Nuclear power and the Second Law

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October 2019
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Note
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Thermodynamics

The nuclear energy system is a technical means to unlock the potential energy embedded in uranium atoms and to convert it into electricity, useful energy, a process involving a number of energy conversions. Energy conversions are governed by the laws of thermodynamics. Thermodynamics is the science of energy conversions and lies at the base of all sciences. Consequently the generation of nuclear energy is subject to the laws of thermodynamics.
Several basic notions are important in the assessment of nuclear power and the sustainability of the world economic system:

- energy
- First Law
- spontaneous changes
- entropy
- Second Law

Energy

Energy is a conserved quantity and a basic notion: its definition cannot be deduced from other notions. A usable description of energy is:

Energy is the entity making changes possible.

Energy can manifest itelf in various forms: electricity, kinetic energy, heat, radiation and chemical energy. Potential energy is the energy, not readily observable, present in fossil fuels and uranium, but also in a given mass at a certain height above the surface of the earth. The energy in fossil fuels is actually chemical energy, which is usually set free as the combustion heat of the fuels.
The SI unit of energy, used throughout this study, is the joule, symbol J. Other energy units are ambiguous, because of different possible definitions. For example, there exist six definitions of the British thermal unit (Btu) and five of the calorie (cal). A joule is a small unit (about the energy of one heart beat), so usually large multiples are used, see Table 1.

Table 1
Multiples of the SI energy unit joule, in addition to the conversion factors of three commonly used non-SI units.

name	symbol	quantity
kilojoule	kJ	10^3 J
megajoule	MJ	10^6 J
gigajoule	GJ	10^9 J
terajoule	TJ	10^{12} J
petajoule	PJ	10^{15} J
exajoule	EJ	10^{18} J
kilowatt-hour	kWh	1 kWh = 3.6 MJ
British thermal unit	Btu	1 Btu = 1.055 kJ
tonne oil equivalent	TOE	1 TOE = 42 GJ

In the context of this study, which addresses the practical implications of thermodynamics with regard to sustainability, the following pragmatic definitions are used, in addition to the forms mentioned above:

- useful energy
- embodied energy.

Useful energy

What in daily life is called the 'generation of energy' from fossil fuels or uranium is nothing else than the transformation of the potential energy, embodied in the mineral energy carrier, into another form of energy, which can be used to fulfil a desired energy service. Usually the potential energy is set free as heat, which can be converted into mechanical energy and electricity, or can be used directly in high- and low-temperature industrial processes, or for space heating. The chemical energy in a gaseous fuel can also be converted directly into electricity by means of fuel cells. Mechanical energy and electricity are often called 'work' in the physical sciences.
Here we use the designation 'useful energy' for any form of energy which flows in one direction (the desired direction), for example electricity through a copper wire, heat flow from a gas burner to a kettle, which can be used for fulfilling a specific energy service. Note that useful energy and work are not necessarily identical.
Useful energy is freely available energy which can be used instantly for any purpose, for example electricity to produce aluminium or to power computers, or heat to produce cement.
Useful energy may also be wasted and converted into useless heat and entropy

Potential energy

Potential energy, sometimes also called latent energy, is energy still locked in a material. Of practical interest in this study are the energy in chemical compounds and in uranium.
Fossil fuels contain a hidden form of energy that becomes available as heat by burning the fuel. The potential energy set free by chemical reactions is sometimes called chemical energy, but this term has no simple and unambiguous definition. Uranium contains nuclear energy, another form of potential energy, which can be set free by fissioning uranium nuclei. Nuclear energy is released as heat and radiation.

Embodied energy

In physical analysis of energy systems the notion 'embodied energy' is used: the useful energy required to produce a given material or product from raw materials. An example is the energy required to produce a kilogram of steel from iron ore. Note that embodied energy and potential energy are not identical.

First Law

The First Law is the well-known law of energy conservation:

> *Energy cannot come into being from nothing, neither be destroyed.*

The energy of the universe, in a thermodynamic sense, is constant.
Energy can be transformed from one form into another, for example light into electricity by a PV solar cell and heat into mechanical energy by a car engine, but energy can never been lost. Confusion may be evoked by expressions in daily life, like 'energy generation' and 'energy loss'. These terms are related with energy quality.

Spontaneous changes

Some changes happen spontaneously, other don't. A cup with hot tea cools down to the temperature of the surrounding air; a cup of cold tea never gets hotter by cooling down the surrounding air. A piece of charcoal (carbon) burns to hot carbon dioxide, but an amount of hot carbon dioxide never forms spontaneously a piece of pure carbon. Reheating the tea or reconversion of the carbon dioxide into carbon again is possible only by doing dedicated work.

Not all spontaneous processes will start spontaneously: sometimes a small amount of activation energy is needed to get the process going. For example one spark is needed to ignite any amount of oil, wether 1 gram or millions of tonnes: once started the spontaneous process continues until the last drop of oil has burned. The same holds true for fission of fissile uranium atoms: once started the chain eaction will go on as long as sufficient fissile material is available. An uncontrolled fission chain eaction results in a nuclear explosion. The function of a nuclear reactor is to keep the fission rate under control.

When a change occurs, the total energy in the universe remains constant, according to the First Law. Spontaneous changes are always accompanied by a reduction of the quality of the involved amount of energy: during the change the energy quality is degraded to a more dispersed form. Spontaneous processes are consequences of the natural tendency of the universe towards greater entropy, a greater dispersion of matter and energy.
The reversal of a spontaneous process, in many cases only theoretically possible, would require investment of useful energy and dedicated effort.

Examples of spontaneous processes are: the dispersion of CO_2 from burning fuel into the atmosphere, the rusting of steel in the open air and the decay of dead organisms.

Entropy

System and system boundaries

In thermodynamics a system is defined as a given quantity of matter and space which is the subject of a given scientific study or discussion. The remainder of the universe is called the surroundings of the system. To avoid ambiguities the boundaries of a given system should be accurately defined. Observations that are valid within the boundaries of a given system are not necessarily valid outside the boundaries of the system in question.

Biosphere

All human activities occur within the biosphere, a thin layer around the Earth in which life has developed and can exist. The biosphere is the only place where human life is possible. From a thermodynamic point of view the biosphere is a finite amount of matter and space, a system.
The biosphere can be considered as an aggregate of numerous coupled subsystems. A part of those subsystems are abiotic, for example the climate system. Other subsystems are biotic and are called ecosystems, for example the rain forests and the fish stocks in the Northern Atlantic. Also the human economic activities as a whole are a subsystem of the biosphere. The biosphere is a finite system, consequently all its subsystems are finite systems.

If we want, for example, to analyse the impact of nuclear power on the human environment, the complete nuclear process chain should be the observed system and the biosphere its surroundings.

