the plant itself);
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 reserves – reserves that can not properly be labelled ores, since they can deliver no energy above that required for their use.

In Chapter 2 we give the energy costs of mining and milling the uranium fuel for nuclear reactors, as well as the steps leading to the production of fuel elements. But since the environmental destruction becomes gigantic as ores become leaner, in Chapter 4 we consider separately the energy costs of repairing the damage, including sequestration of the highly radioactive spent fuel elements and of depleted uranium, and returning the mining and milling area to "green field" conditions, We realize that it is improbable that mining and milling areas will ever be returned to "green field" conditions. But, in that case, the exposure of life, animal and vegetable, to the radioactive wastes laid bare by these processes will be something that future generations may never forgive us for.

The energy debts incurred by a nuclear power plant have to be paid after the plant has reached the end of its useful life. To summarize, they are:
iv the energy costs of conditioning the extremely radioactive spent fuel elements so that they can be sequestered in a presumably stable geological stratum plus the energy costs of sequestration, Chapter 4);
v the sequestration of depleted uranium left behind by the enrichment (Chapter 4), and
vi the energy costs of dismantling the plant itself, and of sequestering the diverse radioactive detritus (Chapter 3). As mentioned, we have calculated the energy costs of the entire life cycle **with** and **without** including this last energy item.

Paying the costs of the first four 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 that nuclear energy does not result in CO_2 emission.

Up to the present, none of the 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.

Pretending that these debts do not exist does not make them go away. They are not like bad debts that can be simply written off as losses on the ledger. Mankind will have to pay them one day, or pay the consequences of a poisoned environment.

It is important to note that we carry out our calculations, as mentioned, for two cases: the first takes account of all costs and in the second we take all costs into account but leave out the debt of dismantling the reactor system. Specifically, this means in the first case that we assume a debt of 240 PJ (in Chapter 3 this is explained), and in the second we only take account of the building costs, which we estimate to be 80 PJ.

Itemized list of the costs of, and the debts incurred by, the use of nuclear energy.

PROCESS	CHAPTER WHERE THE COST IS DERIVED	ENERGY USED	THERM ELEC RATIO
* MINING AND MILLING,SOFT ORES	Chapter 2, Eq.2.1 -2.2	c = 2.75x10^{-4} PJ/MgU	7.5
* MINING AND MILLING,HARD ORES	Chapter 2, Eq.2.1 -2.2	c = 6.54x10^{-4} PJ/MgU	1.6
CONVERSION TO UF$_6$	Chapter 2, Eq. 3	1.5x10^{-3} PJ/MgU	27
ENRICHMENT	Chapter 2, Eq. 4.1 – 5.4	*5.5x10^{-3} PJ/Mg SWU	0.51
FUEL-ELEMENT FABRICATION	Chapter 2, Eq. 6	3.8x10^{-3} PJ/MgU	2.5
OPERATE,MAINTAINANCE,UPGRADE	Chapter 3	2.0 PJ/300d	11
MINE AREA CLEANUP	Chapter 4	4.5x10^{-6} PJ/Mg TAILINGS	8.0
SEQUESTERING DEPLETED URANIUM	Chapter 4	1.7x10^{-3} PJ/MgU	22
INTERIM STORAGE SPENT FUEL	Chapter 4	9.3x10^{-3} PJ/MgU	15
CONDITIONING SPENT FUEL	Chapter 4	2.0x10^{-3} PJ/MgU	11
EQUESTERING SPENT FUEL	Chapter 4	1.0x10^{-3} PJ/MgU	8.1
CONDITIONING OPERATIONAL WASTE	Chapter 4	4.4x10^{-1} PJ/300d	10
DISPOSAL OPERATIONAL WASTE	Chapter 4	7.1x10^{-2} PJ/300d	8
DISPOSAL ENRICHMENT WASTE		8.5x10^{-5} PJ/Mg SWU	9.9

* The energy used for mining and milling is found by substituting the ore grade, G, and the value of c in the equation:

$$\frac{c}{0.98 - 0.0723 \times G \times \left(\log G\right)^2}$$

* Note that because the standard unit, SWU, is so small we have introduced the unit Mg SWU, that is 1000 times larger.

The derivation of all of these costs are is repeated in Chapter 5, where the references to the literature from which they are derived are also given.

Diverse parameters and quantities (assuming a burnup of 46 GW(th)day/MgHM)

electrical energy produced in full-power 300 days (corresponding to one reload period) 25.92 PJ
number of reloads assumed for a lifetime of 24 full-load years: 28
initial load: 81.2Mg, assay 3.3%, reloads: 20.3 Mg, assay 4.20%
Enrichment: feed assay: 0.71%; tail assay: 0.20%
total mass of natural uranium used in the lifetime of the reactor, 4951.6 Mg
gross lifetime electricity generation,0.1518 PJ/Mg = 151.8 EJ/Tg natural uranium

Nuclear power plant parameters

We assume that the energy is produced in a pressurized water reactor (PWR) based on a “once through” fuel cycle (without reprocessing of spent fuel).

