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Nuclear energy - The solution to climate change?

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ABSTRACT

With increased awareness of climate change in recent years nuclear energy has received renewed attention. Positions that attribute nuclear energy an important role in climate change mitigation emerge.

We estimate an upper bound of the CO_2 saving potential of various nuclear energy growth scenarios, starting from our projection of nuclear generating capacity based on current national energy plans to scenarios that introduce nuclear energy as substantial instrument for climate protection. We then look at needed uranium resources.

The most important result of the present work is that the contribution of nuclear power to mitigate climate change is, and will be, very limited. At present nuclear power avoids annually 2–3% of total global GHG emissions. Looking at announced plans for new nuclear builds and lifetime extensions this value would decrease even further until 2040. Furthermore, a substantial expansion of nuclear power will not be possible because of technical obstacles and limited resources. Limited uranium-235 supply inhibits substantial expansion scenarios with the current nuclear technology. New nuclear technologies, making use of uranium-238, will not be available in time. Even if such expansion scenarios were possible, their climate change mitigation potential would not be sufficient as single action.

1. Introduction

The internationally agreed political climate goal of the Paris Agreement is to keep global temperature rise well below 2˚C compared to pre-industrial levels and to make efforts not to exceed 1.5˚C (UNO, 2015). The agreement also calls for early emission peaks and a balance between sources and sinks early on in the second half of this century. National reduction commitments to date are not compatible with the 2˚C target, so further reductions are called for. The 2˚C target was set pragmatically, a target which, on the one hand, is challenging and achievable, but, on the other hand, limits the consequences of climate change to a level that was deemed acceptable. A special report to analyze the difference between the 2˚C and the 1.5˚C target was commissioned as a consequence of the Paris Agreement (Intergovernmental Panel on Climate Change, 2018). It came to the conclusion that half a degree of additional warming made a huge difference in terms of adverse effects and number of people suffering from climate change. It also stated that from a science point of view, 1.5˚C was still achievable, if rapid action were taken. Model calculations show that net zero emissions must be achieved by 2050 on a global scale, and at least a decade earlier in industrialized nations. Therefore the near future is of main interest in climate policy (United Nations Environment Programme, 2010, 2012, 2019).

CO_2 neutral, renewable and low carbon sources of energy have to substitute the currently prevailing fossil fuels and limit additional CO_2 emissions as far and as fast as possible.

1.1. Nuclear power for climate protection?

While many agree that limiting CO_2 emissions is necessary, there is no such agreement on how to achieve this goal. Especially the use of nuclear power for electricity production is under debate. Nuclear power as option for climate protection was proposed as early as 2000 (Sailor, 2000), but the debate went on since then. Recently scientists were writing letters to newspapers and head of states in support (Hansen, 2019) of and warning (Dorfman, 2019) against the use of nuclear power. But also articles in scientific journals disagree on the role that nuclear energy should play in the low carbon future. Some authors (Mez, 2012) question that nuclear power is a low carbon technology and therefore strictly advocate a non-nuclear future. Other authors (Knapp et al., 2010) estimate that nuclear power could be the backbone of electricity

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production in a low carbon future with ten-times the current installed capacity up to 2050, or could at least substitute all coal-fired power plants (Knapp and Pevec, 2018). Others again advocate to at least keep the current nuclear fleet in operation, even if that means paying subsides (Roth and Jaramillo, 2017). In a recent study Buongiorno et al. (2019) describe the potential of nuclear power as low carbon technology, but see cost reduction as the main obstacle. Parsons et al. (2019) see nuclear energy essential in meeting the climate goals and the Paris Agreement. Nuclear energy is described there as “one low-carbon dispatch able option that is virtually unlimited and available now”. Also IAEA published a report on a wide range of aspects of nuclear power as climate mitigation technology (International Atomic Energy Agency, 2018). On the future contribution of nuclear power on climate change mitigation the report describes a wide variety of scenarios, from phaseout to expansion scenarios with, accordingly, very different contributions. However, large scale national nuclear programs do not seem to lead to significantly lower carbon emissions, as Sovacool et al. (2020) show, correlating CO_2 emissions and electricity generation of 123 countries over 25 years.

We add to the debate by evaluating the climate protection potential of nuclear power for the next twenty years, and by looking on the needed uranium resources.

1.2. CO_2 emissions from nuclear power plants

The direct CO_2 emissions from nuclear power plants during operation are low. However, looking at indirect emissions as well and considering the whole life cycle of nuclear power (uranium mining, milling, conversion, enrichment, fuel fabrication, construction and dismantling of the nuclear power plant, spent fuel processing and storage), nuclear power is certainly not emission-free. A review article, summarizing estimates of CO_2 emissions from nuclear fuel cycle analyses, reports values as low as 1.4 g CO_2 /kWh_e up to 288 g CO_2 /kWh_e, with a mean over all reviewed studies of 66 g CO_2 /kWh_e (Sovacool, 2008). The large range in CO_2 emissions per kWh is due to different uranium ore grades, different methods and techniques prevalent during mining, milling, enrichment and fuel fabrication, and different sources of power used for mining and enrichment. A similar work by Beerten et al. (2009) reported 32 g CO_2 /kWh_e for a European context.

Most of those studies assess the g CO_2 /kWh_e cost of nuclear power at their operating life, while the CO_2 emissions from the nuclear life cycle will change not only during their operating life, but also after. Ores with a higher grades of Uranium are mined first, and extraction of Uranium from ores with lower grades needs more energy. Assuming the current energy mix, mining will therefore generate more CO_2 emissions in future. As an exception Warner and Heath (2012) tried not only to harmonize various approaches, but also to give a number for nuclear power CO_2 generation costs by 2050. Jacobson (2009) presented life cycle analyses for different electricity generation technologies and included also so called “opportunity cost emissions”, i.e. CO_2 costs due to delays from planning to operation where a faster deployable technology could have avoided emissions. He referenced opportunity cost emissions for nuclear power of 59–106 g CO_2 /kWh_e in addition to the CO_2 costs from the nuclear lifecycle of 9–70. In total he stated for nuclear energy costs of 68–180 g CO_2 /kWh_e. The author elaborated on the argument of nuclear opportunity cost emissions in a recently published book (Jacobson, 2020).

As mentioned, uranium mining could generate more CO_2 emissions in future due to higher energy need. But assuming the energy mix in future will comprise more low CO_2 or even CO_2 neutral power sources, a prediction on overall CO_2 emissions from the nuclear life cycle is subject to high uncertainties.

