Global context and prospects of nuclear power

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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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Summary

Emissions of anthropogenic greenhouse gases, mainly carbon dioxide, contribute to the global warming, and the combustion of fossil fuels is by far the largest source of anthropogenic carbon dioxide emissions. Nuclear power is depicted in many publications as an indispensable means to mitigate the global carbon dioxide emissions.

The potential contribution of nuclear power to the mitigation of greenhouse gas emissions can reliably be estimated based on global statistical data of the present situation and on scenarios of future nuclear capacity as published by the International Atomic Energy Agency (IAEA).

Assuming that nuclear power is free of greenhouse gas emissions (which it is not), this study shows that the mitigation by nuclear power in 2017 was 4% of the global emissions - if the upstream losses of fossil fuels are taken into account - and would grow to 6% by 2050 in the most optimistic (but unrealistic) scenario. In a more realistic scenario the nuclear contribution would decline to 2% by 2050.

The findings of this study are based on a thermodynamic analysis of the currenty operational nuclear energy system and the proposed concepts of advanced, closed-cycle nuclear energy systems The scheme of this analysis is represented by Figure 1.

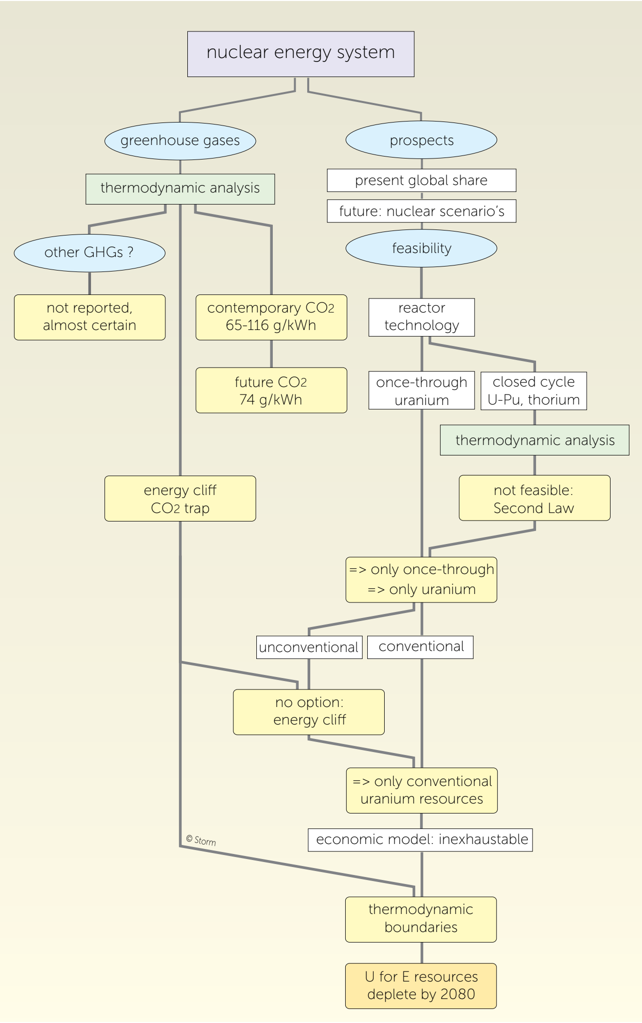


Figure 1

Outline of the thermodynamic analysis of the nuclear energy system in this study.

Statistical data

Global greenhouse gas emissions

Anthropogenic global warming is understood to be caused by the emission of greenhouse gases (GHGs). The global warming potential (GWP) of the gases released into the air vary widely and are measured as a multitude of the GWP of carbon dioxide and expressed in the unit 'gramCO_2-equivalent'. Figure 2 shows the shares of the main categories of GHGs: carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O and fluorinated compounds for the year 2017. The global GHG emissions rise at a rate of some 2% per year.