The parameters of the nuclear power plant and its operation, taken as model in this study, are given below. We have assumed that the highest presently used burnup practice (i.e. giving the most energy from the uranium "burned") of 46 GW(th)day/MgU):

net power	$P(e)$ =	1000 MWe
thermal power	$P(th)$ =	3125 MWth
equilibrium discharge batch average burnup	B =	46 GW(th)day/Mg U initial
core specific power	S =	38.5 MW(th)/Mg U initial
first core mass	m_{fc} =	81.2 Mg U
fraction of core replaced in equilibrium reloading	F =	1/4
assay first core	x_{fc} =	3.3% ^{235}U
assay reloads	X_{rel} =	4.2% ^{235}U
full-power time between reloads	D =	300 days = 0.82 full power years

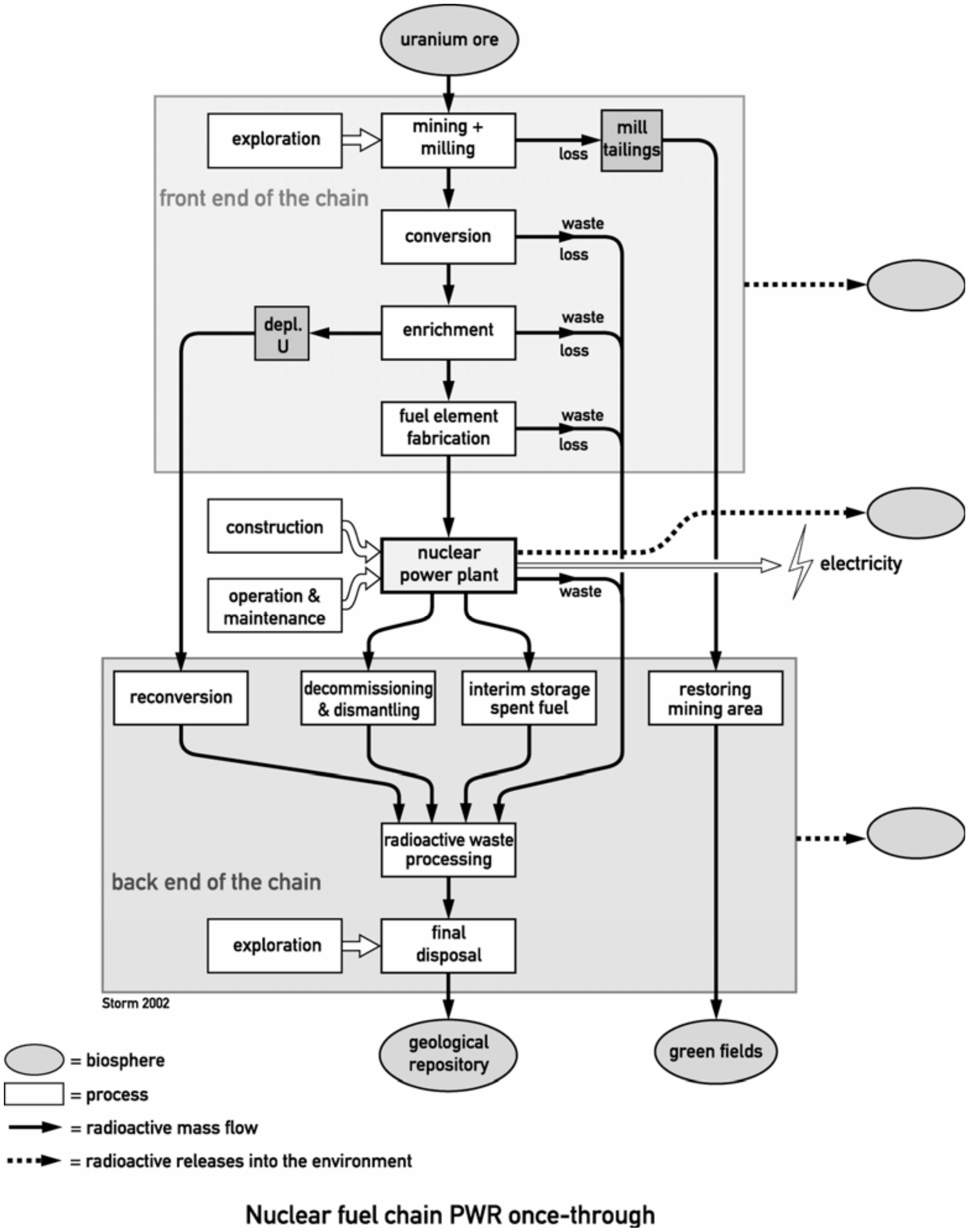
reload mass $m_{rel} = m_{fc} \bullet F = 20.3$ Mg U

$$m_{tot} = m_{fc} + m_{rel} \bullet \left(\frac{T_{100}}{D} - 1 \right), \text{ for } T_{100} \geq D \qquad \text{(Eq. 1)}$$

T_{100} = full-power operating time (years) and m_{tot} = total (enriched) uranium consumption.

References [Jan and Krug, 1995], [Scheidt, 1995], [DOE/EIA, 1997].

In the figure (below) we show schematically all of the elements that we have included in the nuclear-plant process chain.



In this figure the entire nuclear chain is illustrated. In the following chapters the various energy costs are calculated.

In Chapter 2 the four boxes (excluding exploration) in the shaded area at the head of the chain are treated. The operation of the reactor itself is analyzed in Chapter 3. The six boxes (excluding exploration) inside the larger box at the tail of the chain comprise the "energy debts". These are the subject of Chapter 4. All of the relevant equations are summarized in Chapter 5.