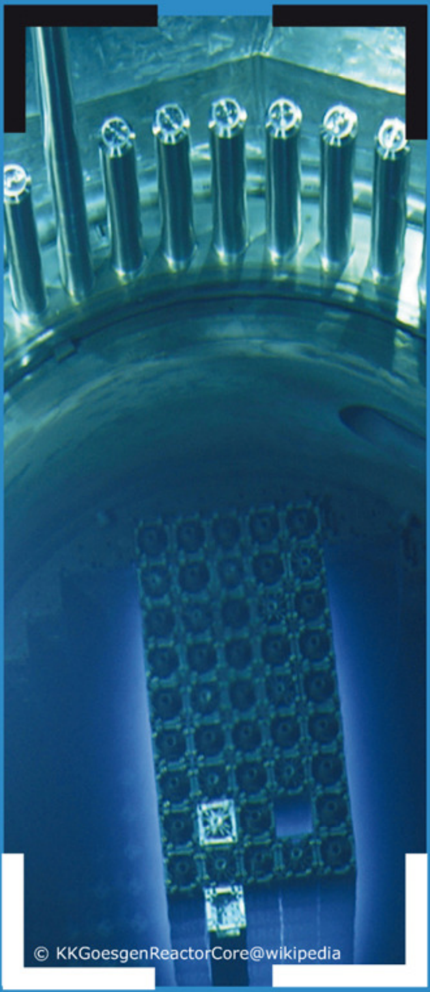
Energy Balance of Nuclear Power Generation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Life Cycle Analysis of Nuclear Power: Energy Balance and CO_2 Emissions

Summary

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Summary

Background

The accident at the Japanese nuclear power plant Fukushima in March 2011 triggered a debate about phasing out nuclear energy and the safety of nuclear power plants. Several states are preparing to end nuclear power generation. At the same time the operational life time of many nuclear power plants is reaching its end. Governments and utilities now need to take a decision to replace old nuclear power plants or to use other energy sources. In particular the requirement of reducing greenhouse gas emissions (GHG) is used as an argument for a higher share of nuclear energy.

To assess the contribution of nuclear power to climate protection, the complete ***life cycle*** needs to be taken into account. Some process steps are connected to high CO_2 emissions due to the energy used. While the processes before and after conventional fossil-fuel power stations can contribute up to 25% of direct GHG emission, it is up to 90 % for nuclear power (Weisser 2007).

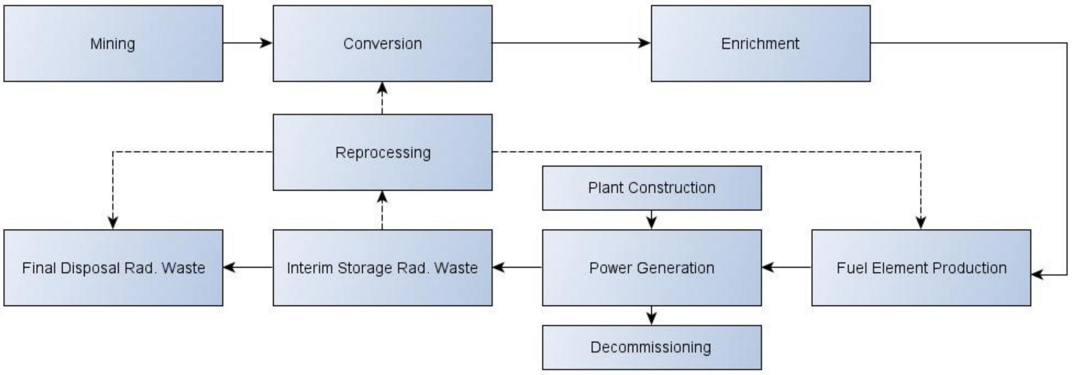

Figure 1: Main process steps of the nuclear fuel cycle

Goals of this Report

This report aims to produce information about the energy balance of nuclear energy production during its life cycle.

The following key issues were examined:

- How will the forecasted decreasing uranium ore grades influence energy intensity and green house emissions and from which ore grade on will no energy be gained any more?
- In which range can nuclear energy deliver excess energy and how high are green house gas emissions?
- Which factors including ore grade have the strongest impact on excess energy?

