Energy debt, latent CO_2 emissions, latent entropy

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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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Introduction

Generation of electricity by from uranium requires a complex system of industrial processes.A nuclear power plant is not a stand-alone system, it is just the most visible component, the pivot, of a sequence of industrial processes. The nuclear process chain has three main parts: front end, mid section and back end. The front end (also called upstream processes) comprises the industrial processes required to fabricate nuclear fuel (enriched uranium) from uranium ore as found in nature. The mid-section encompass the construction of the nuclear power plant and its operation, maintenance and refurbishments (OMR). The back end (downstream processes) includes the industrial processes needed to safely dispose of all radioactive wastes, generated by the reactor and other processes of the process chain: the nuclear legacy.
A metaphor of the complete nuclear sequence, in fact of any industrial production process, may be seen in a common daily household sequence:

Figure 1
Metaphor of the life cycle process chain of any industrial production process, including the nuclear process chain

This study divides the industrial processes related to a given nuclear power plant (NPP) into two categories: *contemporary processes*, occurring in advance of or during operation of the NPP, and the *future processes*, that are to be performed after final closedown of the NPP. Metaphorically speaking: the future processes comprise 'clearing the table and washing the dishes'. The activities of the downstream processes are called 'future processes' because they have to occur in the future. The table is not cleared and not one dish has been washed: after more than 60 years of nuclear power all human-made radioactive materials are still piled up in the human environment in vulnerable temporary storage facilities.

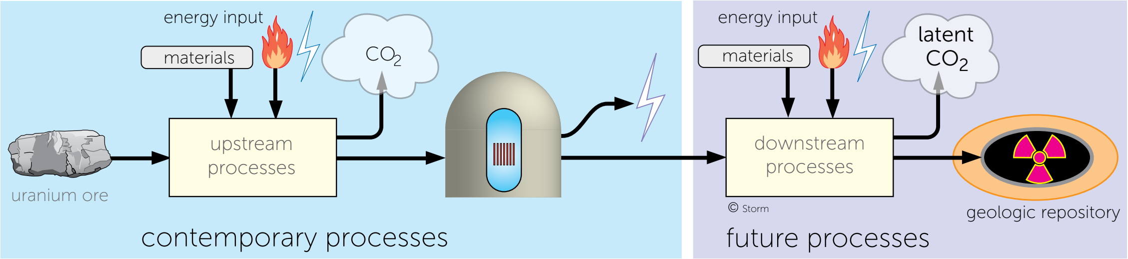

Figure 2
Simplified outline of the nuclear process chain, as it ought to be. The three main parts are the upstream processes or front end, from ore to nuclear fuel, the powerplant itself (construction, operation, maintenance & refurbishments during its operational lifetime) and the downstream processes or back end, comprising the safe and definitive sequestration of all radioactive wastes. Most activities of the downstream processes are still to be done. In 2019 not one geologic repository in the world was operational.

Each process of the nuclear chain consumes materials and energy and emits CO_2 and possibly also other greenhouse gases (GHGs). Fission of uranium in the nuclear reactor is the only process in the chain that does not emit CO_2. Emissions of other GHGs by the nuclear system are not mentioned by the nuclear industry, although a number of processes of the nuclear chain most likely do emit also other GHGs.

A nuclear power plant of 1 GWe irreversibly generates each year an amount of human-made radioactivity equivalent to more than 1000 exploded atomic bombs of about 15 kilotons (Hiroshima bomb). Each year the civil nuclear power plants of the world add more than 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 of 1 GWe during one year at full power. The irreversible and harmful consequences of these disasters are noticeable on continental scales, affecting hundreds of millions of people, costing hundreds of billions of dollars, and will continue for centuriess into the future.

Adequate fulfilment of the downsteam (back-end) processes of nuclear power plants is a *conditio sine qua non* to avoid dispersion of the remaining 99.99% of the *nuclear legacy* into the biosphere and to keep vast areas on the Northern Hemisphere habitable. Fulfillment of the downstream processes may take a period of 100-150 years after closedown of the nuclear power plant, according to estimates by large nuclear institutes.

For estimation of the CO_2 emissions of nuclear power, the industrial processes comprising the nuclear process chain are divided into two categories: *contemporary processes*, occurring in advance of and during the operational lifetime of the nuclear power plant, and the *future processes*, occurring after final shutdown of the power plant. The contemporary processes encompass the upstream processes, needed to recover uranium from ore and to fabricate fuel elements for the reactor, in addition to construction of the nuclear power plant and operation, maintenance + refurbishments during the operational lifetime of the reactor. The future processes encompass the activities needed to manage all radioactive waste generated during operation of the nuclear power plant in the safest possible way and to isolate it from the biosphere.

