Methodology of energy analysis

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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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Usefulness and work

The construction of a nuclear power plant requires exceedingly high quality standards with regard to the materials and the craftwork needed to manufacture the components, e.g. the reactor vessel. The operational lifetime of a nuclear power plant is determined by the quality of the reactor vessel and associated components. Many of these components cannot be replaced, once the reactor has started up.

To achieve a high level of safety and a long lifetime, the properties of the materials and of the components as a whole have to be predictable to an extremely high degree under stressful circumstances, such as high pressures and temperatures, neutron radiation and corrosion processes.
To achieve the required high specifications one has to start from very pure materials and the fabrication processes have to occur under tightly controlled conditions. The amounts of rejected materials and components in a production process increase with increasing quality requirements.

A high predictability of the properties and the behaviour of a piece of equipment under extreme conditions translates into a low entropy per unit mass: the lower the entropy of a piece of equipment the higher its usefulness. Lowering of the entropy of a given amount of matter is possible by applying work: high-quality usable energy, such as mechanical energy and electricity. The amount of work to be applied per unit mass increases exponentially with decreasing entropy. Consequently, the production of 1 Mg reactor-grade steel requires much more useful energy than 1 Mg steel intended for the construction of a garden fence.
More work implies not only more direct energy input, but also a larger infrastructure of skilled people and facilities to run the process and to perform an adequate quality control.

The minimum amount of work needed to lower the entropy of a given mass to a certain low level, is determined by the Second Law, one of the basic thermodynamic laws governing all changes in the observable universe. Advancement of technology only can help coming closer to the thermodynamic minimum of the required work, but the limit never can be surpassed. A thermodynamic efficiency of 30% of an industrial process (e.g. aluminium production) is considered very high, most processes have lower values. An efficiency of 30% means that the actual work done to perform a given process is over three times as high as the thermodynamic minimum of that process.

The materials used in the construction of a nuclear reactor and associated energy conversion components cannot be substituted by other materials without any problem. The materials are carefully chosen for their specific properties, such as strength at high temperatures and pressures, corrosion resistance, chemical properties and nuclear properties (e.g. deterioration by neutron radiation, generation of radionuclides by neutron capture, permeability to tritium).
Above considerations bring the conclusion that the construction of a nuclear power plant requires more work per unit construction mass than a non-nuclear power plant, which has less critical requirements than a nuclear power plant.

Energy investment versus monetary investment

Any industrial activity consumes a certain quantity of useful energy, which does not change appreciably as long as the involved technology used does not change. Technical improvements may reduce the energy requirements per unit activity, but there are thermodynamic limits which cannot be surpassed, but only can be approached. For example, the production of 1 kg steel from a certain iron ore is a mature industrial process and its specific energy requirements have a nearly fixed value which may be reduced only marginally by technical improvements.

Energy is a conserved, unambiguously defined quantity, independent of time, place and culture and is not prone to inflation, stock rates or other unpredictable economic factors. Energy analysis is a reliable tool in gaining a clear understanding of long-term prospects of the global energy supply and the resources of mineral energy resources. By means of a thermodynamic analysis it is possible to assess reasonably accurate the specific consumption of materials and energy of a given industrial activity, even if this activity has to be performed in the future. Likely the production of steel and concrete in 2050 will consume nearly as much energy per Mg as today. An important feature of a thermodynamic analysis is that its results do not depend on time or place of the involved activity, contrary to a financial analysis.

Economic calculations are done in monetary units. The price of a service or good is not an unambiguously defined and conserved quantity: it depends on preferences and a number of factors, varying in time and from place to place. An example of this feature is the oil price. The price of a barrel of oil can vary widely within a short time interval, while its energy content and the energy requirements for extraction, transport and refining remain unchanged.

Industrial processes

Any industrial process consumes useful energy, e.g. process heat and electricity, and ecosystem services (see below). The product can be an ordered material (e.g. steel), objects constructed from ordered materials (e.g. cars), or non-material products such as electricity or internet services. Raw materials, as found in the biosphere, are considered to have zero embodied energy. The input materials, chemicals and equipment of a process have embodied energy, when they are the product of another process, e.g. the production of steel, sulphuric acid and diesel engines.

An assembly of industrial processes may be treated in a similar manner as an individual process. The complete process chain then is taken as one system.

The inputs of a generic industrial process are illustrated by Figure 1, a particular process may have a slightly different outline. There are material and energy flows, which are quantifiable and non-material inputs, which are not unambiguously quantifiable.