Analysis of Existing Literature

Literature makes a connection between ore grade and energy intensity. Energy intensity is the energy used during the complete nuclear fuel cycle, necessary to produce one kWh_{el} (energy input/energy output). A certain ore grade (limiting ore grade) results in an energy intensity of nuclear power of over 100 %. In this case the energy balance turns negative, i.e. no excess energy is generated any more and operating a nuclear power plant with this fuel does not make sense from an energetic point of view.

The ***range of energy intensity*** found in literature (Figure 2) lies for medium ore grades (ore grade between 0,15 % and 0,26 %) between 2 % and 50 %. The latest ISA study (2006) arrived at an energy intensity range of 10 % to 30 %, the average being 18 %.

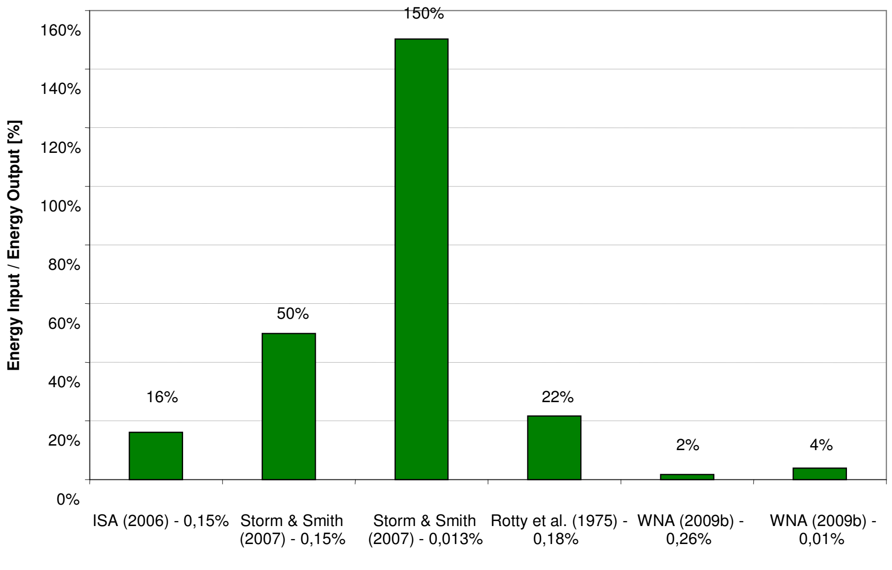

Figure 2: Energy intensity of the nuclear fuel chain – Comparison of overall results of different studies taking the uranium ore grade into account

In spite of the wide range of final results, literature agrees on the key importance of the ***ore grade*** for the energy balance: A low ore grade of around 0,01 % turns the uranium processing into the process step with the highest energy expenditure (over 40 % of total energy expenditure). Energy intensity quoted in literature, however, gives a very high range (4–150 %): Results range from very high excess energy to a negative energy balance.

One of the few studies which take the different ore grades into account is the study by Storm van Leeuwen and Smith (2007; 2008).

According to calculations made by Storm/Smith, ore grades lower than 0,013 % turn the energy balance negative. This ore grade however, will be reached in 2078 assuming the installed nuclear capacity stays the same, while a yearly capacity increase of 2 % would reach this value already in 2059.

The process steps before and after the power plant cause ***green house gas emissions***. Values given in literature for CO_2 emissions of nuclear energy range between 2 and 288 g CO_2/kWh. The highest value of 288 g CO_2/kWh$_{el}$ relates to the very low ore grade of 0,013 % (Storm/Smith 2007). ISA (2006) mentions values of an average around 60 g CO_2/kWh. Figure 3 shows a comparison of different results in literature of CO_2 emissions of nuclear energy according to Sovacool (2008).