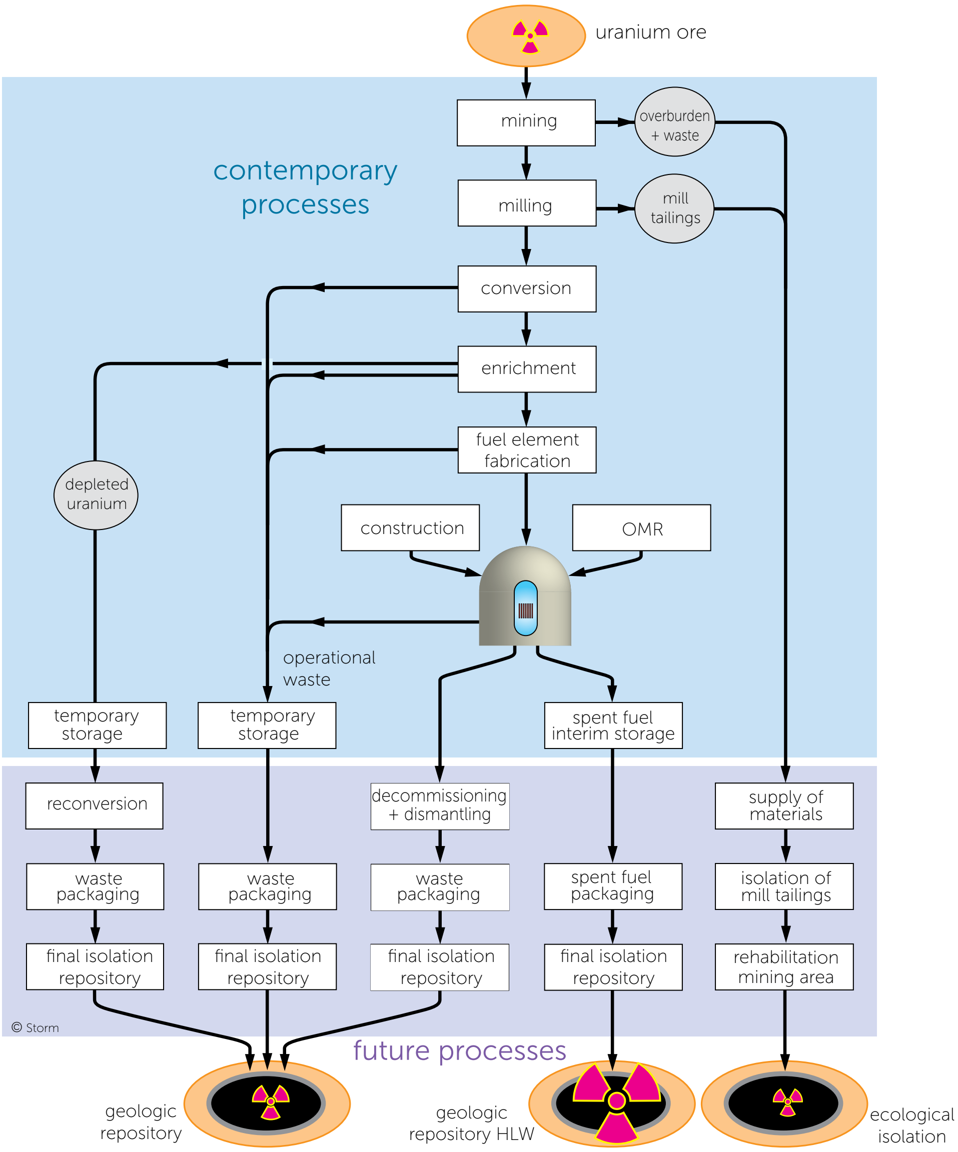

Figure 3

Complete nuclear process chain, divided into two subchains: the contemporary processes (front end or upstream processes) and the future processes (back end or downstream processes of the nuclear process chain). OMR = operation, maintenance and refurbishments. HLW = high-level waste.

