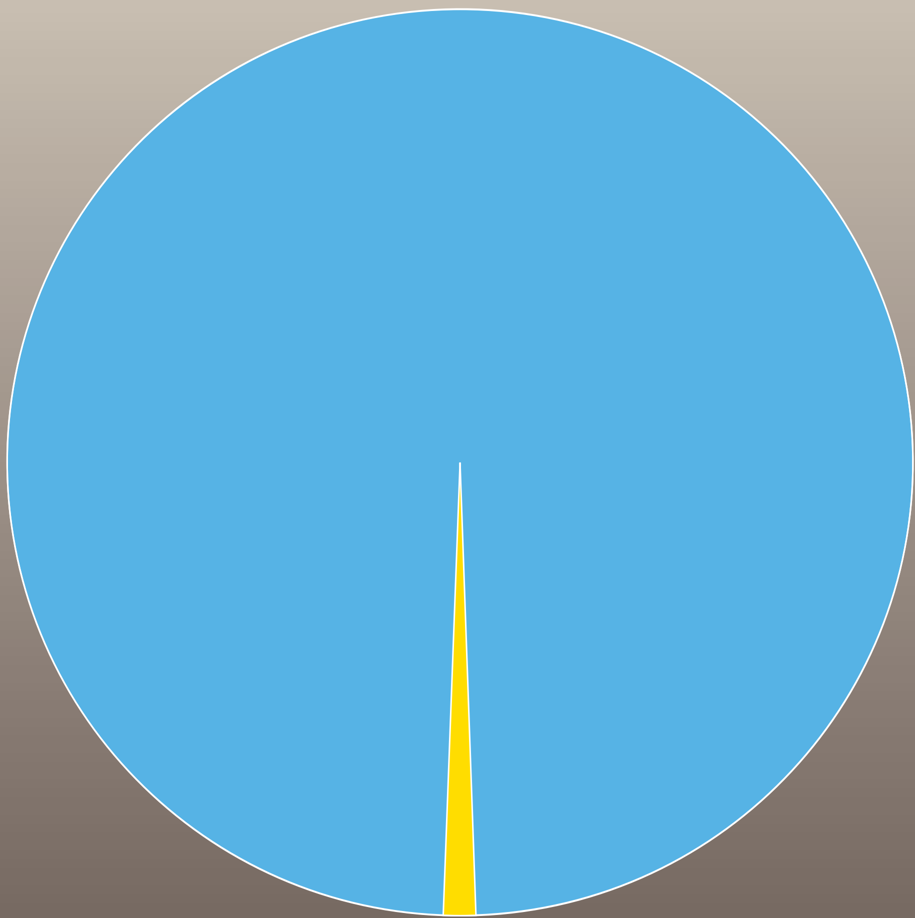
Summary and conclusions

Can nuclear power slow down climate change?



An analysis of nuclear greenhouse gas emissions

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Can nuclear power slow down climate change?

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 conclusions

Starting point

Nuclear power is claimed to be nearly carbon-free and indispensable for mitigating climate change as a result of anthropogenic emissions of greenhouse gases.
Assuming that nuclear power really does not emit carbon dioxide CO_2 nor other greenhouse gases (GHGs), how large is the present nuclear mitigation share and how large could it become in the future? Could the term 'indispensable' in this context be quantfied? These issues are assessed from a physical point of view, economic aspects are left outside the scope of this assessment.

How large is the present nuclear mitigation share?

The global GHG emissions comprise a number of different gases and sources. Weighted by the global warming potential of the various GHGs 61% of the emissions were caused by CO_2 from burning of fossil fuels for energy generation. Nuclear power could displace fossil-fuelled electricity generation, so hypothetically the maximum nuclear mitigation share would be 61% if the global energy supply were to be fully electric and fully nuclear.
In 2014 the nuclear contribution to the global usable energy supply was 1.6% and consequently the nuclear mitigation share was 1.0%.
The International Atomic Energy Agency (IAEA) asserts that the nuclear contribution to the global energy supply was 4.6% in 2014. However, this figure turns out to be based on a thermodynamically inaccurate statistical trick using virtual energy quantities.

How large could the nuclear mitigation to climate change become in the future according to the nuclear industry?