An important notion is that ordered materials, for example chemicals, equipment and buildings, represent a certain quantity of embodied energy, for they are the products of other industrial processes, each consuming useful energy. In addition to ordered materials an industrial process has an input of services, encompassing such things as operation and maintenance, quality control, education of personnel. These activities require useful energy, directly and indirectly, although this energy input is hard to measure.

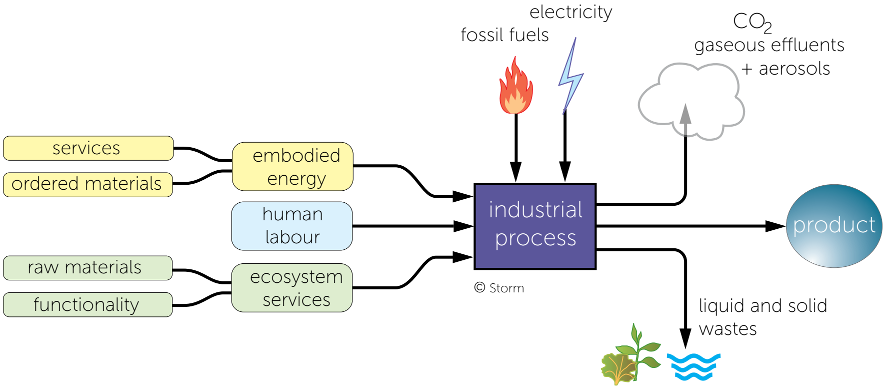

Figure 1

Outline of a generic industrial process with material and energy flows, as used in energy analysis. The direct energy input consists of useful energy, the indirect energy input is the energy embodied in the services and ordered materials. Ecosystem services and human labour and intelligence are not assigned an energy content.

The ecosystem services comprise the input of raw materials as found in nature (minerals, biotic materials, food), and the functionality of partial systems of the biosphere, such as clean air, availability of fresh water, land to build on.

The fourth input of each industrial process is human labour that steers the ongoing processes into the desired direction.

According to the generally accepted conventions of energy analysis, see for example references [Q99] - [Q105], the embodied energy in human labour and ecosystem services are put at zero.

The entropy generation of the process is embedded in the waste streams: waste heat, solid and liquid waste and gaseous effluents. These streams end up in the biosphere. In addition there may be less obvious entropy effects, such as the decline of fish populations and the loss of arable land. See also report m38 *Nuclear power and the Second Law*,

Energy systems

The sole purpose of an energy system is to convert the potential energy in a raw mineral energy resource (fossil fuels, uranium) into a useful energy form, which can be distributed and used for any energy service. The product of an energy conversion system is useful energy made available to users other than the conversion system itself. The nuclear energy system is no exception to the generic energy system, in fact it is the most complex energy system ever designed and comprises a large number of industrial processes. The raw energy resource is uranium ore and the sole product is electricity. The potential energy in uranium, primary input E_o, is system-dependent and is in practice the fission heat released by fission of not more than 5 g nuclei per kg natural uranium (0.5%) in the most advanced power reactors.

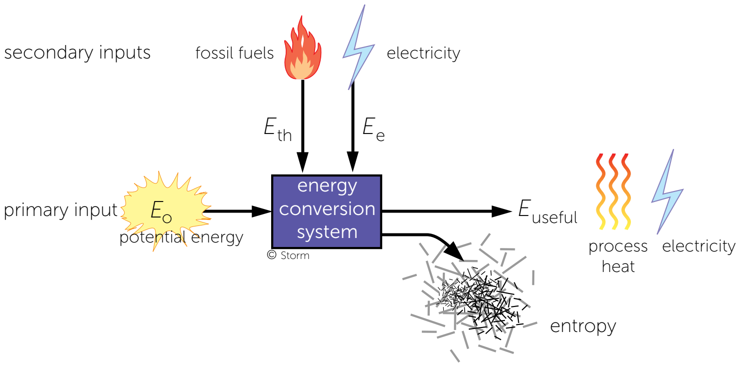

Figure 2

Energy flows of a generic energy system based on a mineral energy resource. The energy system itself comprises a number of industrial processes. The secondary inputs are required for the construction and operation of the system, for the upstream processes (making the energy source available), and for the downstream processes (waste handling). The useful energy can be used for any energy service. Energy services are, among other, transport, work, process heat, electricity. The raw energy resource can be a mineral resource in the earth's crust: fossil fuels, uranium.