Each process of the nuclear chain generates radioactive waste and non-radioactive waste. In this study the scope is limited to radioactive waste. The radioactive waste of the upstream processes, from ore to fuel, contain only naturally occurring radio-isotopes: uranium and thorium plus their decay products. During operation of the reactor the radioactivity of the involved materials rises a billionfold, caused by the generation of dozens of human-made radionuclides, in addition to uranium isotopes. This radioactivity is contained in spent fuel and in materials of the reactor plus associated installations.

Purpose of the downstream processes is to avoid dispersion of these hazardous materials into the biosphere. This study starts from the viewpoint that all radioactive materials should be isolated from the biosphere. To that end the wastes are packed in appropiate containers that are disposed of in geologic repositories. In practice not all radioactive waste of the nuclear chain can be packed in containers, that are, mining waste and radioactive effluents (authorised and unintended discharges) from the nuclear power plant during its operational lifetime.

More details are discussed in related reports, such as:

m04	*Decommissioning and dismantling*
m05	*Downplaying and denial of health effects*
m11	*Health effects of radioactivity*
m17	*Pathways of radioactive contamination*
m21	*Nuclear safety*
m32	*Geologic repositories*
m37	*Problems for the future - message to the future*
m38	*Nuclear power and the Second Law*
m40	*Radioactive waste management, future* CO_2 *emissions*
m41	*Uranium mine rehabilitation*

Energy on credit

Risk factor

Perhaps the biggest risk factor facing nuclear security is not a technical issue, but a paradigmatic one. The chances of nuclear terrorism and criminality and of large-scale nuclear accidents, with irreversible consequences affecting vast areas of inhabited land and millions of people, is greatly increasing as the nuclear industry persists in its current paradigm, characterized by a short time horizon, living on credit and an *après nous le déluge* attitude. The problems ensuing from the back end of the nuclear process chain cannot be handled adequately by the current commercial way of thinking. The security problems and health hazards posed by nuclear power will persist for the next century, even if the waste problem were to be tackled vigorously from this moment on, and even if the world's nuclear power stations were all closed down today.

System boundaries and time horizon

A fundamental issue in the discussion of nuclear energy is the scope of the arguments. Does one take the entire nuclear process chain into account, or only one part of it, usually the most visible part, the nuclear power plant itself? Does one use economic arguments, or physical arguments, or does one conveniently mix up economic and physical arguments without explicitly defining the scope of the arguments? What timescale is used, when discussing nuclear energy? A few years until the next election, a decade according to an authoritative scenario of the nuclear industry, or the whole cradle-to-grave period of a nuclear power station and its associated facilities viewed as one system?

Assessment of the implications of nuclear power should take the whole cradle-to-grave period into account: the timeframe that covers all industrial activities directly related to a particular power plant, from uranium mining through definitive disposal in a geologic repository of the last container of radioactive waste. The cradle-to-grave (c2g) period of a nuclear power plant will last at least a century and the existing nuclear power plants are not much further than halfway through their c2g period. During the second half of its c2g period a nuclear power station does not generate profits anymore. The greatest challenges with respect to nuclear security originate from the activities and processes occurring in the second half of the c2g period. It is precisely these processes which are shrouded by the greatest uncertainties and unknowns. So for appraisal of nuclear security now and in the future assessment of the complete c2g period is of utmost importance.

The nuclear process chain encompasses a substantial number of partial processes, which are run by different companies in widely dispersed places (sometimes on different continents) and often at widely different points in time. The time lag between processes directly related to one particular nuclear power station may vary from a few years to more than a century.

Economic calculations are done by the company, consequently comprising only one partial process of the nuclear chain at a time, and have a short time horizon, usually no more than a couple of years. This way of thinking does not result in a reliable overview of the hazards of the complete nuclear process chain.

Physical energy analysis

Arguments based on the free-market paradigm are not well suited to assess the implications of nuclear power in a global perspective with a long time horizon. Only a method based on unambiguously defined quantities, which do not depend on political and economic viewpoints, is appropriate.

Answers to questions regarding nuclear security, energy security, public health safety and climate security

(CO_2 emissions) of nuclear power can be found only by means of a complete life-cycle assessment (LCA), covering the full cradle-to-grave period, and a physical energy analyis of the complete nuclear process chain. It is essential that all material and energy flows involved in applied nuclear technology are analyzed and accounted for in energy balances. Materials and constructions required in the process chain are represented in the energy balance by the amount of energy consumed by their production from raw materials as found in nature. In this way it is possible to express the material and energy inputs and outputs of a technical system in one unit of one unambiguous quantity: energy units.
These balances should include the investments of future processes that are directly coupled to the present-day operation of nuclear power plants. Energy is a conserved quantity, so unambiguous comparison of the benefits and drawbacks of different energy technologies is only possible by means of energy analyses of the involved energy systems, each spanning their full c2g period. Balances in monetary units depend on a number of variable assumptions, changing with time and location.