Definition of entropy

Entropy is a key notion in understanding the Second Law and, with this law, of many basal phenomena of nature. The definition of entropy can be formulated in various ways, here we use the description:

> *Entropy is a measure of dispersal and randomness of matter, of energy and of unidirectional flow of matter and/or energy.*
> *A more random distribution of matter and energy in a system means a higher entropy of the system.*

The probabilistic notion of entropy is based on the quantummechanical concept of quantisation of matter and energy: mass flows and energy flows occur in quanta, smallest units, for example atoms and energy quanta and photons. The probabilistic base is expressed in the famous formula of Boltzmann:

$$S = k \ln W$$

here is: S = entropy of a given system
k = constant of Boltzmann = 1.3807 J.K^{-1}
W = number of microstates of the system

This formula will not be used explicitely in this study, so above quantities will not be explained here.

Entropy changes

In practice only entropy *changes* of a system can be observed. For understanding some basics of nuclear power and sustainable energy a semiquantitative approach of entropy changes satisfies: we only need to know if the entropy of a system increases or decreases by a given action or phenomenon.

A rise of the entropy of a system means more randomness: more dispersion of matter, energy and directional movement, or in other words: a loss of quality and usefulness of the observed system. For that reason entropy may be described in non-physical terms as a measure of '*mess and uselessness*'.
An entropy reduction of a system means less randomness and a gain of quality and usefulness of the system.
When a steel tube rusts and decays into a pile of brown grains, the mess and uselessness of the original amount of steel have increased, or in thermodynamic terms: the entropy of the system has increased. The amount of iron in the observed system has not changed: the iron atoms of the original tube are still present in the pile of rust grains.

The following phrase is a metaphor of an entropy increase as e result of a spontaneous process:

Any fool can pour a cup of tea into the ocean, but a thousand wise men cannot pull it out again.

Observable anthropogenic entropy effects in the biosphere

All human activities are occurring within the biosphere, so all entropy effects of the human activities remain within the biosphere. The biosphere is the only system in which human life is possible.
A rise of the entropy of the biosphere caused by human activities manifests itself as deterioration of the environment and loss of quality of ecosystem services. In fact, all anthropogenic environmental problems are entropy effects. This is not difficult to recognize, for these are caused by dispersion of matter and energy and by degradation of the usefullness of ecosystem services. At the present conditions the netresult of the human activities is degradation of the quality of ecosystems, causing loss of functionality and loss of usefullness to humankind.

Examples of anthropogenic entropy effects are:

- dispersion of CO_2 and other human-made greenhouse gases throughout the atmosphere
- pollution of air by dust, soot, aerosols, acidifying and radioactive gases
- pollution of ground water, rivers, lakes, sea, air and soil by anthropogenic chemicals
- oil spills
- destruction of ecosystems by mining
- dispersion af radioactive materials into the air, water and soil
- erosion of arable land, loss of topsoil, degradation and decline in soil fertility
- washout of phosphate fertilizers into rivers and sea
- desert forming by overgrazing of grasslands
- decline of biodiversity
- decline of fish populations in the sea
- deforestation
- dispersion and consequently loss of irreplaceable materials, such as platinum and phosphates
- rising global temperatures by greenhouse gas emissions
- loss of ecosystem services.

Most of these entropy effects are irreversible on human timescales.

Ordered materials, functionality and entropy

Materials in the context of economy and society generally are processed materials, for example metals, medicines and plastics. These ordered materials have desired and predictable properties and a high usefullness for specific purposes.

How well is a given material or piece of equipment suited to perform a given task, and what is the mean time between failures? These questions refer to the functionality and reliability of materials and constructions. Functionality has to do with the specific properties of a piece of equipment and the materials it is made from. Reliability has to do with the predictability of the behaviour of the equipment and materials under operational conditions of wear, stress and corrosion.
Increasing the functionality and reliability of materials and machines is the opposite of a spontaneous process and is only possible by means of dedicated effort and investment of useful energy. Degradation of functionality and reliability, that means increase of the entropy of the system, is a spontaneous process.

The more specialistic the task, the higher the required quality standards of materials, design and craftsmanship for production of the material and/or object, and consequently the higher energy input. A higher functionality, or quality, requires a higher investment of useful energy and human skill. This observation follows directly from the Second Law.
Even the most reliable components will ultimately fail as a result of spontaneous processes. Lowering the chance of failure, requires higher quality standards of materials and dimensioning of each component. The chance of a failure can be reduced by maintenance and investment of useful energy, but cannot be eliminated. For that reason an inherent safe nuclear reactor is inherently impossible.

Fallacy of economic growth

A widespread fallacy is the following view:

> 'The economy has to grow to generate the economic means necessary to compensate for the environmental problems.'

Environmental problems are observable consequences of anthropogenic entropy generation. History shows that economic growth invariably implies a growth of the consumption of energy and raw materials and consequently an ever increasing environmental deterioration.
From the Second Law follows that the generation of useful energy from mineral energy sources generates more entropy than can be compensated for by the corresponding amount of useful energy. Compensation of one unit entropy (environmental mess) generated in the past, a multiple of units of entropy would be generated today, irrevocably coupled to the generation of the required amount of useful energy.
Besides, most anthropogenic entropy effects are irreversible as noted above.

Second Law

Visibility of the Second Law

The Second Law of thermodynamics is one of the most basic laws of nature. Up until this moment no phenomena have been observed in the known universe which would be in conflict with the Second Law, so the law is considered to be valid for all known phenomena in nature. The Second Law says that any spontaneous process in a given system will go in the direction of more dispersal of matter, energy and unidirectional movement: to more entropy of the system.
Despite its basic importance the Second Law is rather invisible in most natural sciences and technologies. Usually natural phenomena and behaviour of technical systems can be explained in a way satisfactory for most purposes without using the somewhat elusive notions entropy and Second Law.
The reason why the notions entropy and the Second Law should play now a prominent part in environmental sciences is the scale of the human activities in the biosphere. Human behaviour has observable adverse effects on global scale, for example change of climate and decline of biodiversity. Human activities are not negligible anymore in comparison with the natural processes in the biosphere. Further expansion of human demand of resources and ecosystem services brings us in direct conflict with natural processes and ecosystems on global scale.
The magnitude of the human activities in relationship with the finite size of the biosphere, as a thermodynamic system, forces us to go to the basics of science and to apply the Second Law on environmental issues and sustainability of our society.

Principle of the Second Law

Each change in the universe is coupled to an energy conversion and an entropy effect. A basic formulation of the Second Law is:

> *With every change the entropy of the universe increases.*

.
The Second Law can be formulated in different ways. Selfevidently all correct formulations are based on the same principle: dispersion of matter and randomizing of oriented energy flows by any spontaneous process. In respect of processes of everydays practice and in the context of nuclear power and sustainable energy the following formulation is useful:

> *In a system without energy input from the outside and without material exchange with its surroundings any spontaneous process will increase the entropy (randomness of matter and energy) of the system and decrease its quality and usefulness.*

Probability and the Second Law

In a given system, consisting of a certain amount of materials in a certain volume at a certain pressure and containing a certain amount of energy, the distribution of particles and energy quanta will end up in the most probable distribution by spontaneous processes. Examples are the dispersion of a scent in a closed room and the levelling of the temperatures in a closed room with a cup of hot tea.
Any deviation from the most probable situation will require dedicated effort and useful (directional) energy. The farther the desirable situation deviates from the most probable situation, the more dedicated effort and useful energy is required to reach that situation. In other words: the more specific the properties of the desirable ordered material are, the less probable is the end situation from a probabablistic viewpoint and consequently the more useful energy has to be invested to reach the desirable situation.