The conversion of potential energy into useful energy is inevitably coupled to the generation of more entropy than could be compensated for by the amount of produced useful energy, according to the Second Law of thermodynamics.

Process analysis

During the 1970's and 1980's the methodology of energy analysis has been developed, maturing to a useful tool to estimate with reasonable accuracy the energy requirements of a good or economic activity and to assess the emission of CO_2 and other greenhouse gases (GHGs), see for example [IFIAS 1974] Q99, [IFIAS 1975] Q100, [Roberts 1975] Q101, [Chapman 1975] Q113, [Chapman 1976a and 1976b] Q104 Q106, [Roberts PC 1976] Q105, [Reister 1977] Q97, [Bullard *et al*. 1978] Q102, [Roberts PC 1982] Q103, [Constanza & Herendeen 1984] Q119, [Spreng 1988] Q311. Application of this methodology to assess the energy balance of nuclear power has been peer reviewed in 1985 [Storm 1985] Q2. The same methodology is applied in this study.

Unambiguous definitions of the concepts used in energy analysis are formulated in [IFIAS 1974] and [IFIAS 1976]. In the energy analysis the quantity *enthalpy* ΔH is used, although *free energy* ΔG should be used. For fossil fuels and uranium, the numerical differences between enthalpy and free energy are not large, as shown in [IFIAS 1974], so all energy analyses conveniently use ΔH, here called *useful energy*.

A process analysis starts with mapping out all inputs of the process per unit product and all output flows. The input of processed materials, such as steel and concrete, are the products of one or more preceding industrial processes, each of which with their own direct and indirect energy inputs and GHG emissions. The input of capital goods, for example the reactor vessel, pumps and control equipment, are the products of other industrial processes in the economic system. The process flows of these fabrication processes have the same generic outline as presented by Figure 1. Obviously a full process analysis of the construction of a nuclear power plant becomes rather complicated in this way, so a simple shortcut would be welcome. Usually this done by means of an input/output analysis, which is applied in cases of complex industrial activities.

Input/output analysis

Energy embodied in capital goods and services, sometimes also in processed materials, is difficult to estimate with process analysis and requires a second method: the input/output (I/O) analysis This method has been developed in economics. By the I/O method the embodied energy of a material is approximated by multiplying the price of a material in year *i* by the energy intensity in year *i* of the economic sector which produced the material. Methodological apects of I/O and process analysis are discussed in the above mentioned publications and also, for example, in [IAEA TecDoc-753 1994] Q148.
The concept of the energy/gdp ratio is based on the notion that in a given year the economy consumes a measured amount of energy units and produces a measured amount of units of economic transactions or changes by human action, quantified by the gross domestic product (GDP). The energy input is measured in joules J and the GDP is often measured in US dollars (USD).

The basic energy input of the economic system (see Figure 3) is the gross energy production, consisting of:

- gross electric energy generated by hydro power, nuclear power, wind and solar, plus
- gross thermal energy supplied as fossil fuels and biomass (combustion heat).

The conversion losses and transport- and transmission losses occur within the economic system. In this study the electric energy input is not converted into ‘primary energy uits’ for reasons explained below.

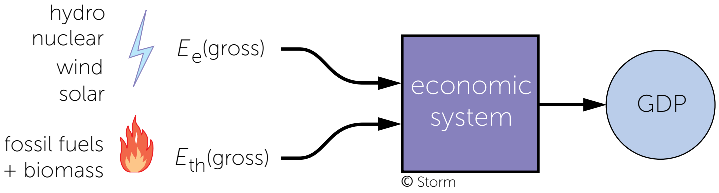

Figure 3
The economic system from an energy point of view. The product of the system in given year is an amount of economic transactions, measured in monetary units, and can be seen as a measure of changes by human action. Every change involves a certain amount of useful energy.

The average energy intensity of one unit of economic transactions e_i in a given year *i* is:

$$e_i = \frac{E_{gross(i)}}{GDP_i}$$

e_i = energy/GDP ratio of year i   J/$_i$
$E_{gross(i)}$ = gross energy production in year i   J
= $E_e(gross) + E_{th}(gross)$
GDP_i = gross domestic product of year i $_i$

eq 1

Activities involving nuclear technology likely require more usable energy per mass unit product than the average activity, as a consequence of the high quality specifications. So, this method may understate the energy invested in the nuclear system.

