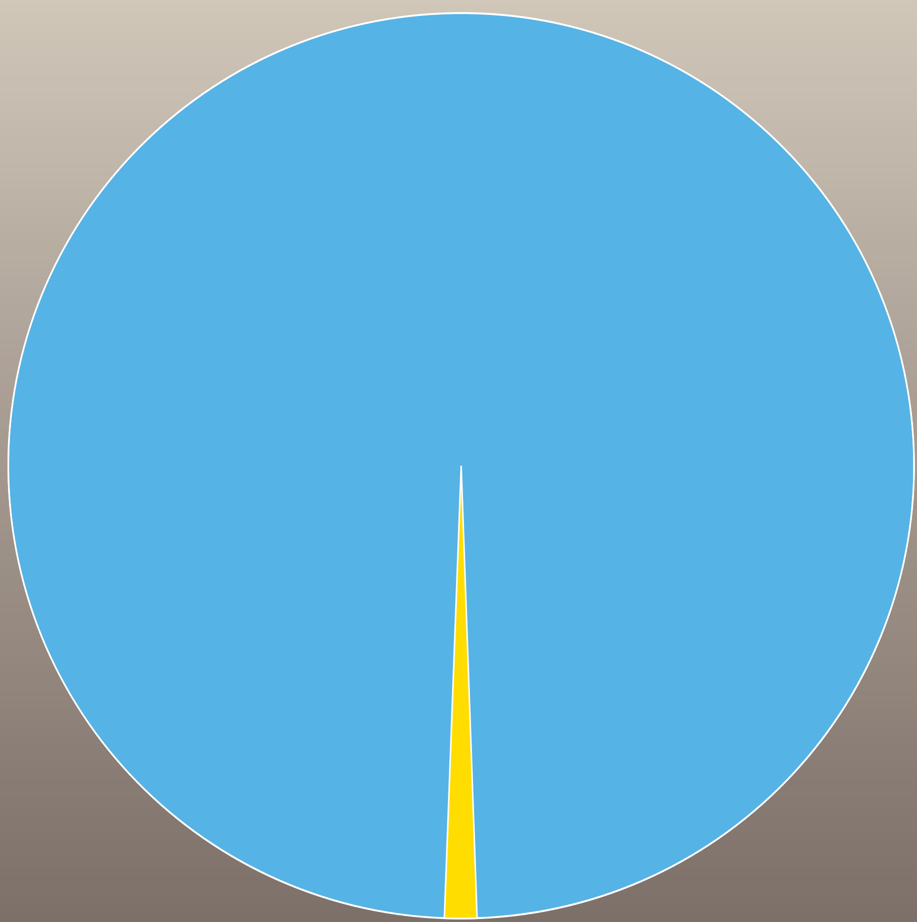
Climate change and nuclear power



An analysis of nuclear greenhouse gas emissions

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With this study WISE hopes to contribute to a thorough debate about the best solutions to tackle climate change. Nuclear energy is part of the current global energy system. The question is whether the role of nuclear power should be increased or halted. In order to be able to fruitfully discuss this we should at least know what the contribution of nuclear power could possibly be.

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Summary and findings

Points at issue

Nuclear power is, according to the nuclear industry, nearly carbon-free and indispensable for mitigating climate change as a result of anthropogenic emissions of greenhouse gases.

In the official publications of the International Atomic Energy Agency (IAEA) and the nuclear industry no figures could be found regarding the present and/or envisioned future nuclear contribution to the reduction of the global emissions of greenhouse gases.

This study assesses the following questions:

- How large would the present nuclear mitigation share be, assumed that nuclear power does not emit carbon dioxide CO_2?
- How large could the reduction become in the future, starting from nuclear generating capacity scenarios published by the IAEA, and also assumed that nuclear power does not emit CO_2?
- How feasible are the projections of the nuclear industry?
- How large could the actual nuclear CO_2 emissions be, estimated on the basis of an independent life cycle analysis?
- Does nuclear power emit also other greenhouse gases?

These issues are assessed by means of a physical analysis of the complete industrial system needed to generate electricity from uranium. Economic aspects are left outside the scope of this assessment. Health hazards of nuclear power are also not addressed in this report.

Present nuclear mitigation contribution

The global greenhouse gas (GHG) emissions comprise a number of different gases and sources. Weighted by the global warming potential of the various GHGs, 30% of the emissions were caused by CO_2 from the burning of fossil fuels for energy generation. Nuclear power may be considered to displace fossil-fuelled electricity generation. In 2014 the nuclear contribution to the global usable energy supply was 1.6% and the contribution to the emission reduction of nuclear power displacing fossil fuels would be about 4.7%, provided that nuclear power is free of GHs (which it is not).