Nuclear lifecycle CO_2 emissions are connected to the energy investment needed for mining an fuel fabrication. Another approach should be mentioned here: Instead of looking at CO_2 emissions, Wallner et al. (2011) looked on nuclear energy return on energy investment, which shows that only a fraction of uranium resources can be utilized in a physically meaningful way. The use of nuclear power is only reasonable if more energy can be generated than needed for mining and enrichment. Wallner et al. (2011) showed that this energy balance turns negative for low grade ores. Still it should be noted that such estimates are subject to uncertainties and dependent on assumptions and technologies used.

The present work will provide an upper bound on the climate change mitigation potential of nuclear power and therefore will neglect CO_2 emissions from the nuclear fuel cycle.

1.3. Method - climate protection potential

In an extensive project, involving a larger interdisciplinary team (Kromp et al., 2013), we looked comprehensively at nuclear power as an instrument to mitigate climate change. A new look was taken at requisites and needed resources, technical potentials, bottlenecks and risks as a basis for the assessment of the perspective of nuclear power. In our current work we expand on selected aspects of our project from 2013, which is the climate mitigation potential of different nuclear energy growth scenarios and estimating how much CO_2 emissions could be saved by the use of nuclear power in the near to medium term future (up to 2040). We then look at needed uranium resources and look at new nuclear technologies that promise better use of uranium. Following we describe the steps we took to arrive at our evaluation, see also Fig. 1:

On one hand we project the nuclear electricity generating capacity in 2040 by looking at announced projects for new NPP builds, life extensions, and shut downs. This projection is called ISR-projection subsequently. The ISR-projection is bounded by the “upper” and “lower” projection of IAEA annual nuclear growth projections, see (International Atomic Energy Agency, 2019), box 1 of Fig. 1. We use these three projections to provide a range on the climate change mitigation potential of nuclear energy based on current planning. On the other hand we evaluate some of the implications of a massive expansion of the use of nuclear energy by assuming that all fossil power plants will substituted by nuclear power plants up to 2040. For this purpose we develop a nuclear “expansion” scenario, box 2 of Fig. 1.

In contrast to the mentioned previous studies we aim to evaluate the climate mitigation potential of nuclear energy as single additional measure to already implemented measures and already agreed current planning. We evaluate how much CO_2 emissions could be prevented by a nuclear policy, assuming that no additional policy measures, apart from a move to nuclear power, are implemented up to 2040. Therefore we need a “baseline” scenario to compare to. We chose the “current policies scenario” of IEA’s World Energy Outlook (International Energy Agency, 2018), which “is a baseline picture of how global energy markets would evolve if governments make no changes to their existing policies and measures”. This means that comparing against the current policy scenario allows to quantify the effect of an increased nuclear share only, box 3 of Fig. 1.

Finally we evaluate how much emissions are avoided annually by nuclear power (box 4 and box 5 of Fig. 1. We compare these to the total global CO_2 and greenhouse gas emissions in 2040. To provide also here a range we compare to the energy related CO_2 emissions, to all fossil related CO_2 emissions, and to the total global greenhouse gas emissions from all sectors, only excluding land use change, see box 6 in Fig. 1. We close by evaluating how much uranium would be needed for the expansion scenario and whether fast breeder reactors could complement or even substitute currently used thermal light water reactors.

2. Nuclear power growth scenarios

There were and there are many projections on nuclear growth rates in the literature. We looked at a number of representative projections from the past fifty years. Projections from institutions like the International Atomic Energy Agency (IAEA), the Nuclear Energy Agency of the

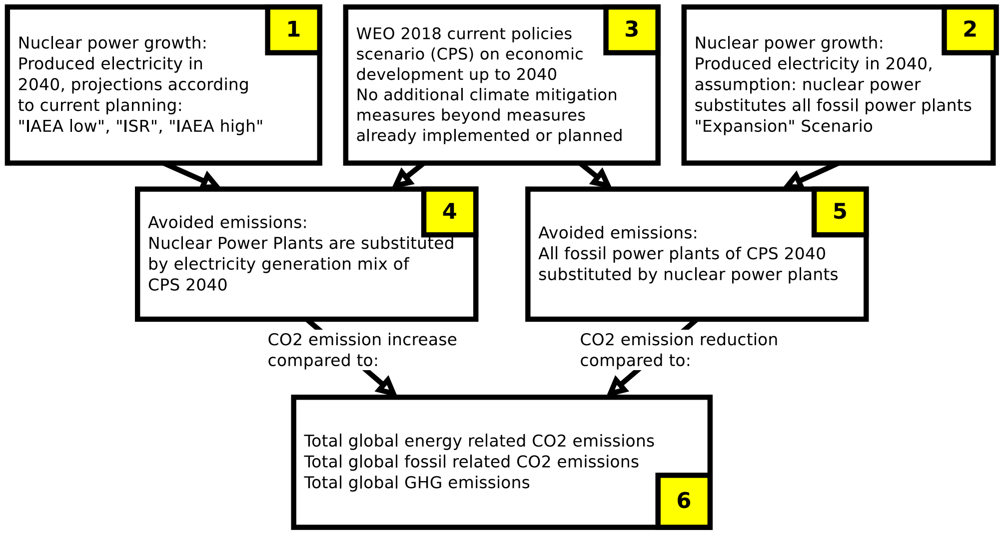

Fig. 1. Climate change mitigation potential evaluation method in six steps.

Organization for Economic Co-operation and Development (OECD-NEA), the World Nuclear Association (WNA) consistently overestimated nuclear energy build rates. Fig. 2 shows estimates on the total installed nuclear capacity in the year 2000 that were published in the 1970s and 1980s. All of them estimated higher capacities than were actually built. Closest to the actual number was the IAEA â€œlowâ€ scenario from the year 1986 (Char and Csik, 1987) that was written under the impression of the Chernobyl accident. The most optimistic scenarios predicted more than 5000 GWe installed capacity (more than 10 times above the actual builds). Projections from later years were less optimistic (see Fig. 3), but still overestimated the actual build rates.

2.1. Projection on nuclear generating capacity in 2040

We developed a projection based on currently announced programmes to build nuclear power plants, to extend life times and to decommission units.

The ISR projection is based on a case by case evaluation. Unless more specific information was available the lifetime of operating reactors was assumed to be 60 years. The longest lifetimes, based on the policies of some countries, was assumed to be 80 years. For reactors under construction and for planned reactor projects data from the utilities, regulatory bodies, state agencies and past construction times were considered. In case of uncertainties expert judgment was used to determine the year of commercial operation. The prospects of newly announced reactor projects and their lead times were estimated based on relevant data from past projects and historical experience. According to our analysis the major part of the nuclear generating capacity for the next twenty years is planned from life time extension projects and only a small fraction is planned from new builds, see Fig. 5.