Energy debt

As a result of the living-on-credit paradigm prevailing in the nuclear industry, all human-made radioactivity ever generated is still stored in makeshift facilities. Isolation from the biosphere of all radioactive materials in the least risky way will require high investments of energy, materials and human resources. Adequate completion of the nuclear back end is a *conditio sine qua non* to secure our children, grandchildren and future generations against the insidious hazards of the tremendous quantities of human-made radioactivity.

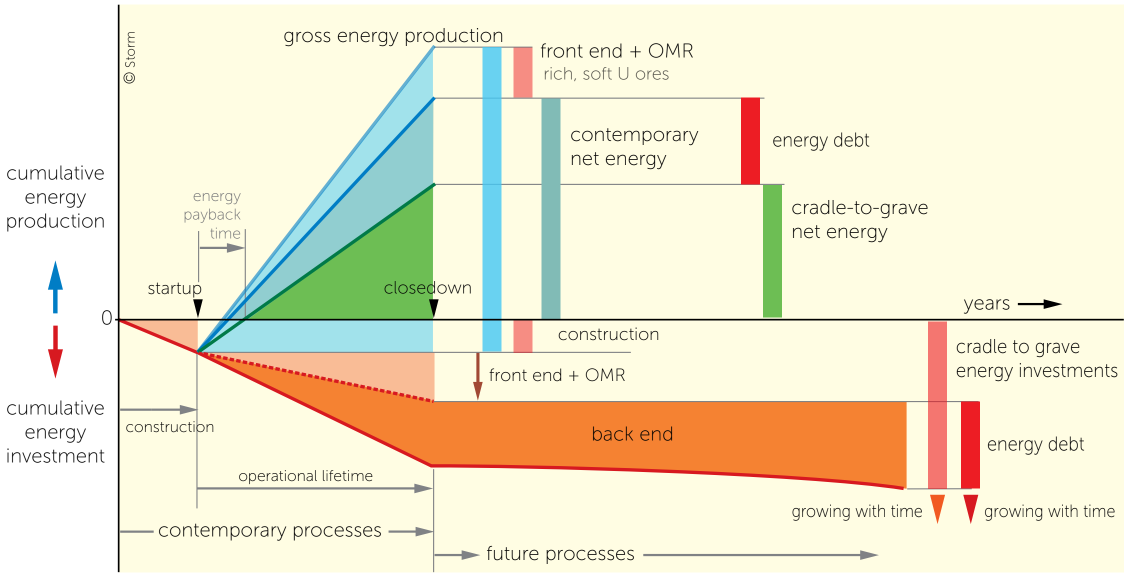

Figure 4
Dynamic energy balance of the nuclear energy system. The vertical scale has energy units, the horizontal scale is a timescale. OMR stands for operation, maintenance and refurbishments. The graph is roughly at scale. The lifetime net energy production will decrease with time, because of the increasing energy input of the front end part due to the decreasing quality of uranium ores. The energy debt increases with time due to spontaneous degrading processes (ageing).

Notably the following activities of the back end of the nuclear process chain will be demanding:

- dismantling and site cleanup of nuclear power plants
- dismantling and site cleanup of reprocessing plants
- durable packaging of spent fuel

- rendering the inventories of plutonium, uranium-233, neptunium and americium unusable for nuclear explosives and packaging the resulting product in durable containers for final disposal in a geologic repository
- cleanup of temporary waste storage facilities
- durable packaging of radioactive wastes other than spent fuel, including reprocessing waste and dismantling waste
- construction of the required geologic repositories
- definitive storage of all radioactive waste in geologic repositories and filling the remaining volumes of the galleries and access tunnels of the repositories with bentonite-sand.

The fulfillment of the back end processes involve large-scale industrial activities, requiring massive amounts of energy and high-grade materials; these future investments are called the *energy debt*.

The energy debt can be roughly estimated by a physical analysis of the processes needed to safely handle the radioactive materials generated during the operational lifetime of the nuclear power plant. The energy debt built up during construction of the nuclear power plant is repaid during the first years of the operational lifetime. Figure 4 represents a dynamic energy balance of the full nuclear process chain, from cradle to grave. For a comprehensive analysis of the energy balance of nuclear power see reports m03 *Contemporary* CO_2 *emissions of nuclear power* and m40 *Radioactive waste manegement, future* CO_2 *emissions*.