We found no hard figures on this issue, for that reason this study analyses the mitigation consequences of the envisioned developments of global nuclear generating capacity. During the past years the International Atomic Energy Agency and the nuclear industry, represented by the World Nuclear Association (WNA), published numerous scenarios of global nuclear generating capacity in the future, measured in gigawatt-electric GWe. Four recent scenarios are assessed in this study, as these can be considered to be typical of the views within the nuclear industry:

- IAEA low: the global nuclear capacity remains flat at the current level until 2050.
- IAEA high: the global nuclear capacity grows to 964 GWe by 2050, nearly three times the current global capacity of 333 GWe.
- WNA low: the global nuclear capacity grows to 1140 GWe by 2060 and to 2062 GWe by 2100.
- WNA high: the global nuclear capacity grows to 3688 GWe by 2060 and to 11046 GWe by 2100.

The nuclear mitigation share in the four scenarios depends not only on the nuclear generation capacity, but also on the growth rate of the global GHG emissions. The IAEA expects a growth rate of the global energy consumption of 2.0-3.5% per year until 2050. This study assumes that global GHG emissions will grow during the next decades proportionally to global energy consumption: also at 2.0-3.5% per year. Based on this assumption – and still assuming nuclear power is free of CO_2 and other GHG emissions (which it is not) – the mitigation shares would be as follows, the high figure at a global growth of 2.0%/yr, the low figure at 3.5%/yr:

- IAEA low: 0.5-0.3% by 2050.

- IAEA high: 1.4-0.9% by 2050.
- WNA low: 1.4-0.7% by 2060 and 1.1-0.3% by 2100.
- WNA high: 4.5-2.4% by 2060 and 6.2-1.8% by 2100.

What next 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? Or: let tomorrow take care of itself?

What global construction rates would be required?

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 rate of 3-4 GWe per year is too low to keep the global nuclear capacity flat and consequently the global nuclear capacity is declining. To keep the global nuclear capacity at the current level the construction rate would have to be doubled. The average global construction rates that would be required in the industry scenarios are:

- IAEA low: 7-8 GWe per year until 2050.
- IAEA high: 27 GWe/yr until 2050.
- WNA low: 25 GWe/yr until 2060 and 23 GWe/yr from 2060 until 2100.
- WNA high: 82 GWe/yr until 2060 and 184 GWe/yr from 2060 until 2100.

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

How are the prospects of new advanced nuclear technology?

The nuclear industry promises the application within a few decades of advanced nuclear systems that would enable mankind to use nuclear power for hundreds to thousands of years. This promise concerns two main classes of closed-cycle reactor systems: uranium-based systems and thorium-based systems:

– uranium-plutonium recycle in conventional reactors, generally light-water reactors (LWRs)
– fast reactors, that are uranium-plutonium breeder reactors
– thorium reactors.

Because of the complexity of this matter the three options are briefly discussed below, starting with a brief description of a crucial component common to all three systems, reprocessing.

Reprocessing
A crucial technical component of the advanced reactor systems is the reprocessing of spent fuel, that is the sequence of physical and chemical processes required to separate spent nuclear fuel into a number of fractions: unused uranium, newly formed plutonium, actinides, fission products and other fractions. The reprocessed uranium and plutonium would be used to fabricate new nuclear fuel to be placed into reactors. In case of a thorium-based system the spent fuel would be separated into unused thorium-232, newly formed uranium-233, fission products and other fractions.
Reprocessing is a complicated, highly polluting, and very energy-intensive process. Decommissioning and dismantling of a reprocessing plant after it has to be closed down requires massive investments of materials, energy and financial resources and likely will take more than a century of dedicated effort.

U-Pu recycle in LWRs

The first option, uranium-plutonium recycle in conventional reactors (LWRs), relates to the use of plutonium as fissile material in nuclear fuel instead of uranium-235, as in enriched uranium; this kind of fuel is usually called MOX: Mixed OXide fuel. If all spent fuel discharged from the current global nuclear fleet (all conventional reactors except one) were to be reprocessed and the plutonium obtained were to be used in conventional reactors, the global uranium demand would decrease by some 18%.

Physical analysis of U-Pu recycle in LWRs proves that the energy balance of the system is negative, meaning that the system is actually an energy sink instead of an energy source. The main cause of this is the required energy input of reprocessing and of the decommissioning and dismantling of the reprocessing plant at the end of its service life.