Nuclear mitigation contribution in the future

A hypothetical nuclear mitigation contribution in 2050, based on two scenarios of the IAEA and provided that nuclear power is free of GHs, comes to:

- scenario IAEA Low, constant nuclear capacity, 376 GWe in 2050: 1.3 - 2.4%
- scenario IAEA High, constant nuclear mitigation share, 964 GWe in 2050: 3.8 - 6.8%.

The high figures are valid at a growth of the global GHG emissions of 2.0%/yr, the low figures at a growth of 3.5%/yr.

Global construction pace

By 2060 nearly all currently operating nuclear power plants (NPPs) will be closed down because they will reach the end of their operational lifetime within that timeframe. The current construction pace of 3-4 GWe per year is too low to keep the global nuclear capacity flat and consequently the current global nuclear capacity is declining. To keep the global nuclear capacity at the present level the construction pace would have to be doubled.

- in scenario IAEA low: 7-8 GWe per year until 2050.
- in scenario IAEA high: 27 GWe/yr until 2050.

In view of the massive cost overruns and construction delays of new NPPs that have plagued the nuclear industry for the last decade it is not clear how the required high construction rates could be achieved.

Prospects of new advanced nuclear technology

The nuclear industry discusses the implementation within a few decades of advanced nuclear systems that would enable mankind to use nuclear power for hundreds to thousands of years. These concepts concern two main classes of closed-cycle reactor systems: uranium-based systems and thorium-based systems. However, the prospects seem questionable in view of the fact that, after more than 60 years of research and development in several countries (e.g. USA, UK, France, Germany, the former Soviet Union) with investments exceeding €100bn, still not one operating closed-cycle reactor system exists in the world.

Failure of the materialisation of the uranium-plutonium and thorium-uranium breeder systems can be traced back to limitations governed by fundamental laws of nature, particularly the Second Law of thermodynamics.

From the above observation it follows that nuclear power in the future would have to rely exclusively on once-through thermal-neutron reactor technology based on natural uranium. As a consequence the size of the uranium resources will be a restricting factor for the future nuclear power scenarios.

Nuclear generating capacity after 2050

The IAEA scenarios are provided through 2050. Evidently the nuclear future does not end in 2050. On the contrary, it is highly unlikely that the nuclear industry would build 964 GWe of new nuclear capacity by the year 2050 without solid prospects of operating these units for 40-50 years after 2050.

How does the nuclear industry imagine development after reaching their milestone in 2050?

Further growth, leveling off to a constant capacity, or phase-out?

Uranium demand and resources

The minimum uranium demand in the two IAEA scenarios can be estimated assuming no new nuclear power plants (NPPs) would be build after 2050 and consequently the NPPs operational in 2050 would be phased out by 2100.

The presently known recoverable uranium resources of the world would be adequate to sustain scenario IAEA Low, but not scenario IAEA High.

According to a common view within the nuclear industry, more exploration will yield more known resources, and at higher prices more and larger resources of uranium become economically recoverable. In this model uranium resources are virtually inexhaustable.

Energy cliff

Uranium resources as found in the earth's crust have to meet a crucial criterion if they are to be earmarked as energy sources: the extraction from the crust must require less energy than can be generated from the recovered uranium. Physical analysis of uranium recovery processes proves that the amount of energy consumed per kg recovered natural uranium rises exponentially with declining ore grades. No net energy can be generated by the nuclear system as a whole from uranium resources at grades below 200-100 ppm (0.2-0.1 g U per kg rock); this relationship is called the *energy cliff*.

Depletion of uranium-for-energy resources is a thermodynamic notion.

Apparently the IAEA and the nuclear industry are not aware of this observation. Some resources classified by the IAEA as 'recoverable' falls beyond the thermodynamic boundaries of uranium-for-energy resources.

Actual CO_2 emission of nuclear power

A nuclear power plant is not a stand-alone system, it is just the most visible component of a sequence of industrial processes which are indispensable to keep the nuclear power plant operating and to manage the waste in a safe way, processes that are exclusively related to nuclear power. This sequence of industrial activities from cradle to grave is called the nuclear process chain. Nuclear CO_2 emission originates from burning fossil fuels and chemical reactions in all processes of the nuclear chain, except the nuclear reactor. By means of the same thermodynamic analysis that revealed the energy cliff, see above, the sum of the CO_2 emissions of all processes constituting the nuclear energy system could be estimated at: 88-146 gCO_2/kWh. Likely this emission figure will rise with time, as will be explained below.

In view of the large specific consumption of materials by the nuclear system of more than 200 g/kWh, compared with 5-6 g/kWh of an equivalent wind power system, it seems inconceivable that the nuclear system would emit less CO_2 than), as stated by the nuclear industry.