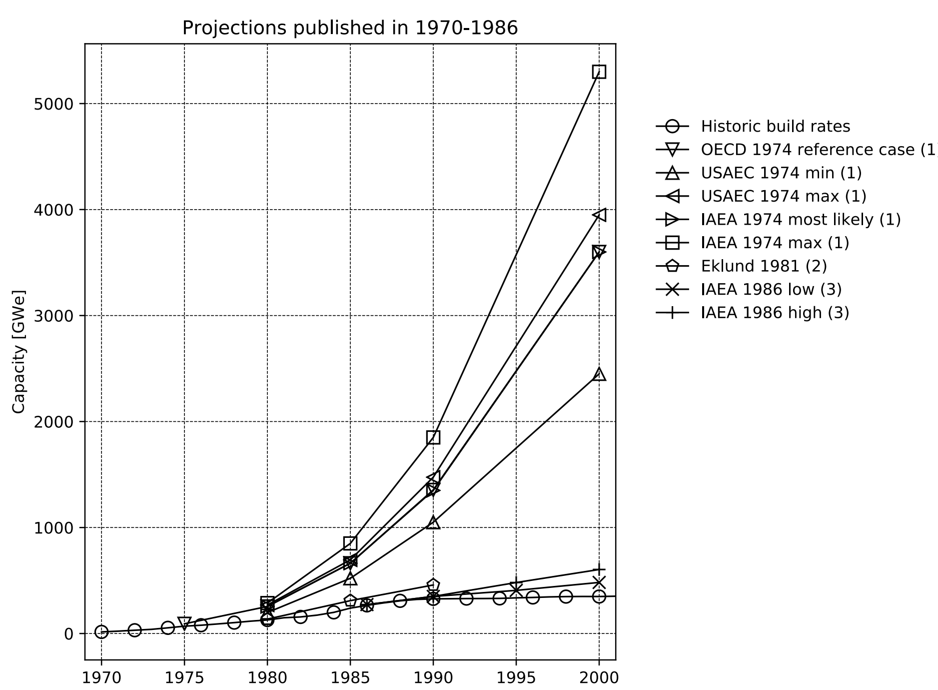

Fig. 2. Past scenarios of WNA, OECD and IAEA on installed nuclear capacity from the years 1970–1986, all projecting higher installed capacities for the year 2000 than was actually the case. (1) refers to Goodman and Krymm (1975), (2) to Eklund (1980), and (3) to Char and Csik (1987).

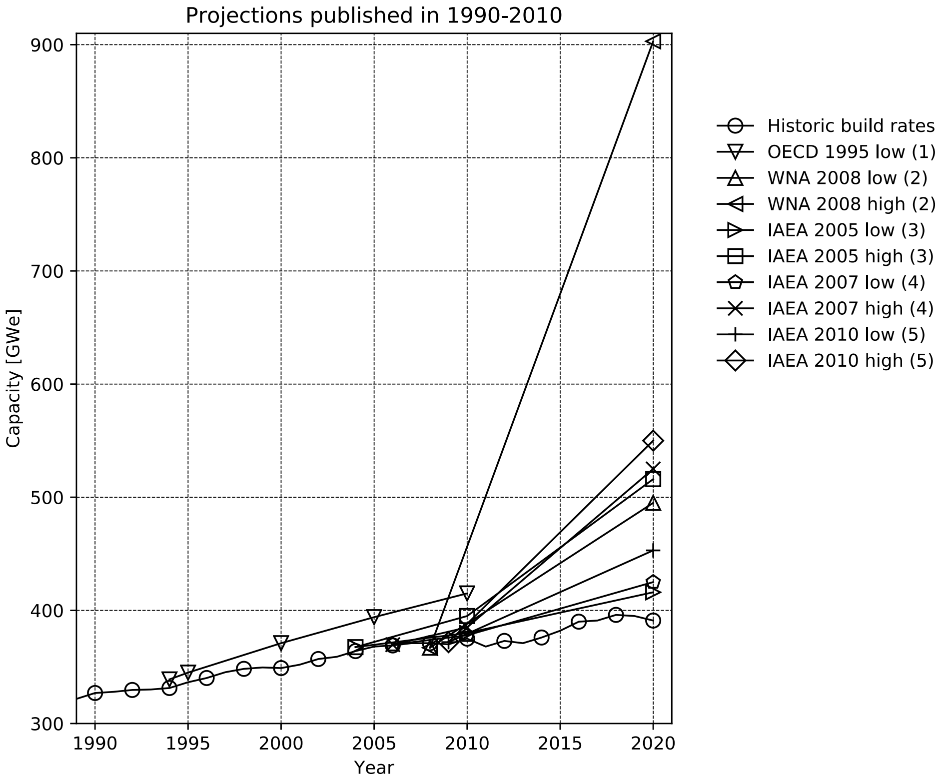

Fig. 3. Past scenarios of WNA (the scenario cites a value for 2008 and one for 2030. The, 2020 value was linearly interpolated), OECD-NEA and IAEA on installed nuclear capacity from the years 1990–2010, all projecting higher installed capacities for the year 2020 than was actually the case. (1) refers to (OECD NEA and IAEA, 1995), (2) to (WNA, 2008), (3) to (International Atomic Energy Agency, 2005), (4) to (International Atomic Energy Agency, 2007), and (5) to (International Atomic Energy Agency, 2010).

IAEA publishes annually projections which are based on currently known planning as well, and in fact, the projected installed capacity of the ISR-Projection is bounded by IAEA "low" and "high" projection of 2019 (International Atomic Energy Agency, 2019) (refer to Fig. 4). It should be noted that since the accident of Fukushima, IAEA projections on future nuclear installed capacity decreased, see for example Ramana (2016).

We use all three projections for the climate change mitigation potential of nuclear power to provide a range for current planning. IAEA assumes a load factor of 0.9 for the year 2040, which might be optimistic given that the major part of the generating capacity will stem from life time extension projects (see Fig. 5). For the ISR projection we calculate with a load factor of 0.8. The numbers of the predictions are presented in Table 1.

Past experience shows that current planning projections tend to overestimate the actual build rates. We therefore do not see our projection as a prediction of a future, rather as a picture of current intentions as publicly announced by competent authorities.