Process analysis may lead to a large underestimation of the total construction energy requirements, when services and supporting activities of the construction are discounted, according to e.g. [Rombough & Koen 1975] and [Bullard *et al.* 1978]. This is the case in a number of energy analyses published in the past. Input/output analysis is well suited to large aggregated activities, like the construction of a nuclear power plant. [Chapman 1975] concluded:

> “In principle this is an unsatisfactory procedure since the inputs to nuclear systems are likely to be uncharacteristic

> products of the sectors documented in the input-output tables. However there are grounds for believing that, provided a product has a large vector of inputs, i.e. requires inputs from many other sectors of the economy, then the average energy intensity derived from the input-output table is fairly reliable."

The I/O analysis may be simplified by using the general energy/gdp ratio of a particular year in a particular country to calculate the net energy requirement of a complex activity. The general energy/gdp ratio (or energy intensity) *e* is defined as the quotient of the total primary energy consumption of a country (in joules) and gross domestic product GDP (often in US dollars) of a given year *i*. Usually primary energy units are applied, which introduces ambiguities, as pointed out in the previous section.
In case of the construction of a nuclear power plant, estimation of the construction energy using the energy intensity *e* from the monetary costs in the same year, according to equation 2, does not introduce a large error. The range in the reported capital costs of nuclear power plants (in the USA ±50%) is larger than the uncertainty introduced by this simplification.

$$E_{\mathrm{constr}} = C_{\mathrm{constr}}(\mathrm{i}) \bullet e_{\mathrm{i}} \bullet a_{\mathrm{i}}$$

E_{constr} = primary energy requirements of construction J
$C_{\mathrm{constr}}(\mathrm{i})$ = construction cost in year i $\$_{\mathrm{i}}$
e_{i} = energy/GDP ratio of year i $\mathrm{J}/\$_{\mathrm{i}}$
a_{i} = multiplier in year i

eq 2

This simplification gives a fairly reliable value of the energy embodied in that activity, including energy costs of craft labour, services, subsidies, etcetera, according to [Tyner et al. 1988] Q124. This conclusion endorses the conclusions of other studies, e.g. [Rombough & Koen 1975] Q120, [Roberts PC 1982] Q103, [Bullard *et al.* 1978] Q102, [Constanza & Herendeen 1984] Q119. As Constanza & Herendeen put it:

> "Embodied energy (calculated the way we suggest) is a good, non-trivial static correlate of the economic value of the relatively large aggregates of goods and services that make up the entries in the I/O tables."

Certainly, the construction of a nuclear power plant is a large aggregate of goods and services. Nuclear technology may considered being high-tech, on top of an extensive industrial and economic infrastructure of other high-tech production processes. The studies of [Rombough & Koen 1975] and [Bullard *et al.* 1978] showed that the value calculated via a detailed I/O analysis is somewhat higher than the value found via the simplified method. Both studies concluded that construction of a (coal-fired) power plant is more energy-intensive than the average economic activity. Likely the construction of a nuclear power plant would be even more energy-internsive, in view of the large amounts of materials with high quality specifications incorporated in the plant.

A more accurate estimation of the construction energy can be found by multiplying the construction costs of a plant (in year *i*) with the energy/cost ratio (in J/$) of the sector 'new construction of utilities', in the same year *i*. This can be done by multiplying the result by a factor *a*, derived from the publication of [Bullard *et al.* 1978]. In this study a constant value of $a = 1.16$ is assumed (valid for the year 1967), although factor *a* is slightly increasing with time and getting more electricity-intensive. In view of the high-tech character of the nuclear industry the multiplicator might by higher for nuclear power plant construction.

Input-output analysis is playing an increasingly important role in assessements of the environmental effects of energy systems [IPCC-*ar5* 2014] Q795.

Different variants of the input/output analysis applied to estimate the energy investments of the construction of a nuclear power plant are addressed in report m39 *Construction and OMR of nuclear power plants*.

Primary energy units in energy statistics

World energy statistics usually are given in primary energy units, such as (metric) tonne oil equivalent (TOE). In that case the calorific equivalents (heat of combustion) of fossil fuels and other fuels are expressed in TOE, e.g. [BP 2017] Q91. BP uses the conversion factor: 1 TOE = 42 GJ. Electricity is converted into primary energy units by multiplying the amount of electricity by a factor *f* and the result is added to the combustion heat from directly used fossil fuels:

$$E_{prim} = E_{th} + f \bullet E_e \qquad \text{eq 3}$$

In the BP statistics of 2006 and later the value $f = 2.6$ is used for nuclear energy and for hydroelectricity, based on a conversion efficiency of 0.38 of thermal energy into electricity.
The BP statistics before 2001 used the values $f = 3$ for nuclear and $f = 1$ for hydroelectric energy.
Thermodynamically any factor $f > 1$ for nuclear energy is inconsequent. One joule electricity, from whatever source, can be converted into one joule heat in an electric boiler or kitchen stove. The sole usable output of nuclear power plants is electricity, as is of hydro, PV and wind. Adding quality to quantity is in conflict with the First Law.