The size of the nuclear energy debt is unprecedented in history. Each currently operating nuclear power plant leaves behind an energy debt as large as approximately one third of its lifetime energy production. During the next decades this debt fraction will rise considerably, due to several factors:

- Increasing amount of radioactive materials generated as long as nuclear power generation is being continued, and an increasing number of temporary storage sites.
- Inevitable deterioration and ageing of materials and constructions of the temporary storage facilities of radioactive waste. The lower the quality of those facilities, the more energy and materials are required to upgrade them to a safe standard.
- Increasing efforts needed for maintenance and safeguarding of the temporary storage facilities, a consequence of the two points above.
- Increasing energy intensity of the required materials, as a result of decreasing ore grades and greater depths of the mineral deposits. For example: with time more energy has to be invested to obtain one kilogram of steel from iron ore deposits in the earth’s crust.
- Increasing energy intensity in extraction of the mineral energy sources (chiefly fossil fuels): more energy is needed to recover a unit of useful energy from the earth’s crust, due to the ongoing depletion of easy oil, gas and coal resources and exploitation of increasingly harder recoverable resources. This effect comes on top of the preceding effects.

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 CO_2 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.

The CO_2 emissions coupled to those processes have to be added to emissions generated during the construction and operation of the NPP if the CO_2 intensity of nuclear power is to be compared to that of other energy systems.

Whether the back end processes would emit also other greenhouse gases is unknown.

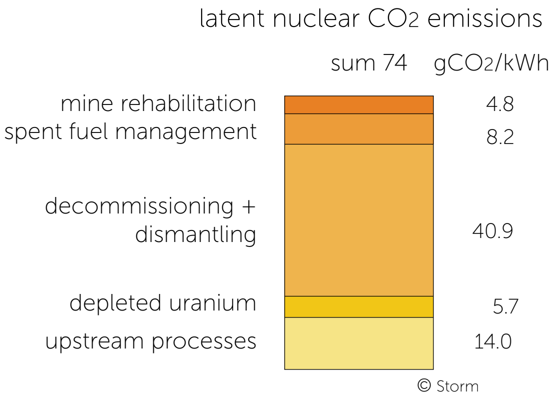

Figure 5

Latent CO_2 emissions of nuclear power. The contribution indicated by 'upstream processes' comprise the emissions of the management and final disposal of the wastes of the upstream processes. For details see report m40 *Radioactive waste management, future CO_2 emissions*. The latent CO_2 emissions are generated in the future, but are directly connected to a nuclear power plant operating today

Claiming that nuclear power is a low-carbon energy system, even a zero-emission system, seems strange in view of the fact that the CO_2 debt built up during the past six decades of nuclear power is still to be paid off.

Economic challenge

Financial debt

Obviously the energy debt will translate into a financial debt, for there is a strong connection between the cost of an activity in monetary units at one hand and the consumption of energy, materials and human effort of that activity on the other hand.

The financial debt ensuing from the energy debt and material debt has a character fundamentally different from the monetary debts economists are used to. Present economic concepts may be iincapable of handling the problems and risks posed by the nuclear heritage, in view of the following characteristics:

- Energy is a conserved quantity and for that reason the energy debt and consequently the corresponding financial debt are not discountable and cannot be written off as uncollectable. The energy debt is not subject to monetary-like depreciation, on the contrary, it will increase with time, as explained above.
- The timescale of over a 100 years is unprecedented in history.
- The massive investments of energy, materials, human resources and economic means do not contribute to the improvement of the economic infrastructure and must be considered to be pure losses. As the investments are used to isolate the radioactive wastes including their safe storage away from the human environment, the profits of the investments are apt to vanish from the economic system forever.
- Increasing energy intensity of materials will translate into a higher cost per unit product. The longer the defnitive and safe disposal of radioactive waste is postponed, the higher the cost per unit waste will have in order to achieve a given level of security.
- In addition to the unavoidable growth over time of the energy debt, measured in physical energy units, energy from fossil fuels will become more expensive with time, due to reasons explained above.

All growth effects come on top of each other and cause a steep exponential growth of the cost of maintaining our security standards. If the world economy stagnates or even declines, it will become more demanding to allocate economic activities to manage the radioactive wastes in the proper fashion. These observations point to an increasing risk of making less than optimal choices on how to isolate the radioactive legacy of nuclear power from the human environment. Consequently the security and health risks of nuclear power rise with time.