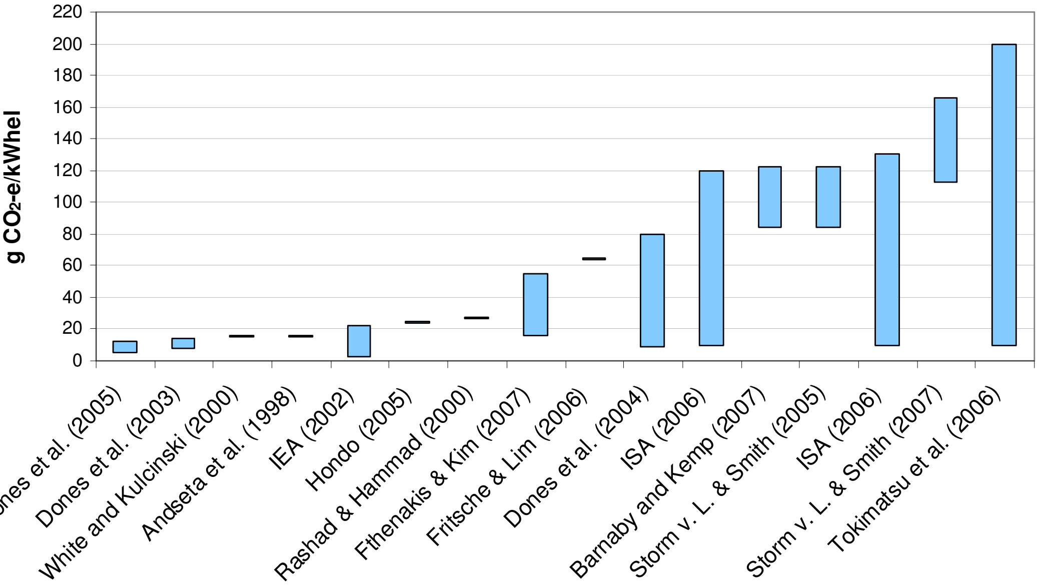

Figure 3: Green house gas intensity of the nuclear fuel chain – Comparison of the range given in different studies (min – max) according to Sovacool (2008)

Goals and Methods of the Energy Balance Nuclear (EBN model)

Because the data found in literature does not give the level of details needed for answering the research questions, the larger part of the nuclear process chain was modelled with our own ***bottom-up calculations.*** The model (***energy balance nuclear, EBN***) compares the energy input required for the nuclear fuel chain with the energy output of the nuclear power plant. The calculations include direct energy i.e. the used electric and thermal energy, as well as the indirect energy embodied in materials. Energy requested for the construction and decommissioning of facilities, which are used in the process chain, also was included in the calculation as far as possible. The major part of the nuclear process chain was modelled this way, the rest of data was taken from literature. Input data was taken from technical literature, further information stems from other mining industries and interviews with experts.

The focus of the calculations lies with ***uranium mining***. It takes into account the declining ore grade as well as the uranium mining at different exploitation depths and used types of mining.

However, the bottom-up method cannot include all process steps which use energy and the results generated by the model therefore represent ***minimum values***, which have the tendency to be higher in the real life cycle of one kWh power generated from uranium.

The EBN model was used to answer following questions:

- Plausible range for energy intensity and green house gas emissions of the nuclear fuel chain
- Sensitivity of the results towards different input parameters
- Threshold grade[1]
- Uranium supply
- Plausibility of results of other studies

Results of the EBN model

To reach a plausible range of results, the EBN model calculated the results for different scenarios: The assumed scenarios differ by types of mines (open cast mining, underground mining, in-situ leaching) as well as enrichment technologies, transport distances and reactor parameters. Table 1 gives an overview over the results in comparison to the range found in the examined literature.

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[1] The threshold grade is reached, when the excess energy from using uranium for electricity generation turns zero.

Table 1: Range of key results compared to literature

	Energy intensity [%]	***CO_2 emissions [g/kWh]***
Results of the EBN model:		
Scenarios with an ore grade 0,1–2 %	2–4	14–26
Scenarios with an ore grade 0,01–0,02 %	14–54	82–210
Threshold grade 0,0086 % in scenario „Average“	100	563
All scenarios	2–54	14–210
Range found in the examined literature	1,7[2]–108	2–288[3]

Scenarios with ore grades between 0,1 to 2 % have an energy expenditure for generating one kWh_{el} between 2 to 4 %. The declining ore grade (*0,01 % and 0,02 %*) increases the energy expenditure to 14–54 %; the resulting CO2 emission amount to 82–210 g/kWh. The ore grade becomes the decisive factor.

Under a certain ore grade (***threshold ore grade***) the energy expenditure for the uranium mining is so high, that the overall energy balance turns negative. Figure 4 shows the threshold ore grade for the scenario „Average“: From a certain ore grade of around 0,02 % on downwards, the requested energy expenditure grows in relation to the output so heavily, until it exceeds it at below 0,008 to 0,012 %. From this ore grade on, the operation of nuclear power plants does not generate any energy surplus any more. With lower ore grades the results also show a high sensitivity towards changes in exploitation depths and mining efficiency.