CO_2 trap

The energy consumption and consequently the CO_2 emission of the recovery of uranium from the earth's crust strongly depend on the ore grade. In practice the most easily recoverable and richest resources are exploited first, a common practice in mining, because these offer the highest return on investment. As a result the remaining resources have lower grades and uranium recovery becomes more energy-intensive and more CO_2-intensive, and consequently the specific CO_2 emission of nuclear power rises with time. When the average ore grade approaches 200 ppm, the specific CO_2 emission of the nuclear energy system would surpass that of fossil-fuelled electricity generation. This phenomenon is called the *CO_2 trap*.

If no new major high-grade uranium resources are found in the future, nuclear power might lose its low-carbon profile within the lifetime of new nuclear build. The nuclear mitigation share would then drop to zero.

Emission of other greenhouse gases

No data are found in the open literature on the emission of greenhouse gases other than CO_2 by the nuclear system, likely such data never have been published. Assessment of the chemical processes required to produce enriched uranium and to fabricate fuel elements for the reactor indicates that substantial emissions of fluorinated and chlorinated gases are unavoidable; some of these gases may be potent greenhouse gases, with global warming potentials thousands of times greater than CO_2.

It seems inconceivable that nuclear power does not emit other greenhouse gases. Absence of published data does not mean absence of emissions.

Krypton-85, another climate changing gas

Nuclear power stations, spent fuel storage facilities and reprocessing plants discharge substantial amounts of a number of fission products, one of them is krypton-85, a radioactive noble gas. Krypton-85 is a beta emitter and is capable of ionizing the atmosphere, leading to the formation of ozone in the troposphere. Tropospheric ozone is a greenhouse gas, it damages plants, it causes smog and health problems. Due to the ionization of air krypton-85 affects the atmospheric electric properties, which gives rise to unforeseeable effects for weather and climate; the Earth's heat balance and precipitation patterns could be disturbed.

Questionable comparison of nuclear GHG emission figures with renewables

Scientifically sound comparison of nuclear power with renewables is not possible as long as many physical and chemical processes of the nuclear process chain are inaccessible in the open literature, and their unavoidable GHG emissions cannot be assessed.

When the nuclear industry is speaking about its GHG emissions, only CO_2 emissions are involved. Erroneously the nuclear industry uses the unit gCO_2eq/kWh (gram CO_2-*equivalent* per kilowatt-hour), this unit implies that other greenhouse gases also are included in the emission figures, instead the unit gCO_2/kWh (gram CO_2 per kilowatt-hour) should be used. The published emission figures of renewables *do* include all emiited greenhouse gases. In this way the nuclear industry gives an unclear impression of things, comparing apples and oranges.

A second reason why the published emission figures of the nuclear industry are not scientifically comparable to those of renewables is the fact that the nuclear emission figures are based on incomplete analyses of the nuclear process chain. For instance the emissions of construction, operation, maintenance, refurbishment and dismantling, jointly responsible for 70% of nuclear CO_2 emissions, are not taken into account. Exactly these components of the process chain are the only contributions to the published GHG emissions of renewables. Solar power and wind power do not consume fuels or other materials for generation of electricity, as nuclear power does.

Latent entropy

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

The entropy contained in spent nuclear fuel will unavoidably be released into the biosphere if no measures are taken to prevent that. The explosions of atomic bombs and the disasters of Chernobyl and Fukushima showed the possible effects of unretained nuclear entropy. Each year an operating nuclear power plant of 1 GWe generates an amount of human-made radioactivity equivalent to 1000 exploded Hiroshima bombs.
As long as the nuclear entropy is enclosed in spent fuel elements it is called the *latent entropy* of nuclear power. The main purpose of the back-end processes of the nuclear chainshould be to keep the latent entropy under control.

E*nergy debt and delayed GHG emissions*

Only a minor fraction of the back end processes of the nuclear chain are operational, after more than 60 years of civil nuclear power. The fulfillment of the back end processes involve large-scale industrial activities, requiring massive amounts of energy and high-grade materials. The energy investments of the yet-to-be fulfilled activities can be reliably estimated by a physical analysis of the processes needed to safely handle the radioactive materials generated during the operational lifetime of the nuclear power plant. No advanced technology is required for these processes.
The energy bill to keep the latent entropy under control from 60 years nuclear power has still to be paid. The future energy investments required to finish the back end are called the *energy debt*.

The CO_2 emissions coupled to those processes in the future have to be added to the emissions generated during the construction and operation of the NPP if the CO_2 intensity of nuclear power were to be compared to that of other energy systems; effectively this is the *delayed CO_2 emission* of nuclear power. Whether the back end processes would emit also other GHGs is unknown, but likely.
Stating that nuclear power is a low-carbon energy system, even lower than renewables such as wind power and solar photovoltaics, seems strange in view of the fact that the CO_2 debt built up during the past six decades of nuclear power is still to be paid off.