Misconception

The view that the solution of the radioactive waste problem is a matter of advanced technology is a misconception, for the immobilization of radioactivity is a Second Law problem. It is not possible by use of advanced, yet to be developed, technology to prevent the spread and dispersion of radioactivity into the environment with less effort than it would require at this moment. Spread can only be limited by dedicated human efforts, using mature conventional technology, involving massive amounts of useful energy and materials. As useful energy and materials are becoming increasingly scarce, the chances of solving the radioactive waste problem in the least dangerous way can only decline with time, and so will nuclear security.

Human resources

An additional problem may become shortages of sufficiently skilled workforces to perform these demanding tasks. If nuclear power is phased out, the required expertise to cope with the nuclear heritage may fade away quickly. The back-end processes of the nuclear chain will take many decades after closedown of the reactor. Great numbers of highly skilled people will be needed to perform these processes. Even these days the nuclear industry has difficulty recruiting and educating enough highly skilled workers to sustain and operate its facilities and nuclear power plants.

Massive amounts of radioactive materials need to be processed after the closedown of a nuclear power plant, a part of which is highly radioactive. Even if the last nuclear power plant were shut down today, the economy has to sustain a nuclear workforce until long past the year 2100. This workforce does not contribute to any improvement of the energy supply. Its sole task is to prevent the nuclear legacy from becoming disastrous. One might wonder if enough young people would opt for the required rigorous education and training and if a free market-oriented economy could easily support such a workforce for such a long period with no return on investments.

Dismantling costs

A first indication of the financial investments to pay off the energy debt is the publication of some preliminary cost figures by the British Nuclear Decommissioning Authority (NDA), amounting to over €7bn per GWe for nuclear power plants, or 100-200% of the original construction cost [NDA 2006] Q365. Most likely the final cost will be higher.

The cost of the decommissioning and dismantling of a reprocessing plant will rise to astronomical numbers. For the reprocessing plant at Sellafield (UK) the preliminarily cost estimates vary from GBP38bn [NDA 2009] Q501 to GBP50-100bn [*Nature*, 23 November 2006 p 245] and will take some 130 years. The cost of dismantling and cleanup of the complex at La Hague in France can only be guessed at, but will almost certainly be higher because it is a larger plant than Sellafield.

Studies by the RAND Corporation [RAND 1981] Q126,]RAND 1979] Q127 proved that the costs of large projects involving new technology are always underestimated at the start. The causes of the cost overruns observed by the RAND studies perfectly apply to the present nuclear projects. Cost overruns are the rule in the nuclear industry.

Compare the preliminary cost estimate of decommissioning Sellafield with the final cost of the American Apollo project, which succeeded in putting the first man on the moon in 1969 (Apollo 11) and landing five crews thereafter. The final cost of the entire Apollo project, which started essentially from scratch, were less than €100 bn in €(2009). So the decommissioning and dismantling of the Sellafield reprocessing plant, will cost the same or even more than the entire, inspiring Apollo project (1961-1975), with its huge technological spinoff.

The decommissioning and dismantling of the US West Valley reprocessing plant, which operated from 1966-1972 and reprocessed 640 tonnes of spent fuel, will cost from 2007 on at least €4bn (€(2009)) and will take another 40 years to complete. Very likely the final cost will be considerably higher. Up until 2007 several billions of dollars already have been spent on West Valley [UCS 2007] Q421. The total cost will amount to more than 40 times (!) the construction cost of the plant. If all goes according to the current plans, the decommissioning and dismantling of the US West Valley reprocessing plant would take a period of 70 years. In the meantime the radioactive pollution of the groundwater and creeks in the vicinity of the plant is still ongoing and so are the health risks to the local inhabitants.

Above figures of Sellafield and West Valley point to a specific reprocessing cost of some €10M per metric tonne of spent fuel, excluding the costs of construction and operation of the plants. How viable is reprocessing from an economic point of view?

The cost of the cleanup of a part of the military nuclear site at Hanford in the USA is estimated at some USD112bn through Fiscal Year 2090 [www.hanford.gov]. These costs probably do not include the cost of dismantling and cleanup of the nuclear facilities at the site. The problems arising with the cleanup, time delays of many years and massive cost overruns, are not encouraging.