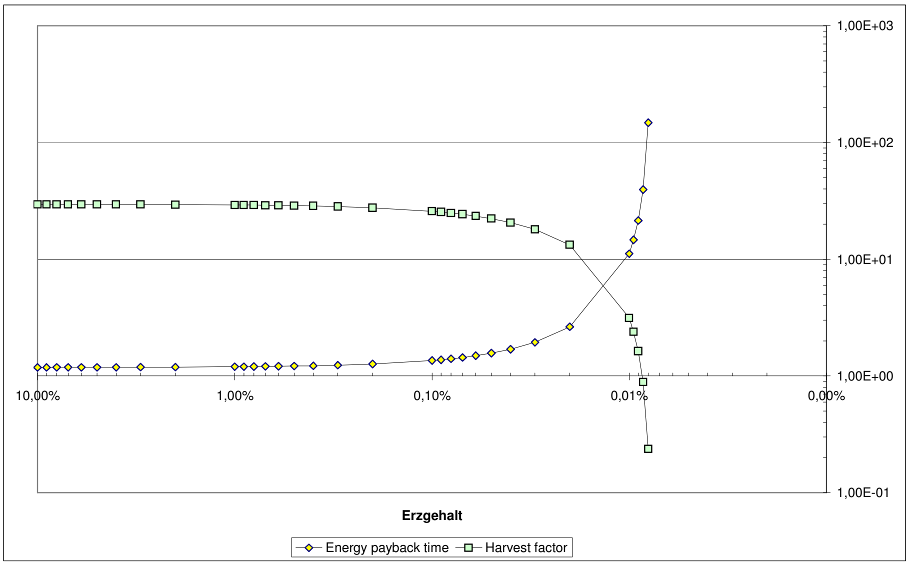

Figure 4: Excess energy in relation to the ore grade

The strong relation of excess energy to the ore grade of the uranium used is of particular relevance, because the trend in the past five decades shows a continuous downward trend

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[2] WNA (2009) bei einem Erzgehalt von 0,26

[3] Storm/Smith (2008) bei einem Erzgehalt von 0,013

of the ore grade and it is forecasted to decrease even further in future. According to the International Atomic Energy Agency (IAEA), one third of the Identified reserves has an ore grade under 0,03 %. In the past five decades, the average ore grade worldwide ranged between 0,05 and 0,15 % (Mudd/Diesendorf 2007b; ISA 2006, p. 96). The majority of global uranium resources consists of so called unconventional resources, where exploitation is very challenging. CO_2 emissions, water and energy requirements as well as uranium mining costs are very likely to rise in future.

Another key issue in this context concerns the uranium supply in the future. Concerning the ***future uranium supply*** several different scenarios were identified (assuming a constant global installed reactor capacity, increase in capacity by 1% yearly, further development of capacity according to the World Nuclear Association scenario) and put into relation to the IAEA data on uranium resources with different ore grade categories.

Assuming the low growth scenario of the World Nuclear Association (WNA) (the installed power plant generation would reach 961 GW in 2050) and the IAEA data on uranium resources, would make the currently operated uranium mines last until 2055. If also mines are taken into account, which are currently being developed, the uranium reserves would last until around 2075 in the low WNA growth scenario.

Assuming low growth of nuclear capacity of 1% only, currently operated uranium mines would last until 2055 in the „Best Case" Scenario would last only for the period 2052-2065. If the current global nuclear generation capacities stay constant, the result will be that the uranium deposits currently mined will be depleted after 2066.

One third of currently operated uranium mines have an ore grade below 0,03 % and therefore also contain uranium ore under the threshold ore grade. The uranium resources which can be used for energy production might be even much lower. Values from literature confirm the relatively short lasting of uranium resources and partly assume even much shorter duration.

In the attempt to react to supply shortages, the ***Generation IV reactors*** are being developed, which partly breed their own fuel. The development of those reactors is however in an early stage, very expensive and characterized by many unsolved issues, e.g. safety problems of the Fast Breeders and thorium reactors and high costs for development and construction.

Conclusions

Newly constructed nuclear power plants are supposed to have an operational life time of 60 years and a lead time between planning and operation of a facility of 10 to 19 years. Nuclear power plants which are currently being planned, would reach their end of expected life time in the period of 2080 - 2090; power plants now starting to operate, would be shut-down at the end of 2070. If the WNA low growth scenario is assumed as a starting point, the currently operated uranium mines would be exhausted between 2043 and 2055. If we assume this scenario to occur, it would not be possible to supply a nuclear power plant built now with uranium until the end of its lifetime.