Fast reactors: uranium-plutonium breeders

The term 'fast reactor' usually refers to the breeder system, a closed-cycle system that would generate (breed) more fissile nuclei from uranium than consumed in the fission process by converting non-fissile uranium-238 nuclei into fissile plutonium nuclei. During the 1980s and 1990s this type of reactor was usually called a 'breeder' or 'fast breeder reactor' (FBR) but this term has disappeared from the publications of the IAEA and the nuclear industry. Now the breeder concept is part of the so-called Generation IV program. This program also includes other types of fast reactors without a breeding capacity that are not discussed here.

The envisioned breeders would be able to extract 50-100 times more energy from a kilogram of natural uranium than the current conventional reactors, that cannot fission more than about 0.6% of the nuclei in natural uranium. The prefix 'fast' refers to the fact that this type of reactors operate with fast neutrons, contrary to the currently operating commercial reactors in which fission occurs by thermal (slow) neutrons.

A breeder (FBR) is not just a reactor but a cyclic system consisting of a fast-neutron nuclear reactor plus a reprocessing plant plus a fuel fabrication plant. Each of the three components of the cycle would have to operate flawlessly and finely tuned to the two other without any interruption. If one component fails in any respect, the whole system fails and breeding is out of question. Operation of the cyclic system is further complicated by the high radioactivity of the materials to be processed, increasing with each following cycle. Four decades of intensive research in several countries and investments of some $100bn, have proven that the breeding cycle is technically unfeasible. The failure to materialize the U-Pu breeder concept can be traced back to fundamental laws of nature, especially the Second Law of thermodynamics. Thermodynamics is the science of energy conversions; it is at the basis of physics, chemistry and biology. From the Second Law follows, among other consequences, that separation processes of mixtures of different substances never go to completion and consequently perfect materials are not possible. Critical in the breeder cycle is the reprocessing of the spent fuel as soon as possible after unloading from the reactor.

Thorium reactors

Thorium is a radioactive metal, more abundant in the Earth's crust than uranium. The concept of the thorium reactor is based on the conversion by neutron capture of non-fissile thorium-232 into uranium-233, which is as fissile as plutonium-239. Application of thorium-based systems would make nuclear power independent of the uranium supply, according to the promises of the nuclear industry.

The fundamental obstacles that render the U-Pu breeder technically unfeasible apply also to the thorium breeder. Another drawback of the thorium cycle is that a thorium reactor cannot sustain a fission process in combination with breeding uranium-233 from thorium-232, but always would need an external accelerator-driven neutron source, or the addition of extra fissile material, such as plutonium or uranium-235 from conventional reactors.

Conclusion
In the end the breeder concepts, U-Pu as well Th-U, turn out to be based on inherently unfeasible assumptions. *Conditio sine qua non* for closed-cycle nuclear generating systems is the availability of:

- perfect materials
- fail-safe and fool-proof technical systems with perfectly predictable properties across decades
- perfect separation of strongly radioactive, complex mixtures of numerous different chemical species into 100% pure fractions.

None of these conditions is possible, as a consequence of the Second Law of thermodynamics, and for that reason materialization of the breeder concept is inherently unfeasible.
From this observation it follows that nuclear power in the future would have to rely solely on once-through reactor technology based on natural uranium. As a consequence the size of the uranium resources will be a restricting factor.

How much uranium would be needed to sustain the various scenario's?

As pointed out above the nuclear generating capacity in the scenarios will not fall to zero at their end date. The minimum amounts of uranium that would be required in the IAEA scenario's are estimated here by assuming no new NPPs would be build after 2050 and consequently the nuclear power plants operational in 2050 would be phased out by 2100. In case of the WNA scenario's extension after 2100 seemed too speculative. The masses of uranium are given in teragram Tg, 1 Tg is 1 million metric tonnes .

- IAEA low: 2.3 Tg until 2050 plus 1.7 Tg during phase-out by 2100, total 4.0 Tg uranium
- IAEA high: 4.5 Tg until 2050 plus 4.8 Tg during phase-out by 2100, total 9.3 Tg uranium
- WNA low: 6.6 Tg until 2060 plus 12.7 Tg from 2060 until 2100, total 19.3 Tg uranium
- WNA high: 17.5 Tg until 2060 plus 58.4 Tg from 2060 until 2100, total 75.9 Tg uranium.