Heading for future disasters

Economic impact of the Chernobyl disaster

The economic damage and losses of the Chernobyl disaster are not easily to define or assess. According to the [Chernobyl Forum 2008] Q497 the total cost in Belarus over 30 years is estimated at US$235 billion (in 2005 dollars). In its report the Chernobyl Forum stated that between 5% and 7% of government spending in Ukraine still related to Chernobyl, while in Belarus over $13bn is thought to have been spent between 1991 and 2003, with 22% of national budget having been Chernobyl-related in 1991, falling to 6% by 2002. Much of the current cost is related to the payment of Chernobyl-related social benefits to some 7 million people across the three countries.

A significant economic impact at the time was the removal of 784,320 ha of agricultural land and 694,200 ha of forest from production. While much of this has been returned to use, agricultural production costs have risen due to the need for special cultivation techniques, fertilizers and additives. The costs of dismantling and cleanup of the Chernobyl site are not included in above estimates.

Economic impact of the Fukushima disaster

Obviously the socio-economic impact of the Fukushima disaster is extensive. Many tens of thousands of people have been evacuated from their homes, without any prospect of a safe return. Various effects of Fukushima are discussed by [Dorfman et al. 2013] Q288.

Liabilities and compensation claims of the disaster might be measured in hundreds of billions of euros. The cleanup of the site is preliminarily estimated at some €250bn [NDreport 2011]. One may wonder if these extreme costs will counterbalance the benefits of nuclear power. Fukushima might be not the last nuclear disaster of its class.

Economic burden

As a result of its *après nous le déluge* attitude the nuclear world is building up an economic challenge of unprecedented size. At some moment the reprocessing plants at Sellafield and La Hague – limiting the scope to the European situation – have to be decommissioned and dismantled. These activities might cost many 100s of billions of euros and will require massive efforts over decades, as pointed out above. The investments are increasing with time due to an increasing contamination of the buildings and constructions with all kinds of radionuclides from spent fuel. Also if the reprocessing plants closed down today, the dismantling investments would still increase over time, due to the unavoidable and progressive degrading processes of the materials and constructions and other causes mentioned above.

Even in times of a booming economy dismantling and site cleanup of a reprocessing plant would be a highly demanding task. What about the prospects in a declining economy?

In addition to the reprocessing plants, all presently operating nuclear power stations are to be decommissioned and dismantled someday. Preliminary indications point to costs of one to two times the construction cost for each reactor.

Après nous le déluge

Any country with an appreciable number of nuclear power plants, such as France, Great Brittain and the United States, should reckon on economic efforts of Apollo project size, many hundreds of billions of euros, to keep their territory (and of the neighboring countries) habitable. Would the decision makers foster such efforts, or does the world need another Chernobyl/Fukushima disaster? That may happen in Europe or in the USA. The current way of economic thinking, pursuing only short-term profit goals, is not reassuring in this respect.

With respect to radioactive waste problems and health risks the nuclear world seems to foster a culture of downplaying and concealing risks combined with an unrealistic belief in unproved and unfeasible technical concepts. This paradigm is exacerbated by a chronic habitus of living on credit that may be best described as an *après nous le déluge* attitude, which seems to be based on questionable arguments and fallacies, such as:

> Technology advances with time and future generations will be richer than our generation, so they will have more economic means and better technological possibilities at their disposal to handle the waste problem.

Or, as John Broome put it [Broome 2008] Q424:

> How should we – all of us living today – evaluate the well-being of future generations, given that they are likely to have more material goods than we do?

A nuclear disaster cannot be prevented by denying its breeding ground.

Latent entropy

Any system that generates useful energy from mineral sources, fossil fuels and uranium, releases unavoidably also a certain amount of entropy into the environment. Entropy may be interpreted as a measure of dispersal of matter, energy and directed flow. More entropy means more disorder. An increase of entropy can manifest itself in many different phenomena, such as dispersal of waste heat, discharges of CO_2 and other GHGs, disturbing ecosystems, pollution of air and water with chemicals. Anthropogenic climate change is typical an entropy phenomenon.

Entropy effects from the use of mineral energy sources can partly be compensated for by investment of useful energy, such as electricity. From the Second Law of thermodynamics follows that the generation of a given amount of useful energy from a mineral energy source is inevitably accompanied by the generation of more entropy than could theoretically be 'neutralised' by that amount of useful energy.