2.2. Expansion scenario

Assuming that policy makers and the nuclear industry would foster nuclear power as low carbon technology and assuming that the related expansion of nuclear energy would economically, technically and politically be feasible, what, theoretically, could be its possible climate change mitigation potential in the critical time frame up to 2040? To arrive at an estimate we assume an extreme expansion scenario. The current role of nuclear energy is almost exclusively electricity generation. So one scenario could be to substitute all fossil fueled power plants (coal, gas and oil) worldwide with nuclear power plants. In this hypothetical case roughly 3500 GWe nuclear power would be needed, (roughly ten times the installed capacity of today).

This would require 3000 to 4000 new units, depending on the rated power of the units. The upper bound projection of IAEA "high" scenario 2019 predicts no more than 400–500 new units up to 2040.

Table 2 reports how much electricity would be generated in 2040 according to the WEO "current-policies" scenario of (International Energy Agency, 2018) from fossil power plants. To estimate how much nuclear capacity is needed to generate this electricity from NPPs the load factor from (International Atomic Energy Agency, 2019) of 0.9 was used.

3. Climate change mitigation potential

We define the ratio of annually prevented CO_2 emissions by total annual emissions of a given year as climate change mitigation potential. We compare the upper bound of emissions that can be prevented annually in 2040 of each of the four assumed nuclear growth projections/scenario to the total global emissions in 2040. In detail, we compare the upper bound of prevented CO_2 emissions with the total CO_2 emissions from the energy sector, with the overall CO_2 emissions tied to fossil fuels and with the total emissions of greenhouse gases from all sectors as CO_2 eq except the emissions from land use change. The WEO 2018 (International Energy Agency, 2018, p. 46) reports total global energy related CO_2 emissions for 2017 to 32.5 Gt CO_2 . Total global fossil related CO_2 emissions for 2017, including e.g. also industrial process emissions and agriculture, are reported (Crippa et al., 2019) for 2017 as 37 Gt CO_2 . Total global greenhouse gas emissions, including emissions from all sectors and not only CO_2 emissions, but also methane, nitrous oxide and flurinated greenhouse gases (excluding emissions from land use change) for 2017 can be found in (United Nations Environment Programme, 2019) and are reported to be 49.2 Gt CO_2 eq. Since we want to evaluate the climate protection potential of nuclear energy in 2040 we need a projection of those emissions. The energy related emissions of the current policy scenario of WEO 2018 are reported to be 42.5 Gt CO_2 in 2040 (International Energy Agency, 2018, p. 46). For a consistent value for the total global fossil and greenhouse gas emissions excluding land use change, we assumed that the ratios of those emissions to the energy related CO_2 emissions stay constant in time. With this assumption the values compute to 48.4 Gt CO_2 and 64.3 GT CO_2 eq for fossil related and total GHG all sectors in 2040 respectively. Table 3 summarizes the various emissions in 2017 and 2040.

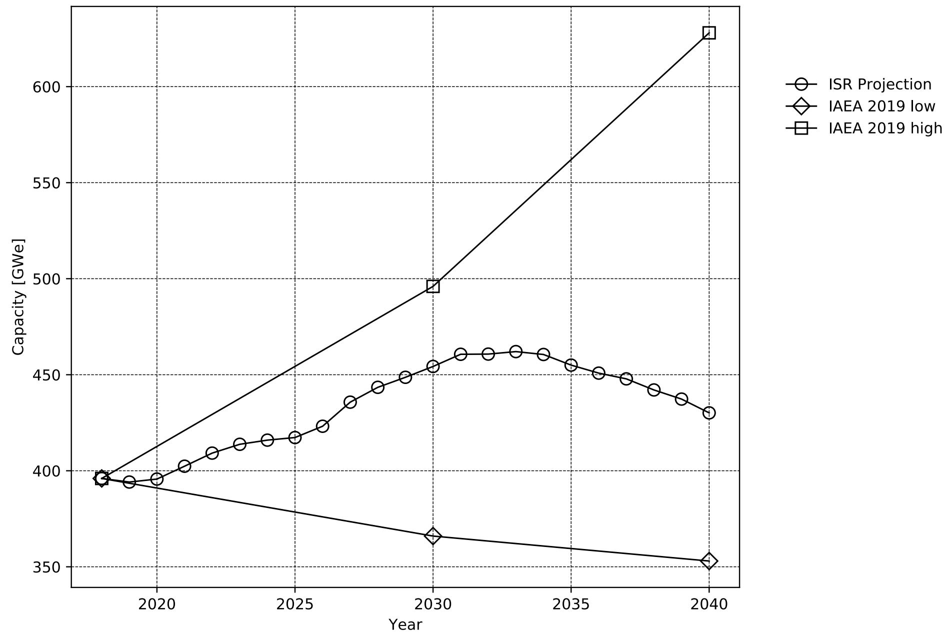

Fig. 4. ISR projection of nuclear capacity bound by IAEA "low" and "high" projection 2019 (International Atomic Energy Agency, 2019).

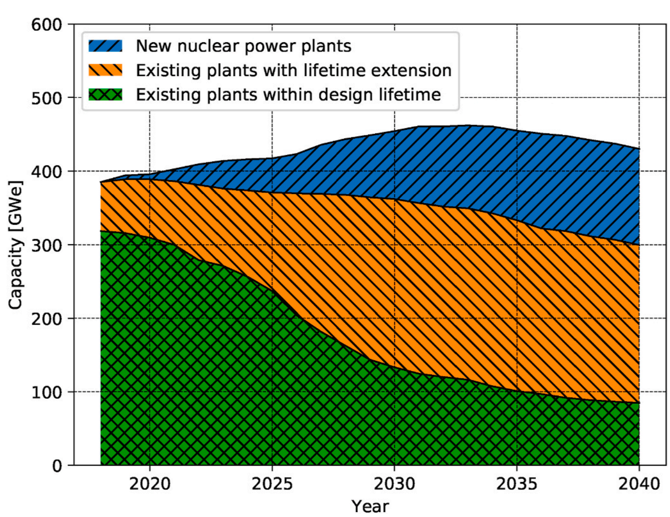

Fig. 5. ISR projection of nuclear capacity, distinguishing between new builds and life time extension projects according to current planning.

Table 1
Nuclear generating capacity according to (International Atomic Energy Agency, 2019) "low" and "high" projections and ISR projection.

	2018	2040 (low)	2040 (high)	2040 (ISR)	
Nuclear Capacity	396	353	628	430	GWe
Nuclear Electricity Production (per year)	2563	2804	4977	3013	TWh

3.1. *Climate change mitigation potential of IAEA "low", "high" and ISR projection*

The (International Atomic Energy Agency, 2019) "low" projection predicts a nuclear electricity production in 2040 of 2804 TWh. To provide an upper bound on the climate protection potential it is assumed that nuclear generated electricity can be produced without emissions. It is further assumed that the nuclear power plants substitute the mix of power plants, the WEO 2018 cites for the "current policies" scenario for 2040 a value of 383 g CO_2 /kWh$_e$ (International Energy Agency, 2018, p. 525). The emissions which can be saved therefore amount to 1.1 Gt CO_2 per year. This is equivalent to 2.5%, 2.2%, 1.7% of the total anticipated energy related, fossil related, and all sector GHG emissions in 2040 CO_2 eq per year respectively.