Obviously the uranium demand in the IAEA scenarios would be higher if the nuclear capacity were to remain flat after 2050, as opposed to phasing out after 2050 as assumed above; in case of a constant capacity after 2050 the total demand would be about 5.7 Tg in IAEA low and 14.1 Tg in IAEA high.
The known recoverable uranium resources of the world in the cost category of up to 130 USD/kg U amounted to 5.9 Tg in 2013 according to the IAEA; the market price in september 2015 was about 82 USD/kg U. An additional amount of 1.7 Tg of uranium is known to exist in the higher cost category 130-260 USD/kg U.

How are the prospects of the global uranium supply?

Uranium in the earth's crust is unevenly distributed among the rocks comprising the crust. The grade distribution of uranium in uranium-bearing rocks in the earth's crust show a geologic pattern common to other metals: the lower the grade of uranium the larger the amounts of uranium present in the crust. The size distribution of uranium deposits show a similar pattern as a result of the geologic ore-forming mechanisms: the larger the size, the more rare the deposits. From this observation it follows that the chance of discovering new resources increases with lower grades and smaller sizes of the deposits. One may assume that the most easily discoverable resources have been found already and that most easily minable deposits are already being mined. The chances of discovering new large high-grade resources seem low; in reality no such discoveries have been reported during the past two decades.
Based on a simple economic model the nuclear industry states that the global uranium resources are practically inexhaustable, apparently suggesting that any scenario could be materialized. However, the generation of nuclear energy from uranium resources is a physical phenomenon governed by the laws of nature, not by economic notions. The economic model does not include physical and chemical realities with regard to uranium deposits in the earth's crust. Thermodynamics sets the boundaries for the resources that fit the conditions of uranium-for-energy resources.

What are the thermodynamic boundaries of uranium-for-energy resources?

Energy cliff

The energy content of natural uranium that is in any sense extractable is limited: the nuclear power stations that would form the backbone of future nuclear capacity could not fission more than about 0.6% of the nuclei in natural uranium.

The thermodynamic boundaries of the uranium-for-energy resources are determined by the energy required to extract uranium from the resources as found in nature. Analysis of the physical and chemical processes needed to recover uranium from the earth's crust and all the processes needed to release the potential energy in uranium and convert it to useful energy proves that the amount of energy consumed per kg recovered natural uranium rises exponentially with declining ore grades. Below a grade of 200-100 ppm (0.2-0.1 grams U per kg rock) no net energy can be generated by the nuclear system as a whole from a uranium resource, this relationship is called the *energy cliff*. From this conclusion it follows that only uranium resources at grades higher than 200 ppm (0.2 g U/kg rock) are actually energy sources.

The ore grades of the known uranium resources which are by definition economically recoverable varies widely: from about 200 down to 0.1 gram uranium per kg rock. A part of the resources classified by the IAEA as 'recoverable' falls beyond the thermodynamic boundaries of uranium-for-energy resources.

*Unconventional uranium resource*s

The nuclear industry classifies the global uranium resources into two categories: conventional and unconventional resources. Phosphates are the main constituent of unconventional uranium resources, other types of uranium-bearing resources (e.g. black shales) are insignificant on global scale.

Phosphates are irreplaceable for agricultural use, so mining of these minerals should be tailored exclusively to agricultural needs. Moreover, the thermodynamic quality of phosphates as a uranium-for-energy source lies beyond the energy cliff: no net energy generation is possible by exploitation of phosphate rock; this holds true also for other unconventional uranium resources, including uranium from seawater.

How much CO_2 does nuclear power emit?

Nuclear CO_2 emission originates from burning fossil fuels in all processes and factories needed to extract uranium from the ground, prepare nuclear fuel from the recovered uranium, construct the nuclear power plant and to safely manage the radioactive wastes. The fission process in the nuclear reactor is the only process of the nuclear system that has (virtually) no CO_2 emission. In addition CO_2 is generated by chemical reactions during the production of necessary materials and chemicals, for example cement (concrete) and steel. A generic NPP contains some 150 000 tonnes of steel and 850 000 tonnes of concrete, in addition to several thousands of tonnes of other materials. The sum of all materials consumed by an NPP during its operational lifetime is about 76 grams per kilowatt.hour delivered to the grid, excluding the mass of rock displaced for mining and final sequestration of the radioactive wastes.