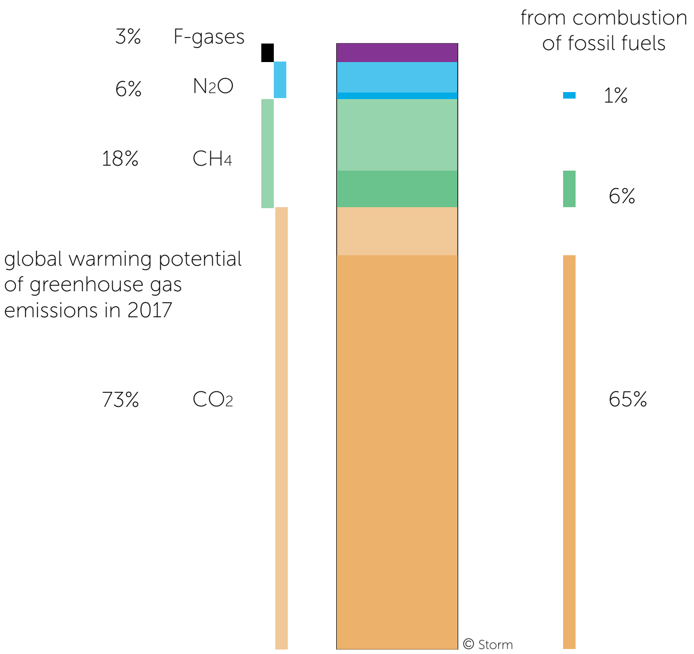


Figure 2

Global GHG emissions in 2017, weighted by their global warming potential (GWP). F-gases are fluorinated gases; 72% of the global GHG emissions are caused by the combustion of fossil fuels. Source of data: [JRC/PBl 2018].

World energy supply in 2017

In 2017 73% of the global warming potential was caused by CO_2, the remaining 27% by methane (CH_4), nitrous oxide (N_2O) and fluorinated gases. According to [JRC/PBL 2018] 72% of the global GHGs originate from the use of fossil fuels, 65% by CO_2, 6% by CH_4 and 1% by N_2O, see Figure 2. For sake of simplicity this study takes only the CO_2 emission by the energy sector into consideration.

In 2017 the nuclear share of the world gross energy production was 1.7%, based on data from [BP 2018]. Most energy statistics give another figure, for example [BP 2018] itself and [IEA 2016], cite a nuclear share of 4.8% of the world energy production in 2017. This divergence has two causes:

- Firstly BP lists only the traded energy, 519 EJ in 2017 (EJ = exajoule = 10^{18} joule) and ignores the non-traded energy supply by traditional biomass and waste.
- Secondly: BP uses the thermal equivalence of the world nuclear electricity production by multiplying it by a factor $f = 2.64$, apparently the IEA uses a factor $f = 3$. This method of calculation results in virtual energy units, and is thermodynamically questionable.