Implications

Within the framework of this study the following implications of the Second Law are important:

- ageing
- safety of nuclear power
- incomplete separation processes
- energy systems and entropy generation
- latent entropy and delayed entropy
- sustainability of energy systems
- ordered (processed) materials
- chemical and radioactive pollution

Mineral energy sources

Energy conversion and the Second Law

From the Second Law follows that the conversion of potential energy embodied in a mineral enery source (fossile fuels and uranium) into useful energy is inevitably accompanied by the generation of entropy. As the energy conversion occurs entirely within the biosphere, the entropy of he biosphere increases correspondingly.

Reducing the entropy of a system, and so increasing its quality and usefulness, can be achieved by investments of useful energy and dedicated human effort. However, generation of the used energy is unavoidaby coupled to the generation of a new amount of entropy, possibly at another place. According to the Second Law the entropy generation of a mineral-based energy system is larger than theoretically could be compensated for by investing the produced useful energy. The net result is that biosphere deteriorates inevitably by the use of fossil-fuels and nuclear power.

The question is not: *if* nuclear power generates entropy,
the question is: *how* becomes that entropy observable?

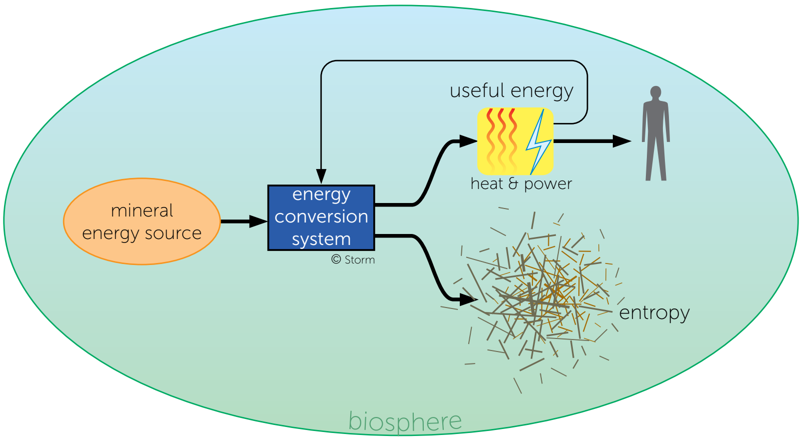

Figure 1

Outline of the principle of the release of useful energy from a mineral energy source. According to the Second Law the amount of energy needed to compensate for the entropy generated is larger than the amount of useful energy made available. A part of the generated useful energy, here symbolized as heat and power, is needed to build, operate and maintain the energy conversion system.

Energy costs energy

To be useful the combustion heat from fossil fuels has to be released at a desirable moment at a desirable place at a desirable rate. This requires a dedicated technical system and human ordering activity.In practice this system is the aggregate of activities and processes of the oil, coal and gas industry, here coined the fossil energy sytem. A sequence of industrial processes have to be passed through before an amount of gasoline becomes available to the consumer: boreholes have to be drilled, crude oil has to be transported and refined and the gasoline has to be transported to the fuel station. Apart from the direct useful energy input to operate the installations, ordered materials are required: oil rigs, chemicals, tankships, oil refineries, etcetera. The fabrication of the necessary materials and equipment also consumes useful energy.

A significant fraction of the energy in the crude oil, as embodied in the oil-bearing formation in the earth's crust, has to be consumed to render the potential energy available as useful energy to the consumer.

To transform the potential energy in uranium into useful energy a chain of industrial processes is needed to prepare the nuclear fuel from the uranium resources as found in nature and a nuclear reactor to release the nuclear energy by means of fission of the fissile uranium nuclei. This nuclear energy system has to comply with very stringent quality specifications and therefore consumes an appreciable amount of energy. To control the fission of uranium-235 nuclei high-grade materials and equipment are required.
A part of the entropy generation occurs during the processes required to prepare nuclear fuel from uranium ore, By far the main part is inextricably related to the fission process itself.
A similar observation holds true for fusion power, if ever possible.

As pointed out above, ordered materials, specific equipment and dedicated human labour is needed to transform the potential energy in mineral energy resources into useful energy and to make the useful energy available to the economic system. The sequence of industrial processes from source to delivery are called the energy conversion system. Obviously the energy system itself consumes energy services: useful energy and ordered materials. The generation of useful energy from mineral energy sources takes useful energy to construct, operate and maintain the energy conversion system.

Nuclear power

Nuclear power may seem to generate little entropy, because only small material flows are visible during operation of a nuclear power plant. However, to assess the nuclear entropy generation the complete nuclear chain should be taken into account during its full cradle-to-grave period. A number of processes of the chain take place at widely different locations, sometimes even on different continents, and at widely different times, often many decades apart. Consequently there are entropy effects that may become manifest only decades after final shutdown of the nuclear power station that generated the entropy.
This study addresses the entropy generated by nuclear power, focused on the radioactivity embodied in the nuclear legacy, and its possible consequences.

Latent entropy

During the fission process in a nuclear reactor the potential energy embodied in the uranium nuclei is converted into radiation and heat. A uranium nucleus fissions into 2-3 free neutrons and two lighter nuclides, the fission products. The neutrons and radiation escape from the nuclear fuel and partly from the reactor. The heat is absorbed by cooling water and removed from the reactor.

A part of the nuclear entropy becomes observable as waste heat, as mixing entropy of escaping radionuclides and as deterioration of materials induced by nuclear radiation, and other effects. The main part of the fission entropy remains enclosed in the fuel elements: a mixture of dozens of different radionuclides and of non-radioactive nuclides. This part of the fission entropy will show its true shape when the cooling is interrupted and a fuel element will melt, releasing all its contents into the environment. Such events happened at Chernobyl and Fukushima, causing massive entropy effects in the environment. Areas of continental scale became contaminated by dozens of different radionuclides that do not occur in nature.

As long as the spent fuel elements remain intact, the main part of the fission entropy remains enclosed in a small volume: that part is called the *latent entropy* of nuclear power. Latent entropy of a system will become free entropy spontaneously in the course of time, without any external influence on the system, or in other words: if no work is done to prevent it.