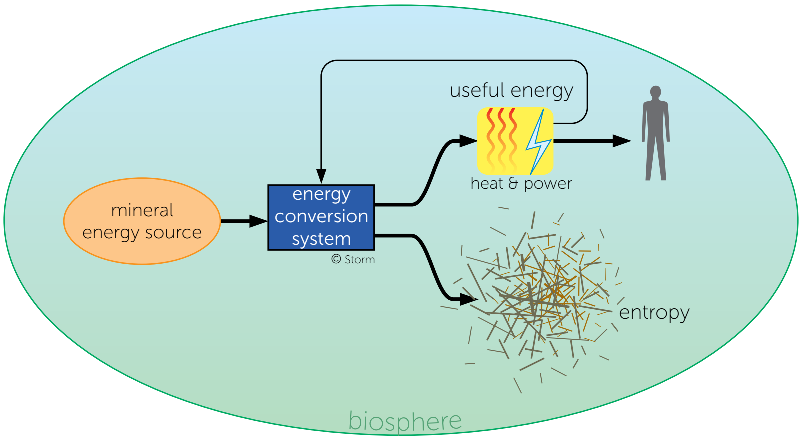

Figure 6

A mineral energy system is a technical system to convert potential energy embodied in a mineral energy source (fossil fuels, uranium) into useful energy (process heat, electricity). Generation of useful energy from any mineral energy source within the biosphere is inevitably coupled with an increase of the entropy of the biosphere, according to the Second Law of thermodynamics. An increase of entropy means loss of quality, diversity and functionality of the ecosystems in the biopsphere.

Uranium is a mineral energy source, so the above observation regarding entropy generation is also valid for nuclear power. In the nuclear power plant the potential energy in the uranium is converted into heat and radiation, and the heat is partially converted into electricity. During these conversions large amounts of entropy are generated. A part of the entropy becomes observable during operation of the nuclear power plant, such as: waste heat, nuclear radiation, dispersal of radioactive and non-radioactive materials. The main part of the entropy is contained in the nuclear fuel elements and the reactor, and its effects are not observable at the moment of its generation. However, the question is not *if* nuclear power generates entropy – the Second Law is relentless –, the question is: *how* can it become manifest?

The entropy contained in spent nuclear fuel will unavoidably be released into the biosphere if no measures are taken to prevent that. The disasters of Chernobyl and Fukushima showed the possible effects of unretained nuclear entropy. As long as the nuclear entropy is enclosed in spent fuel elements it is called the *latent entropy* of nuclear power.

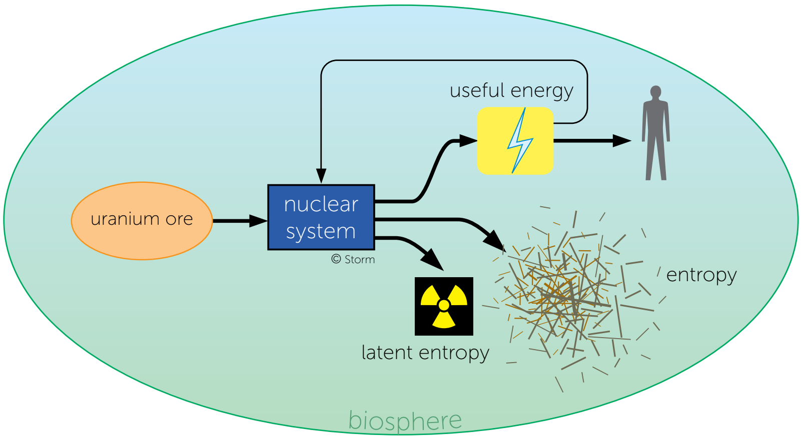

Figure 7
Nuclear power is generated by an energy system, based on uranium as mineral energy source. An important difference of the nuclear energy system with other mineral energy systems is the generation of latent entropy, in addition to the directly observable increase of the entropy of the biosphere. 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.

The latent entropy forms a bill, a legacy, of the use of nuclear power to generate electricity. Thermodynamics tells us that an entropy bill can only be paid by investments of useful energy and dedicated effort. The energy to be invested in the future to pay the bill for the nuclear generated electricity consumed today is called the *energy debt* in this study. If the entropy bill is not paid humankind may expect nuclear disasters that would dwarf Chernobyl and Fukushima.

Thermodynamic aspects of nuclear power are comprehensively addressed in report
m38 *Nuclear power and the Second Law.*

The latent entropy of nuclear power is an important aspect of the nuclear legacy.

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