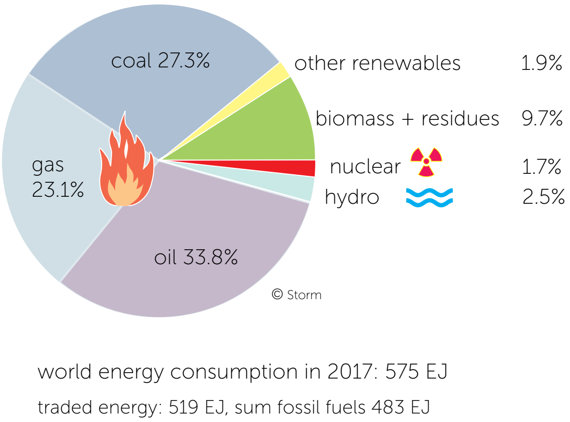
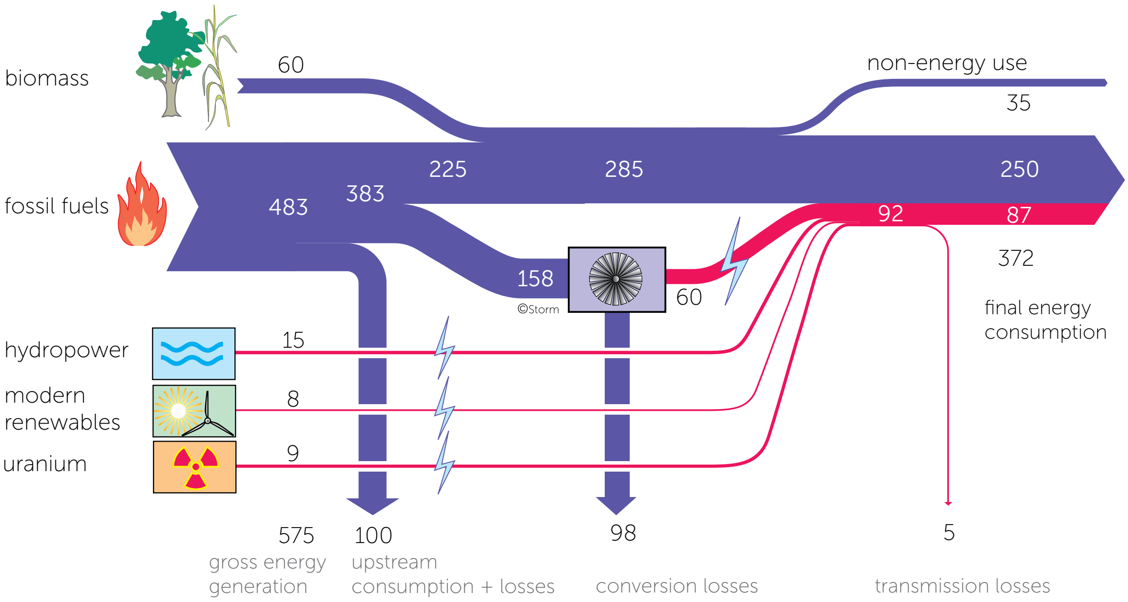


Figure 3

World primary energy production in 2017 was about 575 EJ (exajoule), of which 519 EJ traded energy. The share of nuclear power was 1.7% in 2017. This diagram is based on [BP 2018].

Final energy use in 2017



World energy flows 2017, exajoules (EJ)

Figure 4

Outline of the physical energy flows of the world in 2017, in exajoules (EJ). Not accurately known are the amounts of energy embodied in traditional biomass and in the upstream losses of the fossil fuels. Therefore the world final energy consumption, here presented as 372 EJ, may have an uncertainty range. Sources: [BP 2018], [WEC2016] and [IEA 2016]. This study assumes that 6% of the gross fossil fuel production was used for non-energy purposes in 2017; including the non-energy use of biomass the total amount would be about 35 EJ [Weiss et al. 2009], [IEA 2012].

There are three kinds of energy losses in the world energy system:

- Upstream fossil fuel losses. The recovery from the earth (production), refining and transport of the fossil fuels consume some 23% of the energy content of the fuels. Indirect energy use and losses due to flared and spilled fuels may not be included, so it may be a low estimate. This loss fraction will increase with time, as the most easily recoverable resources available are exploited first and will be depleted first; the remaining resources are less easy to exploit and harder to refine, and consequently will consume more useful energy per unit of extracted fuel. In addition the share of liquified natural gas (LNG) is increasing, leading to higher upstream energy losses, due to liquefaction and transport.

- Conversion losses. In 2017 the average conversion efficiency of fossil fuels into electricity was about 38% [BP 2018], so 62% of the energy content of the fossil fuels are lost into the environment as waste heat.
- The average transmission losses of electricity are estimated at about 6%.

The final energy consumption of the world, that is the gross energy production minus above mentioned losses, amounted to about 372 EJ in 2017. Figure 4 represents the various energy flows.

Prospects

Prospects of closed-cycle fast reactors, also called breeder reactors, and of thorium reactors as net energy source are assessed in reports m01 *Uranium-plutonium breeder systems* and m24 *Thorium for fission power*. According to the nuclear industry the breeder reactors would be able to fission 30-50% of the nuclei in natural uranium. However, an operating breeder cycle has still never been proved in practice, after six decades of research in seven countries and investments of hundreds of billions of dollars. This failure can be explained by basic limitations of technical systems and separation processes, governed by the Second Law of thermodynamics.