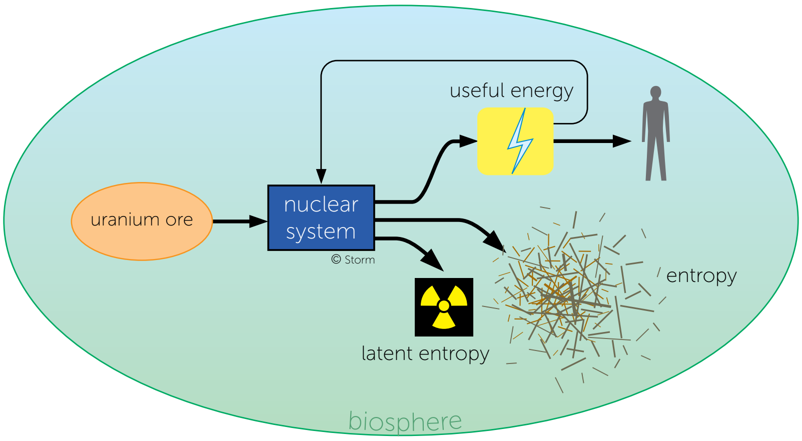

Figure 2

Nuclear power is generated by an energy system, based on uranium, a 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 entropy increase 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.

Delayed entropy

After the fission process stops in spent fuel elements, the entropy production goes on. By radioactive decay of the fission products new nuclides come into being, and radiation and heat is generated. This decay heat generation, called residual heat, is intense enough to melt the nuclear fuel if it would not be cooled during decades after the nuclear fuel is removed from the reactor. Obviously the decay process of radionuclides occur in exactly the same way when the radionuclides are dispersed in the environment.
This kind of on-going spontaneous entropy generation, inextricably bound up with the fission entropy generation, is called the *delayed entropy* generated by nuclear power.

Delayed entropy effects may become seriously damaging in living organisms. The decay of a radionuclide within living tissue will cause damage to adjacent biomolecules by the radiation (alpha or beta, often also gamma), by the recoil effect, and/or by a chemical reaction caused by the mutation of the decaying nuclide; for example, tritium transforms into helium, carbon-14 transforms into nitrogen-14. In addition to the radiation and recoil effect these transformations could also cause damage to DNA and other biomolecules beyond repair. In view of the highly ordered matter (low entropy) of biomolecules the delayed entropy effect by radioactive decay may become considerable. The observable consequences may be death of the organism, cancerous and non-cancerous diseases, congenital defects.

Ageing of materials and structures

An example how the Second Law works out is what happens to a steel structure if left unattended in the open air for a long period. The structure will become useless, due to the spontaneously occurring deterioration of the steel and decay into a pile of rust. The entropy of the system (i.c. the steel structure) increases by spontaneous processes, according to the Second Law. Increasing entropy means decreasing reliability and less usefulness.

Maintenance is required to prevent the structure from becoming useless; in fact maintenance can only delay the moment a given structure has to be replaced. Ageing processes are unavoidable, also under conditions of good maintenance. Even when starting from perfect materials, which is not possible, ageing will occur due to mechanisms such as:

- Diffusion of foreign atoms into the material, for example tritium atoms diffusing into the zirconium cladding of the fuel elements and into the steel of the nuclear reactor vessel.
- Nuclear radiation: atoms are displaced by energetic radiation and consequently disturb the most stable crystal structure of metals; neutron radiation has a more drastic effect, because by neutron capture reactions atoms of other elements come into being, that may be incompatible with the original material.
- Displacement of atoms of the material under thermal and/or mechanical stress. Evidently this effect disturbs the optimal crystal structure of the material and consequently affects its properties negatively.
- Chemical reactions with water, gases from the air and with other substances, e.g. fission products.

Figure 3

Consequences of the Second Law. Any human-made structure will spontaneously degenerate by ageing processes, such as corrosion, weathering and wear; in the long run human-built structures will decay into dust. Ageing goes faster in the presence of nuclear radiation. When left unattended long enough, the steel pole will end up as a pile of dust. The entropy of the pole, the system in this case, has increased by the spontaneous processes. The amount of iron in the observed system has not changed: the iron atoms of the original tube are still present in the pile of rust grains.

Bathtub hazard function

The risks for catastrophic breakdown of technical devices, including nuclear reactors, change as the devices age, much like the risks for death by accident and illness change as people get older. There are three distinct stages in the lifetime of a technical system or living organism:

- the break-in phase, also called the burn-in phase or the infant mortality phase,
- the middle life phase, also called the useful life,
- the wear-out phase.

The risk profile, the failure rate as a function of time, for these three phases curves like a bathtub (see Figure 3). The bathtub curve is drawn from statistical data about lifetimes of both living and nonliving things, such as cars, cats or nuclear reactors.

Applied to technical devices only, the bathtub curve may be considered to be the sum of three types of failure rates:

- Early life ('infant mortality') failures, caused by bad design, defective manufacturing, material imperfections, faulty installation, unanticipated interactions, poor workmanship imperfect maintenance and ineffective operation. The failure rate of this type decreases with time. The steepness of this curve depends on factors such as the amount of 'pre-flight' testing and the effectiveness of the quality control during manufacturing.
- A constant rate of random failures during working life, caused by accidents and random events. The height of this rate depends on, among other things, the quality of the materials, of the design and the professionalism of the operators. In principle the random failure rate does not change with time.
- Wear-out failures, caused by ageing, deterioration of materials, etcetera. This rate increases with time. Wear-out failures are typically the consequences of Second Law phenomena.

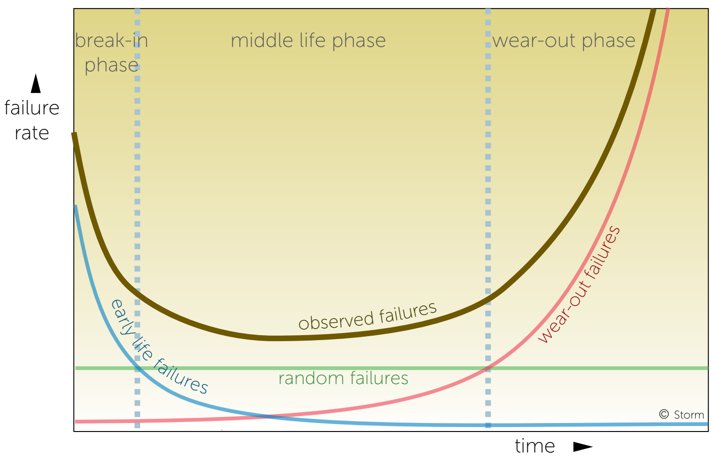

Figure 4

The bathtub hazard curve is the sum of three types of failures rates: the early life failures, decreasing with time, the random failures, constant over time, and the wear out failures, increasing over time. The bathtub curve is valid for technical devices, including nuclear installations, as well as for living organisms.

No human-made structure can be made absolutely fail-safe for an operating lifetime of decades. Accidents and random events are unpredictable by definition. The functionality of materials and structures predictably declines with time by cracking, wear, corrosion and other Second Law phenomena. The rate of wear-out failures predictably increases with time. These observations lead to one conclusion:

Inherently safe nuclear power is inherently impossible.