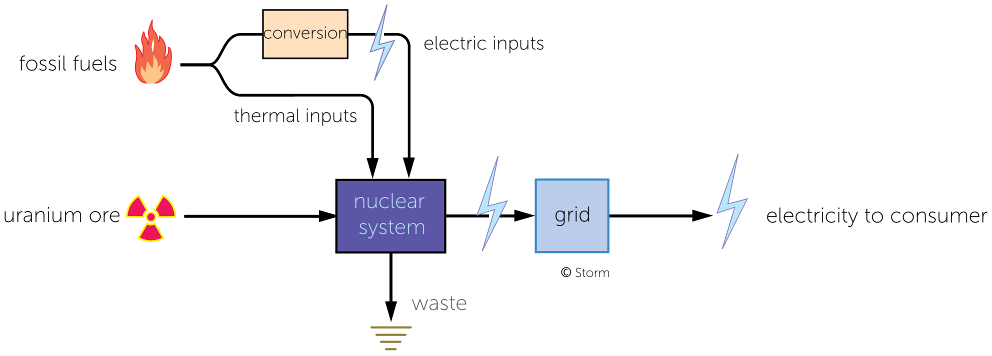

Figure 4
Most studies convert the secondary electric inputs of the nuclear system into 'primary energy units'. The conversion factor depends on the fuel mix of the country of the nuclear power plant and changes over time. Nuclear waste management is in many studies only briefly addressed.

In most energy analyses, e.g. [Lenzen et al.2006] Q325 and [Ecoinvent 2003] Q333, the electric secondary inputs of the nuclear system are converted into 'primary energy units' (see also Figure 4). This method introduces large and needless ambiguities, due to the fact that the conversion factor $f = 2.6$ depends on year, place and implicit assumptions with regard to the generating technology and the final use of the energy. The fuel mix of electricity generation is different from country to country and, additionally, changes over time.
In fact the use of 'primary energy units' in this way conflicts with the First Law of thermodynamics: energy cannot be produced, nor destroyed, only converted from one kind into another. Quality cannot be added to quantity.

In this study electric and thermal energy inputs are kept separated, to avoid confusion and to avoid introduction of parameters which are not physically constants, but depend on assumptions which may change by time or other factors; the conversion factor *f* is such a variable.
In many studies from which data are used in this study, primary energy units are used, sometimes implicitely. In that cases the values are converted into separate thermal and electric values, if the thermal/electric ratio *R* is known, using the equations 4 and 5.
The energy input of a given process $E_{process}$ is defined as the sum of electric and thermal energy flows (see Figure 2), at a given thermal/electric ratio *R*, which depends on sector or process.

$$E_{\text{process}} = E_{\text{th}} + E_{\text{e}} \qquad R = E_{\text{th}} / E_{\text{e}} \qquad \text{eq 4}$$

Combining equations 3 and 4 gives eq 5:

$$E_{\text{process}} = E_{\text{th}} + E_{\text{e}} = \frac{1 + R}{R + f} \bullet E_{\text{prim}} \qquad \text{eq 5}$$

In this study we assumed all electric inputs to be produced by the nuclear system itself. In this way the results of the analysis are independent on place, time and local conditions. Consequently the CO_2 emissions by the nuclear system solely result from burning fossil fuels (mainly diesel fuel) and from chemical reactions (e.g. in the cement production), directly related to the operation of the nuclear energy system.

In practice above convention would correspond with a steady state, a state in which the number of nuclear power plants remains constant and the number of plants under construction equals the number of plants being decommissioned.

This study applies the same method as described above for estimation of the energy investments of decommissioning and dismantling.

Origin of the nuclear CO_2 emission

The CO_2 emissions by the nuclear system result from burning fossil fuel to provide the thermal energy inputs of the process chain and from chemical reactions (e.g. in the cement and steel production), directly related to the operation of the nuclear energy system.