Even if the breeder concept would become operational by 2050, it would take many doubling times, covering a period of one to two centuries, before the present world nuclear generating capacity, based on once-through reactors, could be replaced by breeders. Potential use of thorium as net energy source is even more remote than of uranium-plutonium breeders.

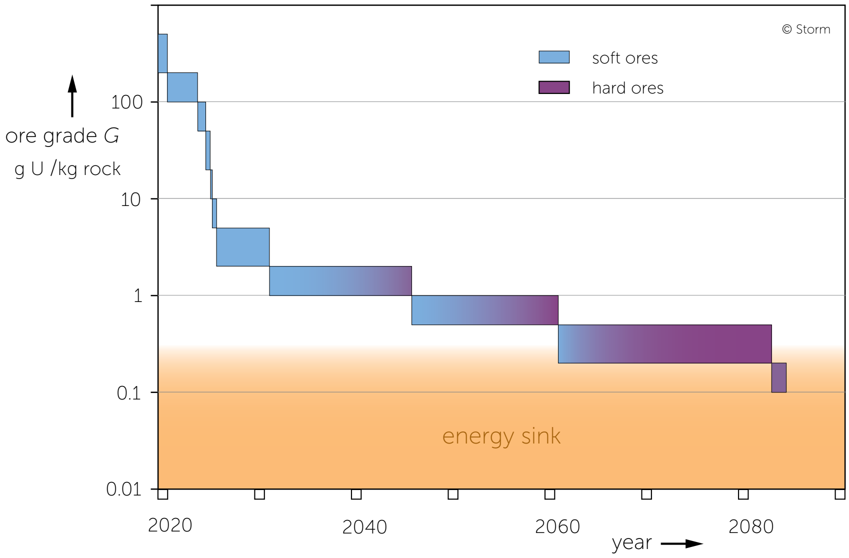


Figure 5

If the global nuclear generating capacity would remain constant at the present level, the energy cliff of the currently known uranium resources would be reached by about 2080; nuclear power would become an energy sink.

An important conclusion of the above observations is that nuclear power during the next decades will rely exclusively on thermal-neutron once-through nuclear reactor technology, and consequently on the

conventional known uranium resources of the world. Thermodynamic properties determine the net energy content of the uranium resources: the energy cliff limits the relevant ore grades and consequently the size of the uranium-for-energy resources, see report m35 *Energy cliff and CO2 trap* and the outline of the analysis in Figure 1. These limits in turn determine the potential contribution of nuclear power to climate change mitigation and energy security into the foreseeable future.
This observation would imply that civil nuclear energy generation at the current global capacity, based on the present operational reactor technology, would be phased out as net energy source by about the year 2080.

Future of nuclear power according to the IAEA

Coupling Figures 2 and 4 into a simplified model this study assumes that in addition to the input of 158 EJ of fossil fuels for generation of 60 EJ of electricity a proportional part of the upstream losses, (158/383)*100 = 41 EJ (rounded), is involved. The total amount of fossil fuels used to generate electricity, 199 EJ, would correspond with (199/483)*65 = 27% (rounded) of the world CO_2 emission, see Figure 2.
In 2017 nuclear power generated 9 EJ of electricity, this would displace a fraction of fossil fuels amounting to (9/60)*199 EJ = 30 EJ, corresponding with a mitigation share of the global CO_2 emission of (9/60)*27% = 4.1%, assumed that nuclear power is free of emissions of CO_2 and of other greenhouse gases (GHGs). Evidently this way of calculating the mitigation share of GHG emissions is also valid for hydro power and other renewables.

How large could the nuclear contribution to mitigation of CO_2 emissions hypothetically become in the future? At what timescale could a higher nuclear contribution be achieved?
As no figures were found in the open literature, this study estimates the hypothetic contribution to the mitigation in the future based on the envisioned developments of global nuclear generating capacity.
During the past years the International Atomic Energy Agency (IAEA) 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.

To gain some insight into this matter this study assesses two recent scenarios of the IAEA that can be considered to be typical of the views within the nuclear industry, again assumed that nuclear power is free of emissions of CO_2 and of other GHGs.
[IAEA-*sdr1* 2015] expects a growth rate of the global energy consumption of 2.0 - 3.5%/yr until 2030. In order to keep this assessment convenient and to place the scenarios of the nuclear industry in a global context after 2030-2050, this study assumes a constant growth rate of 2% until 2100, and the global GHG emissions growing at the same rate of 2% per year until 2100.