Limitations of separation and purification

Separation processes

Separation processes play a vital role in the process industry, especially in the nuclear energy system. The nuclear process chain starts with the extraction of uranium from its ore, a sequence of physical and chemical separation processes.
Separation processes are based on chemical and physical distribution equilibria. These dynamic equilibria are governed by the laws of thermodynamics and never go to completion, as a consequence of the Second Law. For that reason it is impossible to separate a mixture of different chemical species into separate fractions without losses.
Separation becomes more demanding, requiring more useful energy and specialistic materials and equipment, and goes less completely as:

- more different kinds of species are present in the mixture,
- the concentration of the desirable species in the mixture is/are lower,
- the constituting species of the mixture are chemically and/or physically more alike,
- the purity specifications of one or more of the fractions are more stringent.

Purification

Purification of a substance is based on separation processes, aimed at removal of contaminants from the substance. A higher purity means a lower concentration of contaminants. Extracting a species at a lower concentration requires more useful energy and is coupled to greater material losses. Higher purity means better predictable properties of a material. As pointed out above 100% pure materials are impossible. Purity specifications depend on the application of a material. Actually purity in the process industry is an economic notion.
One of the many purifications performed in nuclear technology is the fabrication of Zircalloy, the clading material of nuclear fuel. Zircalloy is made of exceedingly pure zirconium, with a few percent of another very pure metal added. Zirconium as found in nature is always contaminated with hafnium, a highly undesirable element in nuclear cladding. So natural zirconium has to be purified, an intricate process requiring a high input of useful energy and auxiliary chemicals, because hafnium and zirconium are chemically much alike.

Extraction of uranium

Above observation means that the extraction of uranium from uranium-bearing rock, usually named mining and milling, consumes more energy per kilogram recovered uranium and goes less completely with decreasing ore grade. That implies that the recovery yield (the fraction of uranium present in the rock which is actually extracted) declines with declining ore grade. From rock containing 1 gram per kilogram rock some 95 % can be recovered. At a content of 0.1 g/kg less than 50% of the uranium present in the rock can be recovered, the other 50% are lost in the waste stream (mill tailings). This phenomenon greatly contributes to the phenomenon of the energy cliff.
The specific energy consumption of the extraction of uranium, measured in energy units per kilogram recovered uranium, is determined by two variables: the dilution factor and the extraction yield. The dilution factor is proportional to the uranium content of the ore: to get hold of 1 kg uranium from ore at a grade of 1 kg U/tonne at least 1 tonne of rock has to be processed, from ore at a grade of 100 g U/tonne at least ten times as much rock has to be processed and at least ten times as much energy is consumed per kg recovered uranium.

On top of the dilution factor comes the declining recovery yield of the extraction process with declining ore grade, and consequently the specific energy consumption per kg recovered uranium rises steeply at low uranium ore grades. As the energy production per kg recovered uranium has a fixed value, the energy invetment of the uranium recovery surpasses the energy content at a given ore grade. This is called the energy cliff. The critical ore grade lies in the range of 0.1-0.2 gram uranium per kg rock, depending on the ore properties.

Of course the phenomenon of steeply rising energy investment per kg metal with declining ore grade is not typical for the recovery of uranium from the earth's crust.

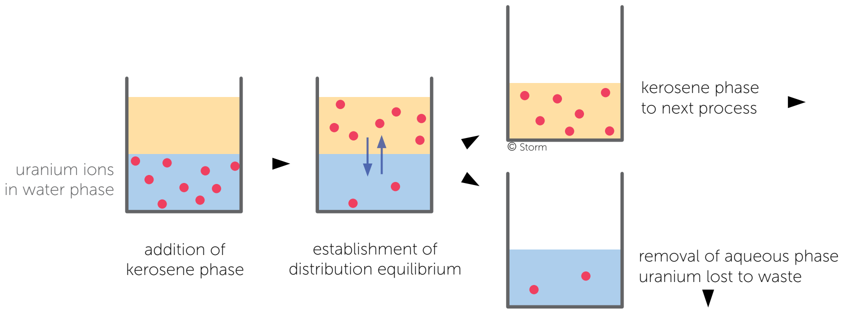

Figure 5

To recover uranium from its ore, the rock is ground to a fine powder. By means of chemicals the uranium atoms are dissolved as ions in a watery solution, together with some other elements from the host rock. Then a special mixture of kerosene and chemicals is added in which the uranium ions better dissolve than in the water phase. After some time a distribution equilibrium is established, when the number of uranium ions diffusing from the water phase to the kerosene phase equals the number diffusing in the opposite direction. When the two liquid phases are decanted, inevitably a part of the original amount of uranium ions are left in the water phase and are lost in the waste stream.

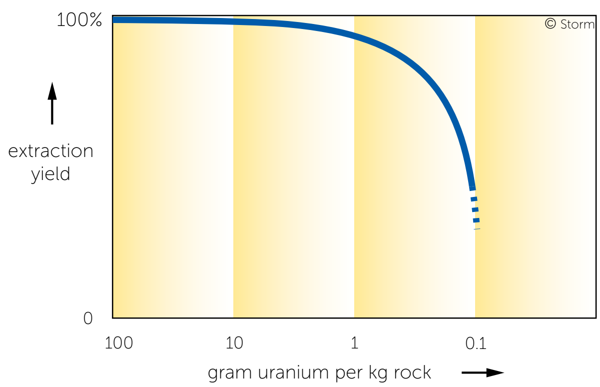

Figure 6

Maximum attainable extraction yield (also named recovery yield) of uranium from its ore, as function of the uranium content of the ore. The yield is defined as the actually recovered fraction of the uranium as present in the original rock. In practice the yields are generally lower than in this diagram. The world averaged uranium content of the currently exploited ores is 0.5-1 gram uranium per kg rock.

Uranium recovery from natural resources is addressed in reports m26 *Uranium mining and milling*, m29 *Uranium for energy resources* and m35 *Energy cliff and CO_2 trap*.

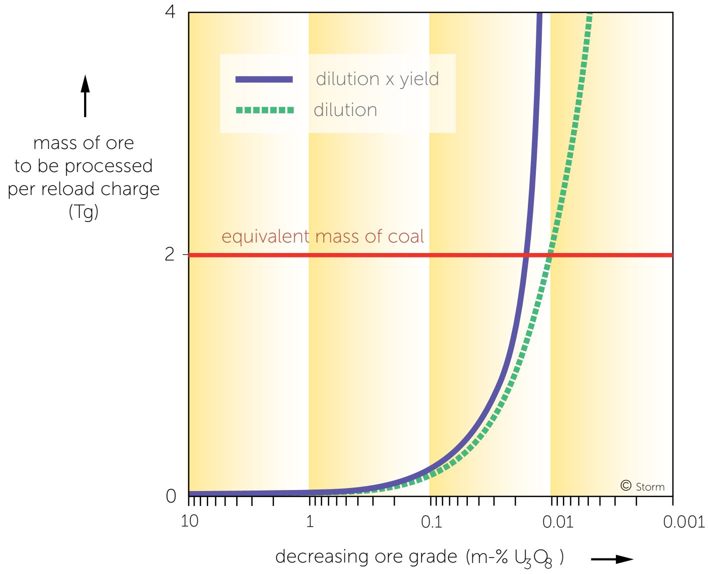

Figure 7

The dilution factor is the relationship between ore grade and energy investment per kg recovered uranium (green dotted line). On top of this comes the effect of the recovery yield, which declines with declining ore grade. A lower yield means that relatively more ore has to be processed to obtain the same amount of uranium and consequently more ore has to be processed to obtain a given amount of net energy. Below a certain ore grade the amount of uranium ore to be mined and processed is larger than the amount of coal to be burnt to yield the same amount of net energy: the coal equivalence.