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 gram CO_2 per kilowatt.hour. This figure is based on the assumption that all electric inputs of the nuclear process chain are provided by the nuclear power plant itself, to avoid discussions of the local fuel mix of electricity generation.

The large uncertainty range is chiefly caused by uncertainties regarding the processes of the back end of the process chain, these are the processes needed to safely isolate the inevitable radioactive wastes from the biosphere, including the dismantling of the NPP after its service life. The emission figure will rise with time, as will be explained below.

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, and several other physical and chemical factors that are not discussed here. 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 of this practice the remaining resources have lower grades and uranium recovery becomes more energy-intensive and more CO_2 intensive. Consequently the specific CO_2 emission of nuclear power will rise with time; when the average ore grade approaches 200 ppm, the specific CO_2 emission of the nuclear energy system will 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 will run aground in the CO_2 trap within the lifetime of new nuclear build.

Does nuclear power also emit 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.

Unknown are the GHG emissions of the construction of a nuclear power plant, with its large mass of high-quality and often exotic materials. Unknown are the GHG emissions of the operation, maintenance and refurbishment of nuclear power plants. Unknown are the GHG emissions of the backend of the nuclear process chain: the handling and storage of spent fuel and other radioactive waste.

It is inconceivable that nuclear power does not emit other greenhouse gases, this matter is still a well-kept secret. Absence of published data does not mean absence of emissions.

Does nuclear power emit other climate changing gases?

Nuclear power stations 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. Would nuclear power exchange alleged mitigation of CO_2 emissions for enhanced emissions of climate changer krypton-85?

Are the published nuclear GHG emission figures comparable to 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 emissions cannot be assessed.

When the nuclear industry is speaking about its GHG emissions, only its 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 greenhouse gases. In this way the nuclear industry gives a false and misleading 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 a very incomplete analysis 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 either not taken into account, or use unrealistically low figures. It is these exact components that are the only contributions to the published GHG emissions of renewables. Solar power and wind power do not consume materials for conversion into electricity, as nuclear power does.

What is the energy debt and what are the delayed CO_2 emissions of nuclear power?

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 investments for construction of the nuclear power plant and those for running the front end processes are offset against the electricity production during the operational lifetime. 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 greenhouse gases is unknown.
Claiming 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.

What consequences of the energy debt could be expected?

As a result of the living-on-credit paradigm prevailing in the nuclear industry, all human-made radioactivity ever generated is still stored in makeshift facilities, if not already dumped into the sea, lakes, rivers or unattended landfills. The isolation from the biosphere of all radioactive materials in the least risky way is a *conditio sine qua non* to secure our children, grandchildren and future generations against the insidious hazards of the tremendous quantities of human-made radioactivity.

Realization of the nuclear scenarios combined with the currently prevailing après nous le déluge culture of the nuclear industry would greatly enhance health hazards and risks of accidents and terrorism. We could expect increased dispersion of radioactive materials into the environment due to the unavoidable and progressive deterioration of the materials housing the radioactive wastes of the nuclear chain, combined with increasing amounts of radioactive wastes, stored at an increasing number of temporary storage facilities.
The risks of severe accidents like Chernobyl and Fukushima would increase due to an increasing number of nuclear power plants and spent fuel cooling pools, this in combination with the progressive ageing of nuclear power plants and reprocessing plants. Other hazards are posed by an increasing number of transports of radioactive materials. If reprocessing of spent fuel were to be continued in the future the risks of nuclear terrorism would grow day by day, because an increasing amount of plutonium and other fissile materials would be transported and stored at different places.

Economic preferences and commercial choices can greatly increase nuclear hazards, the more so if the global economy stagnates or declines. There is the relaxation of the official standards for operational routine discharges of radionuclides into the environment by nuclear power plants and reprocessing plants. Due to ageing the frequency of leaks and spills will rise at an accelerating rate and so will the costs to repair the leaks and to prevent their occurrence. Raising allowable radioactive discharge limits for the nuclear operators keeps their costs down, while resulting in higher exposure standards for the general public, often by large factors, without scientific justification. Similar relaxation of exposure standards may be expected in case of a future nuclear accident, as occurred after the Fukushima disaster.
Another example is the relaxation of standards for clearance of radioactive construction materials for unrestricted use in the public domain. This will become a hot issue when heavily contaminated nuclear installations are dismantled; safe guardianship and disposal of the massive amounts of radioactive debris and scrap will be very expensive.