Repeating the calculation for the "high" projection (International Atomic Energy Agency, 2019), which predicts a nuclear electricity production in 2040 of 4977 TWh, the upper bound of emissions that can be saved amount to 1.9 Gt CO_2 , a share of 4.5%, 3.9% and 3.0% of yearly total CO_2 eq emissions in 2040.

The ISR scenario which lies between "low" and "high", predicts at most 1.2 Gt of avoided CO_2 emissions in 2040, which are 2.7%, 2.4% and 1.8% of global energy related, fossil related, and all sector GHG emissions.

Table 2
Nuclear capacity needed to substitute all fossil power plants by 2040 according to "current policies" of (International Energy Agency, 2018) in a massive expansion scenario.

Electricity generation by coal in 2040	13910 TWh
Electricity generation by oil in 2040	610 TWh
Electricity generation by gas in 2040	10295 TWh
Electricity generation by nuclear in 2040	3648 TWh
Total needed nuclear generated electricity	28463 TWh
Assumed load factor of NPPs in 2040 International Atomic Energy Agency (2019)	90%
Nuclear capacity needed	3610 GWe

Table 3
Total global annual energy related CO_2 emissions, fossil CO_2 emissions and greenhouse gas emissions of all sectors except land use change for the year 2017 and 2040.

	2017	2040
Total global energy related CO_2 emissions (Gt CO_2 /yr)	32.5	42.5
Total global fossil related CO_2 emissions (Gt CO_2 /yr)	37.0	48.4
Total global GHG emissions except LUC (Gt CO_2 eq/yr)	49.2	64.3

3.2. Climate protection potential of an expansion scenario

We repeat the evaluation for the expansion scenario presented in section 2.2. This scenario assumes that all electricity which is predicted to be produced by coal, oil or gas fired power plants in the "current policies" scenario of (International Energy Agency, 2018) is produced by nuclear power plants instead. This would amount to an electricity production of 28463 TWh annually. WEO 2018 specifies the emissions in 2040 from all fossil fired power plants in the current policy scenario as 17.6 Gt CO_2 (International Energy Agency, 2018, p. 585), emissions that could be prevented in this scenario. This are 41.4%, 36.4% and 27.4% of energy related, fossil related, and all sector GHG annual emissions in 2040.

All results are summarized in Table 4, together with a value of the climate change mitigation potential of the current fleet of NPPs in 2017. It was assumed that all NPPs would be decommissioned and substituted by a mix of power plants. In the year 2017 the current mix power plants in OECD area had a CO_2 cost of electricity generation on average of 382 g CO_2 eq/kWh (OECD, 2020). Nuclear electricity production in 2017 were 2563 TWh, which, according to the above, prevented CO_2 emissions of 1.0 Gt in the year 2017.

It should be noted the present paper aims to provide an upper bound on the climate change mitigation potential of nuclear power and therefore assumed that the nuclear generated electricity is CO_2 emission free. This is not a realistic assumption. To give an indication how the results would change assuming emissions, Table 5 shows the avoided emissions assuming that nuclear electricity is produced emission-free, at a cost of 30 g CO_2 /kWh$_e$ and 60 g CO_2 /kWh$_e$.

4. Uranium resources

A vast nuclear expansion scenario like the scenario mentioned in 2.2, with ten times the installed capacity of today's fleet, requires roughly ten times the fuel of today's fleet.

Current operating reactors utilize the thermal neutron spectrum and energy is generated by fission of the isotope uranium 235. Natural uranium consists to 99.3% of the isotope uranium 238 and to 0.7% of isotope uranium 235. The uranium ore concentrations in rock mined today typically range from 0.03 to 0.34%, except for some Canadian mines, where the concentrations can reach up to 20% (mass percent).

Table 4
Climate protection potential, upper bound, of nuclear power 2017, IAEA 2019 "low", ISR, IAEA 2019 "high" projection and expansion scenario in 2040, annual nuclear generated electricity, prevented CO_2 emissions in Gt CO_2 and as percentage of total global energy related, total fossil related and all sector GHG excluding LUC emissions.

	Produced electricity	CO_2 avoided	of energy	of fossil	of GHG
World NPP fleet 2017	2563 TWh	1.0 Gt	3.0%	2.6%	2.0%
IAEA "low" projection 2040	2804 TWh	1.1 Gt	2.5%	2.2%	1.7%
ISR projection 2040	3013 TWh	1.2 Gt	2.7%	2.4%	1.8%
IAEA "high" projection 2040	4977 TWh	1.9 Gt	4.5%	3.9%	3.0%
Expansion scenario 2040	28463 TWh	17.6 Gt	41.4%	36.4%	27.4%

Table 5
Prevented CO_2 emissions, upper bound, in Gt CO_2 as shown in Table 4, assuming no emissions, 30 g CO_2 /kWh$_e$, and assuming 60 CO_2 /kWh$_e$ intensity of nuclear generated electricity.

	CO_2 avoided (emission free)	30 g CO_2 /kWh$_e$	60 g CO_2 /kWh$_e$
World NPP fleet 2017	1.0 Gt	0.9 Gt	0.8 Gt
IAEA "low" projection 2040	1.1 Gt	1.0 Gt	0.9 Gt
ISR projection 2040	1.2 Gt	1.1 Gt	1.0 Gt
IAEA "high" projection 2040	1.9 Gt	1.8 Gt	1.6 Gt
Expansion scenario 2040	17.6 Gt	16.8 Gt	15.9 Gt

As of 2017 about 8 million tons of uranium were evaluated by the IAEA as so called Identified Resources,[1] recoverable at costs of less than 260 USD per kg uranium. Of these resources, 4.8 million tons are assigned to the category of reasonably assured resources, the rest (3.2 million tons) are inferred resources (OECD NEA and IAEA, 2019). In the past decade, uranium production was roughly 60 000 tons per year with a maximum of about 62 000 tons uranium in 2016. Two thirds of the uranium are produced in three countries in Australia, Canada and Kazakhstan. Kazakhstan is the largest producer of uranium, providing 40% of the global uranium production (WNA, 2019). Current demand by nuclear power reactors is a little higher than the uranium production. The difference is mainly covered by stockpiles at the moment. Other, so called secondary resources, such as dismantled nuclear warheads and, to a lesser extent, uranium from reprocessing and re-enrichment of depleted uranium were bridging the gap between primary mine production and demand of power reactors in the first decade of the century.