Declining thermodynamic quality of mineral resources

A second effect accelerates the entropy generation associated with the energy production in the biosphere, even if the demand of useful energy would remain constant: the declining thermodynamic quality with time of the remaining mineral resources. Lower thermodynamic quality results in a higher entropy generation per unit delivered useful energy. The easiest reoverable resources are exploited first, so the remaining resources are harder to exploit. Harder means higher requirements of useful energy and ordered materials per unit recovered mineral.

These developments are observable in the fossil fuel recovery from the crust: deeper wells at more remote and harsh locations are needed, the recovery of oil from tar sands consumes at least half of its energy content, recovery of gas from shales (fracking) consumes a substantial part of its energy content and cause extensive damage to ecosystems. Coal mining meets similar problems. The average uranium ore grade declines and the the mining companies have to dig deeper. The easy oil, gas and coal, having a high thermodynamic quality, are getting depleted. Exploitation of increasingly lower-quality resources is the trend.

Sustainable energy supply has to be based on an energy source outside of the biosphere, so the associated entropy generation stays outside of the biosphere. Man has one: the sun.

Enrichment of uranium

Natural uranium, at the isotopic composition as found in nature, contains 0.7% of the fissile uranium-235 atoms and 99.3% of the non-fissile uranium-238. For use as nuclear fuel the uranium has to be enriched in U-235 atoms. This involves a physical separation process, based on the slightly different masses of the U-238 and U-235 atoms, which is done by means of diffusion or ultracentrifuge plants. Due to the scantness

of the physical differences between the two isotopes, a large number of separation steps are needed to enrich the uranium to the desirable isotopic composition of 2-5% U-238. As a result enrichment is a very energy-intensive process.
It is not possible to extract all U-235 atoms from natural uranium, a consequence of the Second Law as pointed out above, Unavoidaby the enrichment process generates a large waste stream of depleted uranium with a lower content of U-235 atoms than natural uranium of 0.2-0.3%.

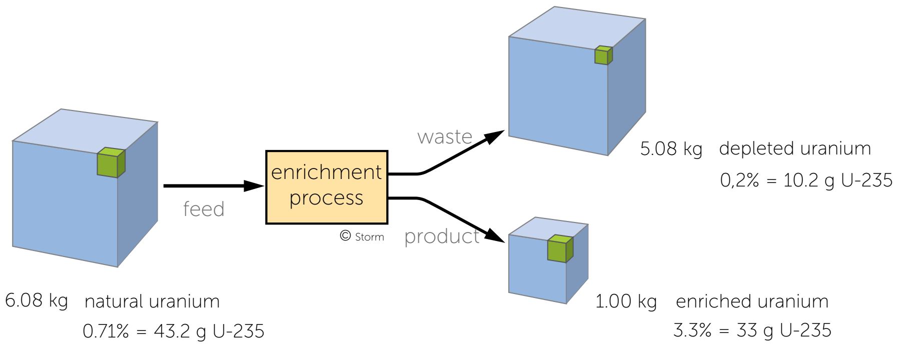

Figure 8
In an enrichment plant natural uranium is split up into two fractions: enriched uranium containing 2-5% U-238 and depleted uranium containing 0.2-0.3% U-235; in this symbolic diagram 3.3% respectively 0.2%. In practice the U-235 atoms are randomly dispersed between the U-238 atoms. To produce nearly pure uranium-235 (weapons-grade) a much larger amount of natural uranium has to be processed, generating a massive waste stream of depleted uranium.

Reprocessing

Reprocessing of spent nuclear fuel is an intricate sequence of separation processes, aimed at the recovery of plutonium and unused uranium from spent fuel.
Reprocessing is a pivotal process in several advanced nuclear concepts, such as closed-cycle reactors, breeders, partitioning + transmutation of long-lived radionuclides and nuclear fusion. Separation of the involved highly radioactive mixtures, containing dozens of kinds of radionuclides, into pure fractions is impossible, as follows from the Second Law. The separation losses increase with with a higher number of chemical constituents, and with higher radiation levels, due to deterioration of the separation chemicals and equipment.
One consequence of the inherently incomplete separation is that all nuclear concepts relying on 100% separation efficiency are doomed to fail.
Another consequence is that a reprocessing plant generates large waste streams, which are larger and more hazardous as the radioactivity of the spent fuel is higher.

Due to the inherently incomplete separation, a part of the uranium and plutonium end up in the waste streams, and the recovered uranium and plutonium are contaminated with other nuclides. Purification of the uranium and plutonium generates large waste streams, as a consequence of the high purity specifications of the two metals.
The other radioactive (and non-radioactive) consituents of spent fuel are distributed over large volumes of solid and liquid waste. Gaseous and volatile radionuclides are set free from the spent fuel during the first steps of the reprocessing sequence, are not retained and are released into the human environment. In addition the waste streams originating in the last steps of the separation and purification processes are released into the human environment. Inevitably these waste streams contain all kinds of radionuclides, those with high water-solubility in high concentrations, those with low water-solubility in low concentrations. For above reasons reprocessing is an extremely polluting process.

Little has been published on the discharges of non-radioactive pollutants, especially greenhouse gases, by reprocessing plants. From a chemical point of view it seems unlikely that reprocessing would not emit greenhouse gases other than CO_2.

The volumes of the decommissioning and dismantling waste of a reprocessing plant may amount to hundreds of thousands cubic meters. This waste stream is never mentioned by the nuclear industry. Unavoidably a significant part of this future radioactive waste stream will end up uncontrollably in the human environment. The cost of decommissioning and dismantling of the reprocessing plant at Sellafield (UK) is estimated at some €100bn, more than the total cost of the American Apollo program, in €(2010), which resulted in the landing of six crews on the Moon (1969-1972). These preliminary cost estimates, which most likely will turn out to be too low, are an ominous indication of the unheard scale of decommissioning and dismantling a eprocessing plant.