The ***contribution of nuclear power to climate protection*** is relativized when taking into account the declining ore grades: Nuclear power can be referred to as “low-carbon” when the ore grade are high (0,1 bis 2 %). However, ore grades around 0,01 % make the CO_2 emissions increase up to 210 g CO_2/kWh_{el}. Those emission values are still lower than those of coal or oil (600–1200 g/kWh_{el}), but significantly higher than for wind (2,8–7,4 g/kWh_{el}), hydropower (17–22 g/kWh_{el}) and photovoltaics (19–59 g/kWh_{el}). Moreover it would be costly and slow to use nuclear power as means for reducing green house gas emission; it would take decades, until a net reduction of GHG would have occurred (Pasztor 1991; Findlay 2010). The CO_2 avoiding costs of nuclear power are than for any other possible technology except traditional coal fired power plants. Wind power stations and cogeneration of heat and power are 1,5 times more cost-effective in reducing CO_2 than nuclear power, energy efficiency measures are 10 times more cost-effective.

Further problems of nuclear power generation remain unsolved:

- **Accident liability** is unsolved. Worldwide, nuclear power plants are legally exempt from the liability for catastrophic accidents.
- ***Health risks*** from radiation of nuclear power plants cannot be excluded. In Germany, a study conducted by the German Deutschen Kinderkrebsregister (German Paediatric Cancer Registry) proves increased leucemia rates for children in the surroundings of nuclear power plants. (Kaatsch et al. 2007).
- While the Operationable[4] uranium resources will not last longer than this century, the highly radioactive waste has to be stored safely for thousands of years. No ***storage concept*** was developed yet for the 245.000 tons of spent fuel elements nuclear power generated already worldwide.
- Nuclear power used for electricity generation is the biggest driver of proliferation of fissile material. Without nuclear power generation, proliferation attempts could be identified undisputedly, because each effort to acquire fissile material would clearly serve military purposes.

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[4] Operationable uranium resource: defining uranium reserves of a uranium mine operating or with uranium in stand-by for mining

- ***Nuclear power leads to higher electricity prices***, because direct and indirect subsidies cover up the enormous costs of nuclear energy. Worldwide no reactor was built, where private investors would have carried the financial risk. If nuclear power in a liberalised market would actually lead to low electricity prices, it should not be a problem to find private investment to build new reactors.

Nuclear power is a high-risk technology due to the risks connected with it. However, in connection with the need of protecting the climate, this energy form is also called “low-carbon”.

While nuclear power using uranium with high ore grades produces lower green house emissions than coal and oil, the resources of rich uranium ores and uranium in general are – as fossil fuels – limited. Because in future a decreasing ore grade in the available resources has to be assumed, the **CO_2 emissions of nuclear power** can reach up to **210 CO_2/kWh_{el}**.

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The Austrian Institute for Ecology is a well-established research and consulting institution, active in the field of ecology and sustainability since 1985. We work for and with the political representation and administration, business and interest groups as well as those directly affected by social change. Our experts from different fields offer a broad range of approaches of topics and methods. We respond to the ambitious challenge of achieving sustainable development in its ecological, social and economic dimension. Our field of competence Society-Science-Technology serves to research and evaluate among other issues the sustainable potential of technologies to solving global problems. We assess chances and risks of technologies during their life cycle for the environment, society and health. Since 25 years we have been working on the issue of nuclear power, the impact of the fuel cycle from uranium mining to the final disposal on people and environment, safety and the risk of nuclear facilities, consequences of severe accidents and issues of radiation protection.

AUSTRIAN ENERGY AGENCY

The Austrian Energy Agency, founded in 1977, is developing, supporting and implementing measures for a sustainable energy supply and efficient energy use. Innovative energy technologies, energy efficient systems and renewable energy sources are among the relevant topics. The Austrian Energy Agency contributes to the shaping and implementing energy, technology and research policy on the federal and the national level in the Austrian political system. In addition, the Energy Agency cooperates on the national, the international and EU-level in the framework of projects with different institutions to achieve a sustainable energy supply. The Austrian Energy Agency employs an interdisciplinary team of around seventy people.

This study provides information on the energy expenditure for nuclear power production over the whole life cycle. We look into the following key issues: Which factors including the ore grade have the biggest influence on the excess energy? At which ore grade no excess energy is generated any more? Can increased use of nuclear power contribute to climate protection? For most steps of the nuclear fuel cycle a bottom-up model was used.