Scenario 1, IAEA Low: constant nuclear capacity,

The low scenario of the IAEA as published in [IAEA-*rds1* 2015] and [IAEA-*ccnap* 2016] corresponds with a constant nuclear generating capacity until 2050. In this scenario 1 this study conveniently assumes that the global operating nuclear capacity would remain flat at the current level of 376 GWe and the annual electicity production would remain 9 EJ/year.

The world energy consumption would rise by 2%/yr and consequently would reach a level of 1105 EJ/yr by the year 2050, and the global fossil-fuelled electricity generation would reach 115 EJ/yr. The nuclear contribution would have declined then to 9/1105 = 0.8% of the world energy supply.

The nuclear mitigating contribution would decline from 4.1% in 2017 to about (9/115)*27 = 2.1% by 2050, if both the global energy production and the CO_2 emissions would rise at 2%/yr, and assumed nuclear power would be free of CO_2 emissions.

Scenario 2, IAEA High, constant mitigation

In its high scenario [IAEA-*rds1* 2015] foresees a nuclear capacity of 964 GWe by 2050, a more recent figure is about 900 GWe [IAEA-*ccnap* 2016]; this study starts from the higher figure. Both estimates by the IAEA are significantly lower than the figure of 1092 GWe by 2050 published in 2014.

The World Nuclear Association WNA, representative of the nuclear industry, published scenarios involving drastically enlarging the global nuclear capacity. In its Nuclear Century Outlook Data [WNA-*outlook* 2015] WNA presented scenario's of higher global nuclear capacity; these scenarios are not discussed in ths study.

Assumed that the new nuclear power stations would operate at the same average load factor as the currently operating NPPs, the nuclear electricity generation would be 26 EJ/yr by 2050.

In scenario 2 the world energy consumption would reach a level of 1105 EJ/yr by the year 2050, and the global fossil-fuelled electricity generation 115 EJ/yr. The nuclear contribution would rise to 26/1105 = 2.4% of the world energy supply from 1.7% in 2017..

The nuclear mitigating contribution would rise to about (26/115)*27 = 6.1% by 2050, if both the global energy production and the CO_2 emissions would rise at 2%/yr, and assumed nuclear power would be free of CO_2 emissions.

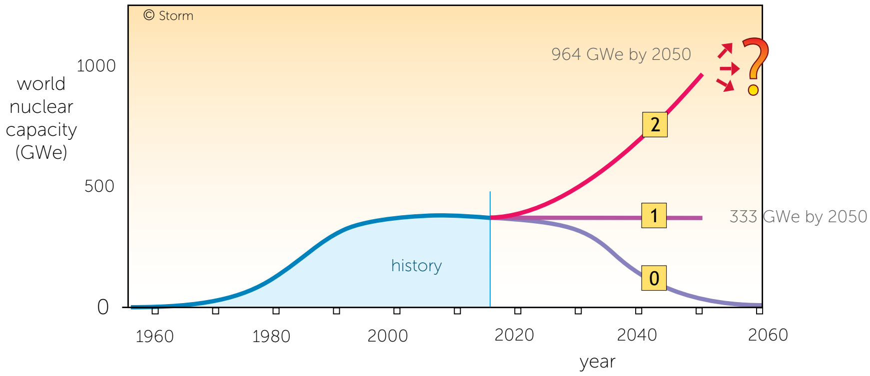


Figure 6

Three scenarios of the nuclear capacity until 2050. Scenario 0 represents phase-out of the existing nuclear capacity in the coming decades. Although the global capacity trend is declining, Scenario 0 is a hypothesis and is not discussed in the text. Scenario 1 represents the IAEA low scenario, and Scenario 2 the IAEA high scenario, discussed in the text. Both IAEA scenarios end by 2050, the IAEA did not indicate what they envision after that year. This issue is discussed in the next section.