Taking into account only the above mentioned numbers on resources, a simple, static calculation provides a theoretical range for identified resources of 130 years and of 80 years for reasonably assured resources. While this seems a reasonable time frame, it has to be kept in mind that this does not take into account any increase in nuclear power generation. Any increase in nuclear power installed capacity must be matched by the increase in mining capacity to ensure continuous supply of uranium for nuclear power plants. Concerning large, but also medium growth scenarios, two issues arise:

- firstly, the ability to produce enough uranium within the expansion phase of the growth scenario, so the increasing demand can be covered,
- secondly the overall amount of uranium available for the total operating time of current and future plants, which is planned to be sixty years and longer for new reactors.

The first point is illustrated in Fig. 6. Arnold and Gufler (2014) provide a comparison of different uranium production scenarios with a uranium demand scenario of the OECD-NEA/IAEA (OECD NEA and IAEA, 2012). All of the scenarios, even those of the uranium mining industry, show a rather modest increase of production in the short- and midterm. The production numbers are well below a demand scenario which would lead to a doubling in nuclear capacity. Liebert and Englert (2015) note that in "the face of obvious difficulties to sufficiently increase primary uranium production and the expected decrease of availability of secondary resources in the future, uranium supply in the

[1] Identified Resources comprise Reasonably Assured Resources (RAR) and Inferred Resources (IR). "For RAR, high confidence in estimates of grade and tonnage are generally compatible with mining decision-making standards. Inferred resources are not defined with such a high degree of confidence and generally require further direct measurement prior to making a decision to mine." (OECD NEA and IAEA, 2019).

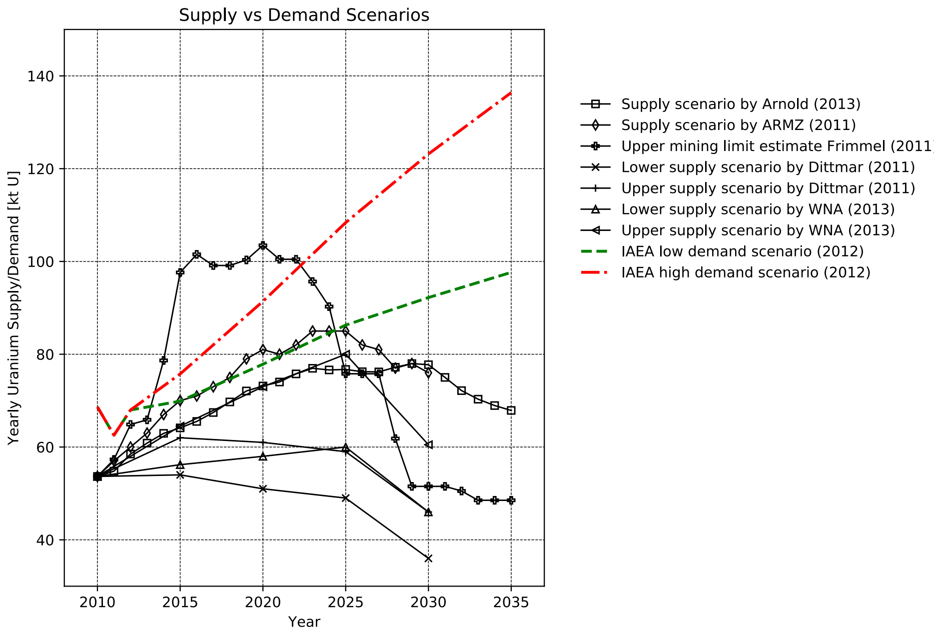

Fig. 6. Comparison of six different uranium supply scenarios from (Frimmel and Müller, 2011; ARMZ, 2011; Arnold et al., 2013; Dittmar, 2011; WNA, 2013), in comparison with the OECD/NEA-IAEA demand scenarios from 2011 (OECD NEA and IAEA, 2012).

next two decades might become problematic". Whether the increase in mining capacity can meet the requirements of high nuclear growth scenario is even more questionable. An uranium market model developed by Monnet et al. (2017) leads the authors to the conclusion that the "uranium market may prove to be under stress in some periods of the 21st century if the demand grows rapidly" (Monnet et al., 2017).

This is even more relevant, as in the past years the uranium industry suffered from low uranium prices and lower demand after the Fukushima accidents. As a result, mines were put on maintenance and projects were shelved. Since the future production depends on the success of the currently planned mining projects, it appears quite possible that an unfavorable development can result in supply shortages or significant price increases. A reason for this is that the time frame from delineation of a uranium deposit until the start-up of a mine can be 15 years or more (Susan Hall and Margaret Coleman, 2013). Further, there is not much interest in developing new uranium deposits at the moment due to persistently low uranium prices (Cameco, 2020; ESA, 2015). The short-term economic view of the companies operating uranium production facilities is in conflict with the long-term aspects and needs of nuclear expansion scenarios. Lastly, it has to be assumed, that uranium ore with higher grades and lower production costs has already been extracted in the past, so production efficiency and economic competitiveness can be expected to decline in the future (Liebert and Englert, 2015).

Even if it were possible to provide the resources in time for a massive growth scenario, uranium resources that can be accessed in an economically feasible manner are limited and the overall amount of uranium is not sufficient to supply all NPPs over the course of their operating life span. While there is some hope for the discovery of new uranium, it is almost impossible to make a forecast for future development of new uranium resources and opinions in expert circles differ widely. In principle, it is certain that there are still considerable quantities of uranium in the earth's crust, but the physical and economic feasibility as well as the thermodynamic meaningfulness of related mining operations are debatable (Englert et al., 2011). Furthermore, past experience of the last 50 years shows that a massive increase in exploration expenditure never led to the discovery of large amounts of exploitable new resources (Liebert and Englert, 2015, p.83). The issue of overall availability of uranium for large growth scenarios can easily be demonstrated with Fig. 7 (Zittel et al., 2013), but was also discussed by others (Englert et al., 2011; Gabriel et al., 2013).