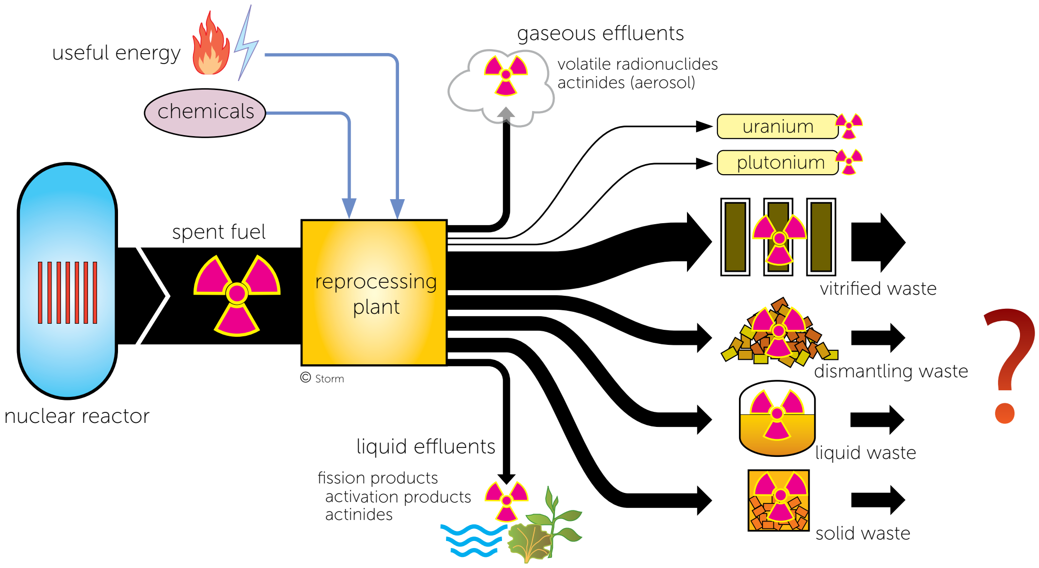

Figure 9

Outline of reprocessing of spent nuclear fuel. Reprocessing is an intricate sequence of separation processes, aimed at the recovery of newly formed plutonium and remaining uranium from spent nuclear fuel. The thicknesses of the black arrows roughly indicate the relative amounts of radioactivity in the various flows of radioactive materials. The querie symbolises the uncertainty concerning the future management of the radioactive materials.

Consequences for advanced reactor concepts

Limitations of separation processes, resulting from Second Law phenomena, have far reaching consequences for the future of nuclear power as a civil net energy source. The currently operating most advanced power reactors cannot fission more than 0.5% of the nuclei in natural uranium. Advanced concepts based on the uranium-plutonium breeding cycle would be able to fission 30-50% of the nuclei in natural uranium. Due to inherently incomplete separation processes these concepts are infeasible. The same holds true for the use of thorium as nuclear fuel by means of the thorium-uranium breeding cycle. Moreover, the energy balances of the breeding cycles would be negative: it would require more useful energy to operate the cycles than could be generated by the cyclic systems.
For more details see reports m01 *Uranium-plutonium breeder systems*, m15 *Plutonium recycling in LWRs* and m24 *Thorium for fission power*. For long-term consequences of nucler power see report m10 *Global context and prospects of nuclear power*.

Reprocessing is also a crucial part of a concept called partitioning and transmutation (P&T). According to this concept spent fuel would be separated into more fractions than by conventional reprocessing. Some fractions would contain long-lived radionuclides that would be transmuted in a reactor into short-lived radionuclides. For the same reasons as in case of the breeder systems, a P&T sytem is infeasible. For more details see reports m16 *Partitioning and transmutation* and m33 *Nuclear waste reduction*.

Reprocessing and entropy increase

The main part of the entropy produced in the reactor by fission of uranium and plutonium nuclei is still enclosed in the spent fuel elements when they are removed from the reactor: the latent entropy. In the reprocessing plant the contents of the spent fuel elements are distributed over substantial volumes of materials. This causes a huge increase of the nuclear entropy: in addition to the increase resulting from the addition of materials used in the separation process ,a large part of the latent entropy becomes direct entropy. The radionuclides from the spent fuel become dispersed in large volumes of materials and a signifficant part of the radionuclides are discharged into the biosphere.
See also report m20 *Reprocessing of spent fuel*.

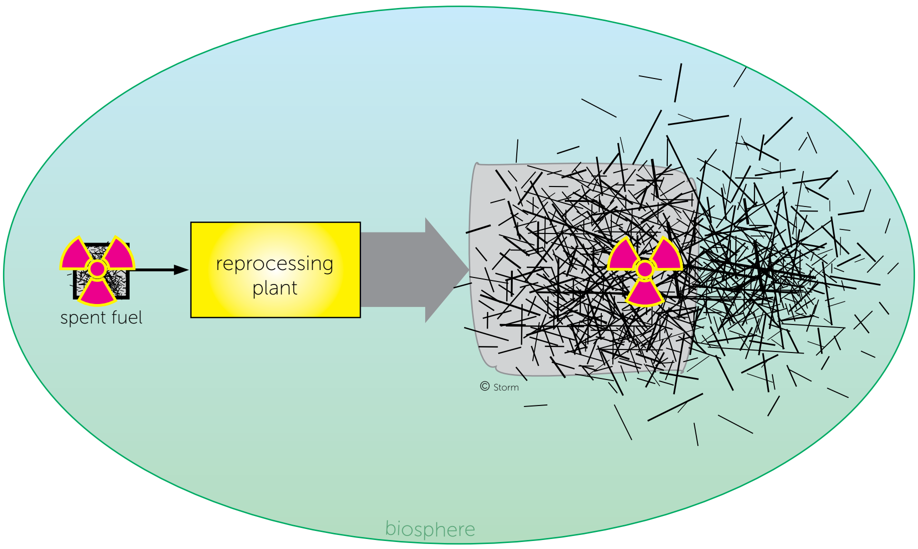

Figure 10
A consequence of reprocessing of spent nuclear fuel. is that the main part of the latent entropy, enclosed in spent fuel and generated during the operation of the nuclear power plant, is set free, greatly increasing the entropy of the biosphere.

Sustainable energy and nuclear power

Sustainability

A sustainable energy system must comply with several conditions, such as:

- inexhaustible primary source
- constant themodynamic quality
- secure energy supply world wide, applicable in all countries of the world, to achieve more geopolitical stability
- fast to implement: construction times of a few years
- no chance of large-scale accidents (oil spills, radioactive contamination)
- without entropy increase of the biosphere, even entropy decrease (increase of quality) if possible

Evidently nuclear power does not comply with these conditions, neither does any other mineral-based energy system (fossil fuels, deuterium-tritium fusion energy). Humankind has one energy source at its disposal that meets the above conditions: the sun.
The existence of green plants in the biosphere proves that is possible to synthesize highly ordered matter from highly dispersed matter resulting in a lower entropy of the biosphere. The net entropy change by the photosynthesis of green plants is negative, that means a decrease of disorder and an increase in quality and functionality. This is possible by using energy from an energy source outside the biosphere: the sun.

Zero entropy energy (ZEE) system

Solar energy reaches the surface of the earth as visible and infrared radiation, a unidirectional flow of energy quanta. The increase of entropy coupled to the conversion of fusion energy in the sun into this energy flow occurs outside the biosphere. To mimic the green plants humankind needs to harvest solar energy reaching the surface. This possible by systems based on mature and proved technologies: photovoltaics (PV), concentrated solar power (CSP) and indirectly by wind turbines. These systems are called zero entropy energy (ZEE) systems, because they can deliver useful energy without an increase of the entropy of the biosphere.