After 2050

The future does not end in 2050. No investor will start the construction of new nuclear power plants in the year 2049 without assured uranium supply. This is one of the consequences of the long-term commitments inherent to nuclear power. The plants coming on line in 2050 should have an assured uranium supply during their lifetime of, say, 40 years. How does the nuclear industry imagine the developments after reaching their milestone in 2050? Further growth, leveling off to a constant capacity, or phase-out?

Extrapolating the course of the nuclear capacity scenarios further has profound consequences for the demand for fissile materials. In order to estimate in a realistic way the minimum amount of uranium, or other fissile material, required to sustain the scenarios, this study presents a variant of extending the scenarios 1 and 2 after reaching the indicated levels in 2050: no new NPPs would be built after 2050. All nuclear power plants then operating would be able to complete their normal operational lifetime and would be phased out, like scenario 0. This approach implies that the curves of scenarios 1 & 2 are slightly modified to give them a smooth transit to the phase-out, see Figure 7.

Obviously the nuclear contribution of the GHG mitigation after 2050 would decline to zero bij the year 2100 in the phase-out scenarios.

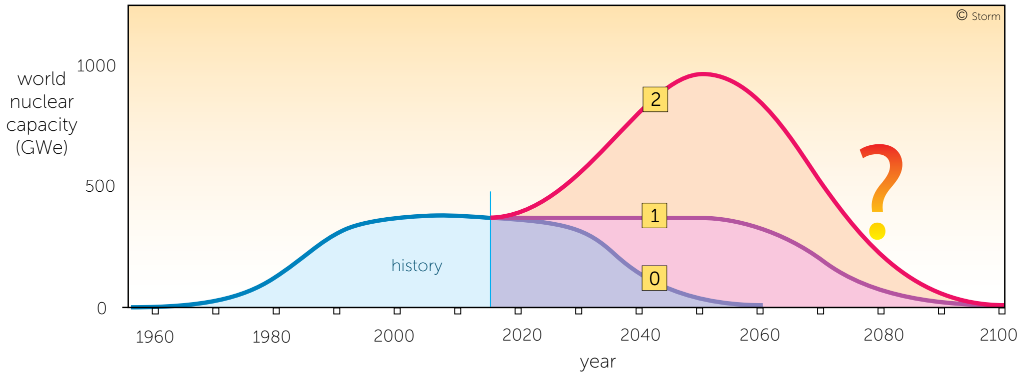


Figure 7

Scenarios 1 and 2 expanded to the year 2100, depicting the hypothetical case of phase-out after reaching the projected capacity by the year 2050. On the basis of these scenarios the minimum amount of uranium needed to materialise the scenarios 1 and 2 can be estimated.

Discussion

In the IAEA High scenario the nuclear mitigation constribution would grow from 4% in 2017 to 6% by 2050. In view of the current developments in the nuclear world, with a steadily declining nuclear capacity, the IAEA High scenario seems not very probable. Even the 'IAEA Low' scenario seems questionable. From a practical point of view the maximum attainable mitigation share in 2050 would be 2% in scenario 1 (IAEA Low), even if nuclear power would be free of GHG emissions.

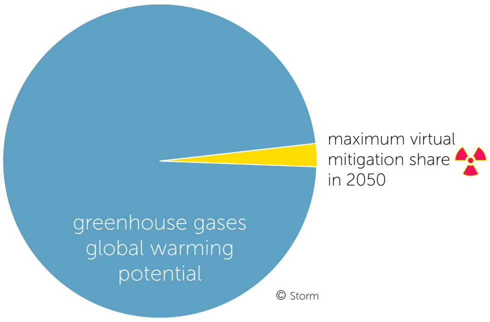


Figure 8

Maximum nuclear contribution to the mitigation of the global greenhouse gas emissions in 2050 in the IAEA Low nuclear scenario, even if nuclear power would be GHG free.

An obstacle to materialisation of the various scenarios is a drastic scaling-up of the global construction capacity of new nuclear power plants.

To keep the nuclear capacity at the present level almost the complete current fleet of nuclear power plants would have to be replaced by 2060, because the currently operable reactors would have reached then the end of their operational lifetime. This means that during the next decades each year an average of 7.5 GWe of new nuclear power plants have to come on line, two times the current global construction rate of 3-4 GWe/year.