We assume that our expansion scenario (section 2.2) would be implemented between 2020 and 2040 and that the installed nuclear capacity would be linearly increased to reach its final value by 2040. It is further assumed that the reactor fleet consumes 180 t uranium annually for each installed GW of power. The cumulative uranium demand up to 2040 would amount to 7.2 million tons uranium, so that identified resources (in part with already very high production costs near 260 USD per kg) would be exhausted to a great extend. Already by 2030 the annually needed uranium would exceed today's demand by five to nine times and it is already questionable if production could keep up with the demand. In addition new reactors are build for life times beyond sixty years. After 2040 the demand would exceed 6.5 million tons uranium per decade, which is more uranium than was mined in the last 75 years. With life times of at least sixty years for new reactors the additional uranium demand for a reactor fleet with 3600 GWe capacity would sum up to roughly 30 million tons uranium, which is more than even the speculative resources. It is inconceivable to make such huge amounts available.

5. Fast breeder reactors - the solution?

Nuclear technologies that could overcome the problem of the limited availability of the isotope uranium 235 are fast breeder reactors. Fast breeder reactors utilize the possibility of uranium-238 to transmute to the isotope plutonium-239, which is again fissile and can be used as reactor fuel like uranium-235. Since the abundance of uranium-238 is 99.3%, compared to the abundance of uranium-235 which is 0.7%, this technology, in principle, permits to extend the existing uranium resources. To qualify as breeder reactor a reactor has to "breed" more plutonium from uranium-238 than fissile material burned in the process. This means that on average at least 2.3 free neutrons have to be produced per fission, one to induce further fission, one to be captured by uranium 238 and breed Plutonium, and 0.3 neutrons to account for losses and neutron captures in other materials. Among other things, the requirement of more than 2.3 free neutrons per fission makes the use of fast neutrons necessary, opposed to the "thermal", slowed down, moderated neutrons utilized in the "thermal" light water reactors today.

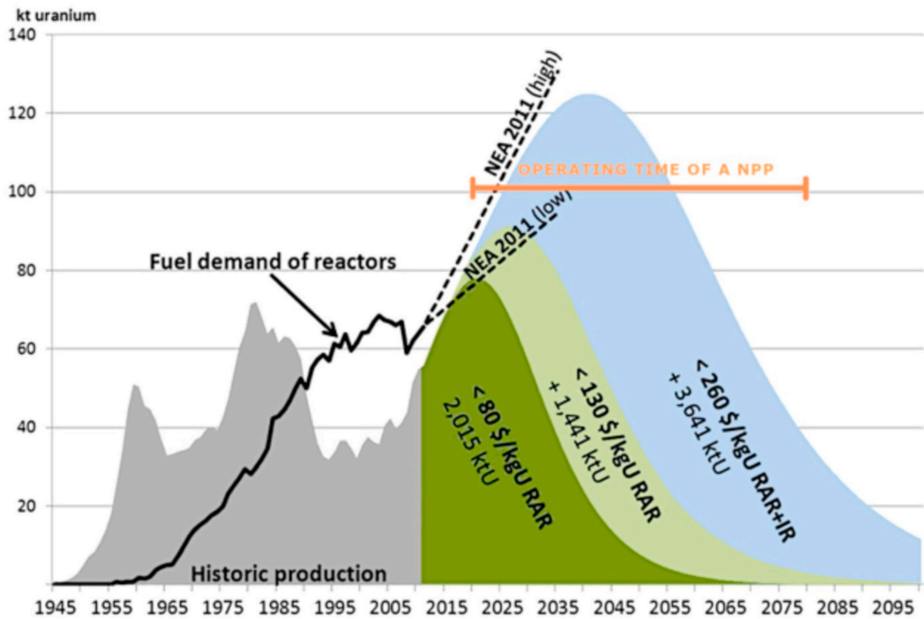

Fig. 7. Approximation of resource availability via bell-shaped curves for different cost and resource categories by (Zittel et al., 2013). It is compared with the projected uranium demand for OECD-NEA/IAEA high and low nuclear power build rate scenarios from 2011 (OECD NEA and IAEA, 2012). While a little outdated, the main conclusion still holds true. For large growth scenarios there are not sufficient resources identified to provide fuel for the 60-year operating time of future nuclear power plants. Different uranium production scenarios in comparison with the IAEA 2011 demand scenario.

Pistner and Englert (2017) gave a comprehensive overview on fast breeder reactors that were deployed as early as 1947[2] up to now. Not counting experimental reactors, six reactors that could classify as prototype reactors and two reactors reaching a commercial scale were build and operated up to now. But fast reactors have had a very poor operability record with one single exception the BN-600 fast breeder reactor at Beloyarsk in Russia has a lifetime load factor of roughly 75% The other fast reactors had lifetime load factors significantly below that.

- BN-350 (Aktau; Kazakhstan), 44.48%, BN-600, same location, 75%, and BN-800, lifetime load factor of 67%.
- Fermi Unit 1 (United States), 3.41% in 1971, the only year of data available in IAEA's PRIS[3] database, and during the time it operated it was under trial operation.
- Monju (Japan) was connected to the grid on August 29, 1995 and has been closed since December 8, 1995, except for a brief period of operation in 2010.
- Phénix (France), 41.34%.
- Prototype Fast Reactor (Dounreay, United Kingdom), 23.87%.
- Superphénix (France), lifetime value not estimated in PRIS, but its best year was only 32.18%.
- India operated the Fast Breeder Test Reactor (40 MWt design) from 1985. The FBTR was shut down from 1987 to 1989, and operated at only 1 MWt till 1992. Power was raised to 10.2 MWt in 1993 and to 11.5 MWt in 1997. Reactor Power was increased several times over the years up to 32 MWt end of 2018. In 2010 the operating life was extended for 20 years to 2030.

This means that most of the fast reactors deployed so far still have the character of experimental or demonstration reactors. The most promising designs so far for fast reactors are based on sodium as primary coolant, sodium fast reactors (SFR). Sodium gets activated during its passage through the reactor core, sodium-24 with a half life of ~ 15h is generated by neutron capture, as well as sodium-22 by (n, 2n) reaction with a half life of 2.6 y. Poplavskii et al. (2004) reports the activity in the primary coolant of the BN-800 to be $\sim 10^{15}$ Bq/ton, while activity in the coolant of a typical light water reactor is $\sim 10^{11}$ Bq/ton (AREVA, 2013), 10 000 times less. The excess activity stems mainly from sodium-24, which decays roughly within one week.

Sodium reacts with air and water which means that a sodium leak, either to the atmosphere or to the tertiary loop, typically featuring a steam turbine and water as fluid, will lead to a fire and bears additional risks for accidents. The reactor compartment typically is flooded with an inert gas like Argon. SFR design therefore has to include safety features to prevent inflow of oxygen and to quickly detect leaks, to terminate fires from leaks in the steam generators. Nonetheless sodium leaks and sodium fires could not be prevented, neither in French SFRs (Schneider, 2009), nor in BN 350 and BN 600 (Poplavskii et al., 2004). The biggest sodium leak and fire at Monju SFR in Japan (1995) led to the shut down of the plant (Kondo, 1998). Pillai and Ramana (2014) argued that the large number of sodium leaks observed at SFRs might hint at a systemic problem of these kind of reactors.