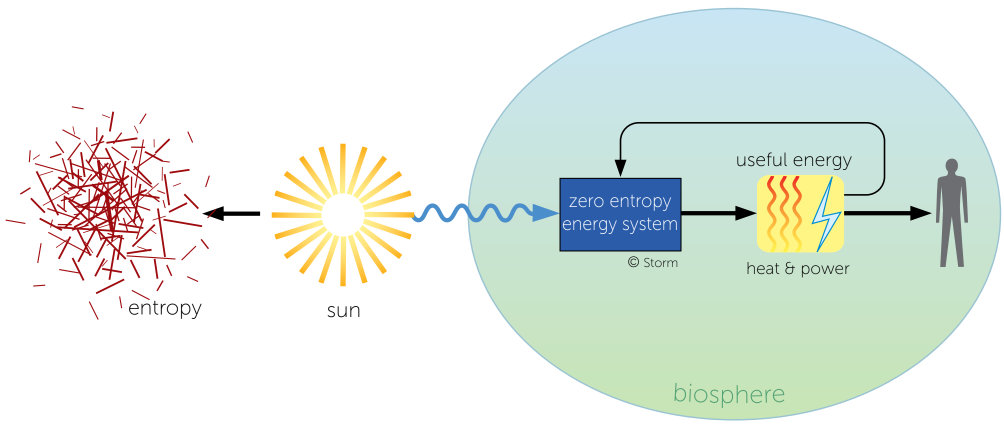

Figure 11
Schematic representation of a zero-entropy energy supply of the human activities. The energy conversion in the sun generates entropy, accordingly to the Second Law. However, the entropy effects remain in space. The released energy reaches the surface of the Earth as UV, visible and infrared radiation, nearly free of entropy.

From a thermodynamic point of view the sun and the biosphere are two coupled systems. The sum of the entropy changes in both systems is an entropy increase, so the Second Law is obeyed.

Energy and entropy payback times

Evidently any renewable energy system requires the investment of useful energy for construction, operation, maintenance and decommissioning + dismantling at the end of the operational life. Consequently these activities generate of an amount of entropy. The primary energy source, solar radiation, is nearly entropy-free As the production of the energy is nearly entropy-free the entropy payback time of a ZEE system might be not much longer than its energy payback time. In practice the energy payback times vary from several months for wind power to 1-3 years for photovoltaics (PV), depending on the latitude of its use.
The energy payback times of mineral-based technologies vary from several months for gas-fired electricity generation to 10 or more operating years for nuclear power plants. It should be noted that the mineral-based energy technologies are generating large amounts of entropy during their entire operational life and consequently no entropy payback times can be defined.

Cradle-to-grave entropy balances

Comparison of the merits of the various energy systems, ZEE and non-ZEE, on equal arguments is only possible by means of energy analyses of each system, accounting for the full cradle-to-grave period of each system. The cradle-to-grave (c2g) period of any industrial system comprises three phases:

- front end (upstream processes), including the construction of the system,
- operation, maintenance and refurbishments,
- back end (downstream processes), including diamantling of the system and waste management, restoring the involved sites to a greenfield situation.

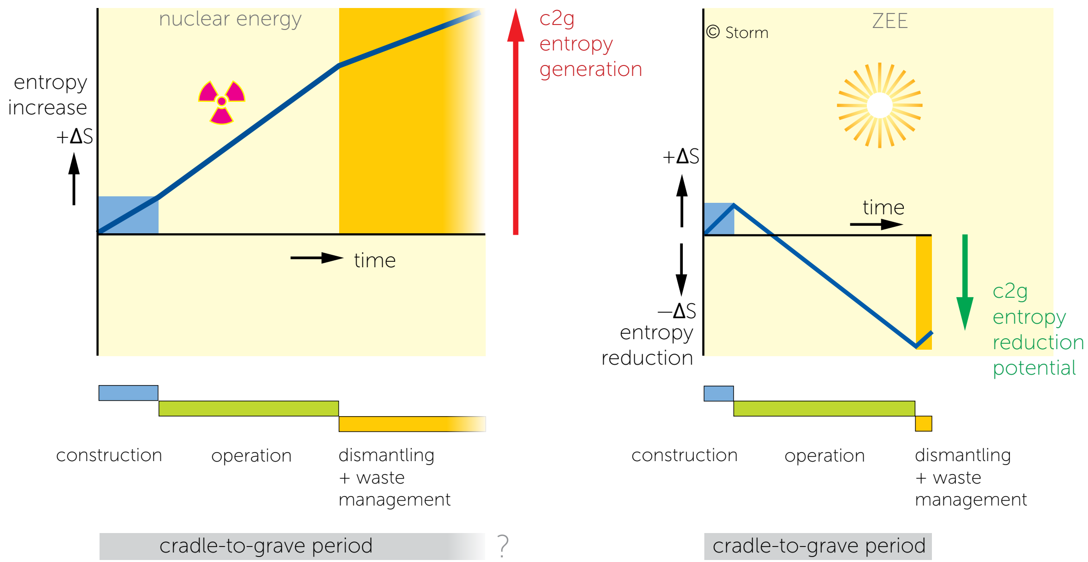

Figure 12

Entropy generation and entropy reduction of two energy systems: nuclear energy and a solar-based energy system, the diagrams are not to scale. The cradle-to-grave period of nuclear power is long: 100 -150 years. A ZEE system, except hydropower, has a much shorter period: something like 40-50 years. The downstream processes of the nuclear system are systematically postponed to the future, so its duration is unknown.

Figure 12 represents the dynamic entropy balances during the cradle-to-grave period of nuclear energy and

of a ZEE system.
Nuclear power is advocated as a sustainable energy system, a vision based on misconceptions and fallacies, the back-end (downstream) processes of nuclear power are downplayed or even ignored. The nuclear back end is heavy compared to all other energy systems: its duration is unprecedently long (100-150 years) and it requires massive investments of ordered materials and useful energy: of the same order of magnitude as the front end processes and construction combined. All nuclear waste ever generated and all nuclear reactors ever operated are still awaiting safe and definitive isolation from the direct human environment. Consequently the entropy generation related to an amount of useful energy produced during a given period goes on for decades to a century after the last joule of useful energy left the nuclear power station. The cradle-to-grave (c2g) period of a given nuclear power plant has a clear start, but its completion is clouded in uncertainties. No other energy system exhibits such a feature.

Other mineral energy systems, the fossil systems, exhibit a similar entropy course like nuclear: a net entropy increase of the biosphere during the full c2g period.

Operation of a ZEE system produces negligible amounts of chemical pollution and no radioactive waste. The production of the materials of the components of a PV orCSP farm or a windpark generates entropy and chemical wastes, but only at a few production locations, not at the many sites of the useful energy generation. After final shutdown the materials of the dismantled installations can be recycled to a high degree. Hydropower forms a special case in with respect to several features.
During its operation a ZEE system delivers nearly entropy-free useful energy, which can be used to lower the entropy of the biosphere and consequently inprove its quality. Measured over its c2g period a ZEE system has a potential for a net entropy reduction of the biosphere.