In the IAEA high scenario the required average construction rate in the period 2017-2050 would have to be about 27 GWe per year, about 8 times the current rate.

In view of the massive cost overruns and construction delays of new nuclear power plants already plaguing the nuclear industry during the last decade it is not clear how the required high construction rates could be achieved.

Adoption of innovative technology

World nuclear capacity

From the time the first nuclear power stations came online in the 1950s the world nuclear capacity grew exponentially during 1960s and 1970s. During the 1980s and 1990s the capacity started leveling off and remained about constant during the last two decades, see Figure 8.
At present more nuclear power plants are reaching the end of their operational lifetime than new ones come online. Without new nuclear build the current world nuclear fleet would be closed down by the year 2050-2060.

Adoption curve

The graph of the world nuclear capacity over time (Figure 8) fits remarkably well a smooth S-curve, known in mathematics as the logistic function (Figure 9). The logistic curve is typical for the adoption of innovations among organisations and social systems and is therefore also known as the adoption curve or diffusion curve.
First the phase of early adopters of the innovation and slow growth of the number of adopters, than an adoption phase with exponential growth and finally a phase in which a level of maximum adoption of the innovation is reached. Curves similar to the nuclear capacity versus time curve exist, for example, with regard to the diffusion of the steam engine into the economic system in the 19th century and of the internal combustion engines and the gas turbines in the 20th century. The adoption curve is also common with the introduction of new technologies for the consumer, for example the color tv, cellphone, computer and internet,
Most new technologies follow a similar maturity lifecycle: from early development to maturity and implementation, to obsolescence and phase-out.

Maturity and obsolescence of nuclear power

From the constant level of the world nuclear capacity during the past decade one may conclude that nuclear technology has reached the phase of maturity. This observation seems to be in conflict with the fact that the costs of nuclear power plants are still escalating and are hardly controllable. Likely the chronic cost escalation of nuclear projects has other causes than technical immaturity: the tremendous complexity of the nuclear energy system and the fact that nuclear power never has been, and never will be, independent of massive state support, directly as visible financial streams and indirectly via disguised channels.

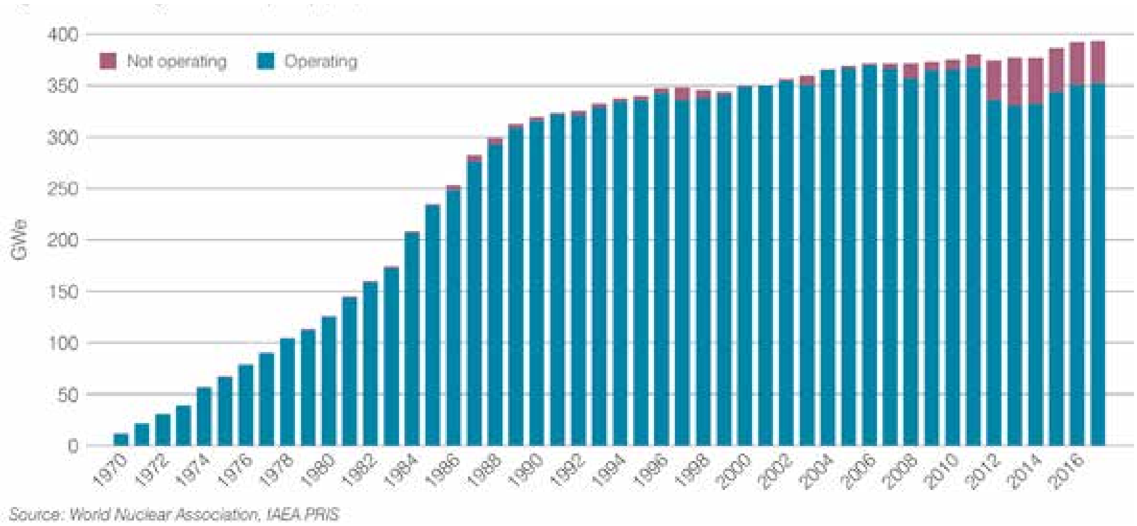
In view of the foreseeable decline of the world nuclear capacity during the next decades, the current nuclear technology is entering obsolescence. A gradual phase-out of the current nuclear power technology seems inevitable. This observation is sustained by the declining availability of high-quality uranium resources, on which the viability of current nuclear power plants is based.