How independent is the information supply to the public on nuclear matters?

Communication between the nuclear industry and the general public is dominated by the International Atomic Energy Agency (IAEA). The authoritative 'nuclear watchdog' IAEA has the promotion of nuclear power in its mission statement. Moreover, official publications of the IAEA have to be approved by all member states of the IAEA. For these reasons it is a misconception to regard the IAEA as an independent scientific institution.
The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has strong connections with the IAEA and the World Health Organization (WHO) cannot operate independently of the IAEA with respect to nuclear issues. As a consequence statements of the WHO concerning health effects of radioactivity and nuclear activities do not deviate from the offical position of the IAEA.

Are releases of radioactive materials into the human environment really of minor importance?

From the reports of the IAEA, UNSCEAR and WHO on the subject of health effects, especially concerning the disasters of Chernobyl and Fukushima, a picture emerges of the nuclear world marked by *downplaying* and even *denial of health effects* caused by exposure to radiation and contamination by radioactive materials.
Non-cancerous diseases are not recognized as radiation-induced health effects, attention is paid only to acute radiation syndrome (ARS, radiation sickness). Conspicuous are the downplaying and denial of health effects caused by radioactivity using unscientific methods, committing elementary scientific flaws.

Full reliance is placed on (old) models for assessment of exposure doses and of dose-effect relationships, with little or no input of empirical evidence. Biochemical behaviour of radionuclides inside human body are not included. Chronic exposure to a mix of different radionuclides inside the body, via ingestion (food and water) and inhalation (gases, dust) are also not covered. The radiological models applied by the IAEA and nuclear industry turn out to be easily adaptable to economic and financial considerations.

Important international studies on health effects of radiation and contamination by radioactive materials with results diverging from the IAEA viewpoint are not discussed in the official IAEA publications and are even not mentioned.

Conclusions

- Assuming nuclear power emits no greenhouse gases (which is not true), the nuclear mitigation share would grow from the present level of less than 1% to at most 1.4% of the global greenhouse gas emissions by 2050-2060, if the global nuclear capacity were to grow according to scenarios projected by the nuclear industry.

- Materialization of the nuclear capacity scenarios proposed by the nuclear industry are doubtful because of the unrealistically high construction rates of new nuclear power plants that would be required.

- Nuclear generating capacity in the future will have to rely completely on reactors in the once-through mode, because closed-cycle systems, including the thorium cycle, are inherently unfeasible. As a consequence future nuclear power depends exclusively on the availability of natural uranium resources.

- Net energy contribution to the global energy supply by nuclear power is limited by the availability of uranium-for-energy resources. Exploiting resources at ore grades below 0.02-0.01% uranium the nuclear system becomes an energy sink instead of an energy source: nuclear power falls off the energy cliff.

- The average ore grade and other qualities of the yet-to-be exploited global uranium resources decline with time, because the highest quality resources available are always mined first.

- The chances of discovering new major uranium-for-energy resources are bleak.

- Mining of phosphates should be tailored exclusively to agricultural needs, for phosphorus is irreplaceable in agriculture.

- Uranium from seawater is no option. If feasible at commercial scale at all, this resource lies far beyond the energy cliff: no net energy generation is possible.

- From a practical viewpoint only the low IAEA scenario seems feasible, resulting in a mitigation share of 0.5-0.3% of the global GHG emissions by 2050, provided nuclear power is GHG free. The mitigation share would become negligible if the nuclear GHG emissions are taken into account.

- At present nuclear power emits 88-146 gCO_2/kWh. Likely the nuclear CO_2 emissions will grow from the current level to values approaching fossil fuel generation within the lifetime of new nuclear builds in the scenarios of both the IAEA and WNA.

- Emissions of GHGs other than CO_2 by nuclear power are not reported, but are almost certain from a technical point of view.

- Krypton-85, discharged by all nuclear power plants and reprocessing plants, generates greenhouse gases in the troposphere, in addition it causes other weather and climate changing effects.

- The published figures of nuclear GHG emissions are not comparable to the figures of renewables, because different quantities and estimation methods are applied.

- Due to the après nous le déluge culture of the nuclear industry the health hazards posed by radioactive materials in the human environment will increase with time, in addition to risks of Chernobyl-like disasters and of nuclear terrorism.

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