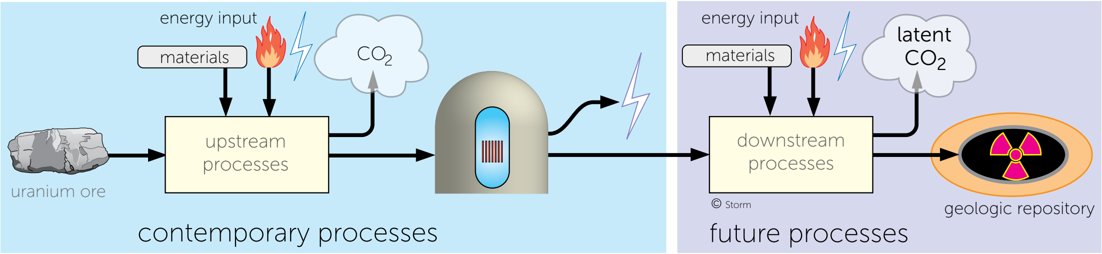

Figure 5
Simplified outline of the nuclear process chain, as it ought to be. The three main parts are the upstream processes or front end, from ore to nuclear fuel, the powerplant itself (construction, operation, maintenance & refurbishments during its operational lifetime) and the downstream processes 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. The notion 'latent CO_2' is addressed in reports m07 *Latent CO_2 and energy debt* and m40 *Radioactive waste management, future CO_2 emissions*.

This study assumes the electric inputs of the contemporary processes, as represented in Figure 5, to be produced by the nuclear system itself. Consequently these inputs are to be balanced with the electricity delivered to the grid E_{grid}. The net electricity delivered to the economic system (consumer) is indicated by E_{net} (see Figure 6). The front-end processes refining + conversion, enrichment, fuel fabrication and construction of the nuclear power plant may be considered to occur contemporarily with the operation of the power plant. Because of the remote locations of the mines the electric inputs of the recovery of uranium (mining + milling) are generally generated at the site by oil-fuelled generators. For that reason the electric inputs of mining + milling are converted into thermal energy, assuming that the generators at the mines have a thermal conversion efficiency of 40%.

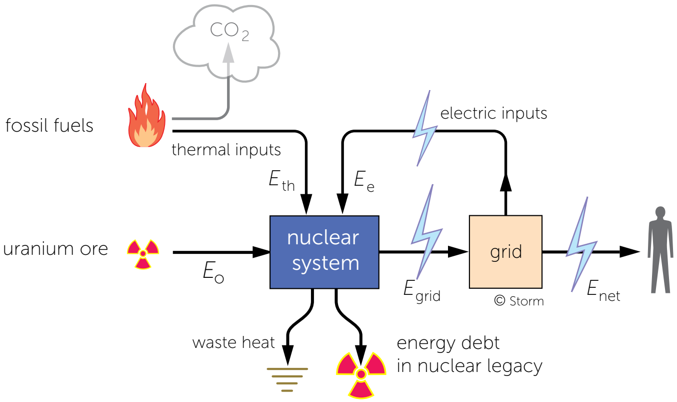

Figure 6
Energy flows of the nuclear energy system. The electrical inputs are assumed to be provided by the system itself (see text). The CO_2 emission by the nuclear system comes from the burning of fossil fuels in the nuclear process chain and from chemical reactions.

The operating plants would provide the electrical energy inputs needed for the front-end processes and for construction and OMR of new power plants, and are balanced with the gross electricity output. Strictly these inputs are not CO_2 free, if the CO_2 emission of the complete nuclear system is calculated on basis of the gross output, as is done in this study. This difference is ignored, in view of the uncertainty range in the values.

A methodological issue arises concerning the back-end processes of a given nuclear power plant, because these could be fulfilled only after closedown of the power plant, as pointed out in the first section. No advanced technology is needed to complete the back end. Like other industrial processes the back-end processes require inputs of materials and energy and emit CO_2 and possibly also other GHGs. The consumption of energy and the emission of CO_2 by the back-end processes are to occur during periods of decades to more than a century after the closedown of a particular nuclear power plant: the cause of the *energy debt* and *latent* CO_2 *emission*. The energy inputs are to be provided in the future by the then operating energy systems.

This study assumes the specific CO_2 emission (CO_2 intensity γ) of all thermal energy inputs (fossil fuels) of the nuclear energy system to have a mean value of:

$$\gamma = 75\ \mathrm{g(CO_2)/MJ(th)}\ .$$

Many thermal inputs of the industrial processes of the nuclear system are fossil fuels. Above value might be not overestimated as the average CO_2 emission of fossil fuels.

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