The potential advantages of fast breeder reactors were early recognized and research on sodium fast reactor systems started almost at the same time as research on thermal light water reactors, in the 1960s (Schneider, 2009; Kondo, 1998). In the years 1973–1996 the French Atomic Energy Commission CEA spent 50% more on research of SFR than on light water reactors (Schneider, 2009). But all the effort did not lead to a commercial, widely deployable, nuclear power plant on SFR basis, the technical obstacles were too high. In 2019 CEA abandoned its plans to build its new prototype fast breeder reactor ASTRID after an investment of more than 700 million Euro (NEI, 2019).

Other reactor concepts are not as far in development as the SFR. The "Generation IV International Forum", a framework for international cooperation in research and development for "Generation IV" reactors, issued a roadmap for the development in 2002, which was updated in 2014 (GIF, 2002, 2014). Both report "system development timelines" showing the development phases of "viability" demonstration, "performance" optimization and building of a "demonstration" reactor on a time scale. In (GIF, 2002) the end of "demonstration" phase was scheduled for 2020 for SFR, and for 2025 for gas-cooled fast reactor GFR, lead-cooled fast reactor LFR, molten salt reactor MSR and super critical water reactor SCWR. The update in 2014 shifted those estimates considerably: end of demonstration phase is now predicted to be 2030 for SFR and SCWR and is not reported for the other reactor systems. Commercial scale, widely deployable Generation IV fast reactors cannot be expected to become operational until the 2040–2050 time frame. Instead only small technology demonstrator reactors are expected to be

[2] USA, Experimental Breeder Reactor EBR-I.
[3] Power Reactor Information System.

available before 2040 (De Santi, 2009; IEA/NEA, 2010; Lee and Taylor, 2010; Riou et al., 2009).

6. Conclusions and policy implications

Anthropogenic climate change requires a rapid shift towards a CO_2 neutral economy, if the global average temperature increase is to be kept below 2°C, or, preferably, below 1.5°C compared to pre-industrial levels. By 2050 the economy should be CO_2 neutral, therefore climate change mitigation measures are needed in the near term to medium term future. Such a shift would strongly influence the energy (and electricity) supply system, which is currently based to a larger part on fossil fuels.

The most important result of the present work is that the contribution of nuclear power to mitigate climate change is, and will be, very limited. According to current planning nuclear power would avoid at most[4] annually 2–3% of total global GHG emissions in the years 2020–2040. Moreover, nuclear power cannot be expanded to be the main source of future electricity generation. Expansion scenarios require an increase in uranium mining, which is met by two limitations: uranium production could hardly keep up during the expansion phase, and the overall amount of available uranium is limited. Such scenarios would leave new nuclear power plants without fuel during their planned life time. Fast breeder reactors promise a solution to the problem of limited uranium-235 resources, but will not be available for commercial deployment before 2040–2050. And given the considerable research effort and research times up to now, it is even doubtful if a commercially deployable fast breeder reactor will be available then. But even assuming such a scenario were feasile, even substituting all fossil fired power plants by nuclear power plants would still leave ~ 70% of projected global GHG emissions from other sectors in 2040 and would still require drastic actions to reduce all emissions to zero.

The officially announced plans do not hint at expansion scenarios. They aim at replacing capacity from decommissioned plants with new builds, possibly combined with extension of life time of current operating reactors. Comparing past projections with actual build rates and given the characteristics of nuclear power (long development times, long planning and construction periods, uranium-235 resource limitations of the current reactor technology), keeping the current nuclear capacity for the next years might constitute the upper limit for the use of nuclear power.

However, current nuclear reactors, no matter how safe they may be, always carry a residual risk for severe, catastrophic accidents (Sehgal, 2012) and large releases of radioactive materials (Seibert et al., 2012). New reactors attempt to reduce the residual risk, but even with the future technologies currently envisaged a nuclear catastrophe cannot be fully excluded. The main contribution to current nuclear electricity generation stems from reactors built 1970–1990, which were designed 1960–1980. New reactor technologies promise that the risk for severe accidents is reduced by a factor of ten. However, according to current plans, the major part of future nuclear generating capacity stems from lifetime extensions of existing plants and only a limited part will come from new builds (in 2040 ~ 30% new builds, ~ 70% current operating reactors life time extended and/or in long term operation according to ISR-projection).

Given the modest contribution of nuclear power to climate change mitigation another option is feasible, which is the phase-out of nuclear power. This finding is in agreement with substantial evidence of a comprehensive global energy study of the International Institute of Applied System Analysis (IIASA, 2012). In this study a normative approach was adopted, a scenario that by 2050 society is on a climate pathway to fulfilling the 2°C target while still providing access to modern energy services to all humans. Starting from the goal of a sustainable, CO_2 neutral economy, IIASA (2012) calculates back and investigates which energy pathways lead to such a future. One of the important results of the analysis shows that none of the evaluated boundary conditions make it necessary to use nuclear power. Even high energy demand assumptions without substantial change in the transport system allow other energy sources to substitute nuclear energy.

The current contribution of nuclear energy to climate change mitigation is small and, according to current planning, will stay at this level in the near-to mid term future. Nuclear expansion strategies are not feasible due to resource limitations. New nuclear technologies without those limitations will not be ready in the critical time frame 2020 to 2050 due to the long research, licensing, planning and construction times of the nuclear industry. Current plans would keep the nuclear capacity roughly at its current level mainly by life time extensions of existing reactors. But given the limited contribution to climate mitigation, complete phase out is a feasible option as well. Society must decide, given the drawbacks of the use of nuclear energy (risk of catastrophic accidents, proliferation, radioactive waste), whether the nuclear option should be pursued, or whether other climate change mitigation technologies should substitute the nuclear contribution.

[4] The present analysis gave an upper bound for the nuclear climate mitigation potential, a future analysis may attempt to provide a best estimate value.

CRediT authorship contribution statement

Nikolaus Muellner: Project administration, Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Nikolaus Arnold:** Methodology, Formal analysis, Writing – original draft. **Klaus Gufler:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Wolfgang Kromp:** Funding acquisition, Review & editing. **Wolfgang Renneberg:** Project administration, Conceptualization, Review & editing. **Wolfgang Liebert:** Formal analysis, Writing, Validation, Review & editing, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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