Historic evidence concerning the diffusion of new technologies in social systems, following the adoption curve, shows that large-scale adoption of a new technology occurs only when the new technology offers possibilities existing technologies did not. A technology becomes obsolete when other technologies emerge which are better suited to perform the same task.

An expansion of the nuclear capacity on top of the existing adoption level of nuclear power would imply the availability of a new technology so innovative that it would initiate a vigorous adoption process, not only able to replace the adopters of the existing nuclear technology, but also able to reach a new extra group of adopters. Such a development would be thinkable only by the introduction of an innovative nuclear technology, so powerful that it could oust other energy technologies. Even to keep the world nuclear capacity at the current level the introduction of an innovative technology would be needed, to replace the currently operating power plants, which are of obsolete technology.

Likely the nuclear industry, off course aware of the adoption curve, has the uranium-plutonium breeder cycle, thorium as nucleasr fuel and probably also partitioning and transmutation as energy source in mind, see reports m01 Uranium-plutonium breeder systems, m24 Thorium for fission power and m16 Partitioning and trandmutation.

However, these ‘revolutionary new’ nuclear technologies are not so innovative as the nuclear industry wants the public to believe and will remain feasible only in cyberspace. The Second Law of thermodynamics is relentless , see report m38 Nuclear power and the Second Law.



Source: World Nuclear Association, IAEA PRIS

Figure 8

World nuclear operating capacity, Source: World Nuclear Association, IAEA-PRIS

In 2017 the world nuclear capacity amounted to 352 GWe.

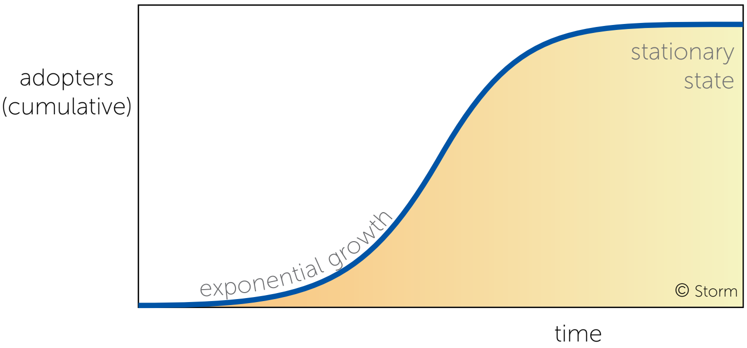


Figure 9

Adoption curve of innovative technologies. This logistic curve represents the cumulative number of adopters of an innovative technology as presented in Figure 10.

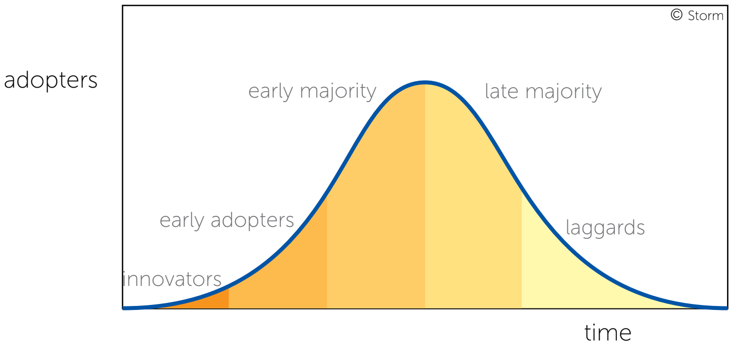


Figure 10
Innovation adoption lifecycle. According to a generally accepted theory on the diffusion of new, innovative technologies or ideas in social systems, individuals can be classified into five groups: innovators, early adopters, early majority, late majority and laggards. In regard to nuclear power, the first two groups may be found in the USA, UK and former Sovietunion; laggards may be found for example in China.

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