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ANALYSIS

How much can nuclear power reduce climate mitigation cost? — Critical parameters and sensitivity

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ABSTRACT

Although large scale nuclear power deployment can reduce greenhouse gas emissions, potential for nuclear power to reduce climate mitigation cost is not well understood. We use an energy system model to estimate the relative savings in mitigation costs enabled by nuclear power as well as their robustness via scenario and Monte Carlo analysis. Nuclear power reduces mitigation costs in all explored scenarios, but the extent varies considerably. Nuclear power reduces costs significantly if carbon storage capacity is low but is replaceable if the capacity is abundant and technology available. The same holds for the cost of renewables. However, providing a full cost benefit analysis of nuclear power is beyond the scope of this paper.
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1. Introduction

If global warming is to be kept under 2 °C with reasonable certainty, greenhouse gas (GHG) emissions must drop by roughly half by mid-century compared to current levels and continue to decline afterwards [1]. The energy system, including heat and electricity production and transport, is the largest source of emitted anthropogenic CO_2, the most important GHG, and therefore the main target for emission reductions. These emissions can be reduced in several ways: by either reducing energy use e.g. via efficiency improvements, by switching to technologies with lower CO_2 emissions or by capturing the emitted CO_2.

Many possibilities exist for supplying energy with low life cycle emissions such as the use of biomass, wind, solar, hydro or nuclear power. However, no single technology will be sufficient to completely solve the problem [2]. Nuclear power has been historically expanded mostly due to growing demand and security concerns [3,4], but accumulating disquiet about climate change has within some circles renewed interest in its prospects to substitute higher emission sources. There are, however, many challenges related to nuclear power. The most notable are radioactive waste production, accidental radiation release risk, nuclear weapons proliferation risk and public resistance [5–7]. These caveats make nuclear power distinctive from other energy technologies and have led many to the conclusion that nuclear power does not have a place in the future energy system as exemplified by recent decisions in Germany, Belgium and Switzerland to phase out nuclear power [8]. Although climate mitigation is possible without nuclear power [e.g. 9,10], by excluding nuclear power from the energy system, climate change mitigation may become more difficult and costly to achieve as shown by a study by the International Energy Agency (IEA) [11] as well as several others [e.g. 12–14].

Nuclear power's potential to reduce the mitigation costs is dependent on other developments in the energy system such as the cost of solar, wind and Carbon Capture and Storage (CCS) technologies; availability of biomass and hydro resources and ability to integrate variable renewables into the system. Assuming that the availability of suitable carbon storage sites is large, the use of fossil fuels could continue for decades, but the question of how much CO_2 can be stored is still open and the degree of uncertainty is high [15]. Similarly, although both wind and solar photovoltaics (PV) have seen major reductions in investment costs, the availability of suitable sites for production (wind) and their variable nature may limit their expansion (wind and solar PV). Biomass production for energy can be limited by concerns for the environment and competition with food production. Environmental concerns also arise in connection to hydro power, and the number of suitable sites is restricted. Since many of these developments are highly uncertain, the robustness of a possible contribution by nuclear power, i.e. its ability to reduce mitigation costs under uncertainty, should be tested across a wide range of possible future scenarios.

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Some studies have attempted to better estimate the possible role of nuclear power in climate mitigation. Vaillancourt et al. [13] studied the role of nuclear power under two different climate scenarios and under various constraints on nuclear power development. They found significant expansion of nuclear power throughout the century in all cases. Mori [16] and Bauer et al. [17] reported significant losses in GDP resulting from early retirement or phase out. In addition, Mori found CCS and nuclear power to be substitute mitigation technologies. Tavoni and van der Zwaan [12] explicitly focused on the relationship between CCS and nuclear power under climate mitigation condition. They concluded that for large scale replacement of nuclear power by CCS, further cost reductions in CCS technologies are necessary. Most recently the Stanford Energy Modeling Forum Study 27 (EMF27) investigated the importance of individual mitigation options by comparing the responses of 18 energy-economy and integrated assessment models to two different climate targets and various technology limitations [18]. The role of nuclear power was investigated via comparison of a phase out scenario to a scenario in which nuclear is part of the portfolio. In this study all models but one found that employment of nuclear power leads to mitigation cost reductions ranging from −2 to 30% of the abatement cost [19]. Yet no systematic exploration of a large number of factors that can possibly affect the role of nuclear power within a model, such as other technologies' costs and carbon storage availability, has been carried out to our knowledge in the literature of global energy systems models. This paper aims to fill this gap.

Specifically, the aims of this paper are to:

- Estimate the effect of allowing a large scale expansion of nuclear power on the climate mitigation cost.
- Understand under which conditions the effect of allowing nuclear power is significant to the cost of climate change mitigation and in which cases the effect is minor.

2. Method

2.1. GET model

We perform this analysis using the Global Energy Transition (GET) model first developed by Christian Azar and Kristian Lindgren [20] and further developed in Hedenus et al. [21]. GET is a cost minimizing "bottom-up" systems engineering model of the global energy system set up as a linear programming problem. The model was constructed to study carbon mitigation strategies over a 100 year period with an objective of meeting both a specified energy demand and a carbon constraint at the minimum discounted energy system cost for the period under study (in general 2000–2100). In order to do this, the model evaluates a large number of technologies for converting and supplying energy based on data related to costs, efficiencies, load factors and carbon emissions among other parameters. In addition resource estimates are included as well as various restrictions on technologies such as a limit for a variable electricity supply. The model focuses on the supply side although some efficiency measures such as electric vehicles are endogenised. In our analysis we use version 8.0 of GET, featuring improved representation of the nuclear cycles. In addition to the Light Water Reactor (LWR) fuel cycle also Mixed OXide (MOX) and Fast Breeder Reactor (FBR) options have been added. For more detail please see Ref. [14].

The model has five end use sectors: electricity, transport, feedstock, residential–commercial heat and industrial process heat. Demand projections are based on the MESSAGE B2 scenarios based on increasing global population, intermediate levels of economic development and a stabilization level of 480 ppm CO_2-eq by 2100 [22], whereas the transportation demand scenarios are based on Azar et al. [20] and assume faster efficiency improvements in transport sector than in B2 scenario. The demands are exogenously given. The model also has perfect foresight and thus finds the optimum that is a least cost solution for the whole study period with a discount rate of 5%. Scarce resources such as oil and biomass are allocated to the sectors in which they are used most cost-effectively. More information about the model framework can be found in Ref. [14].

In the model the world is divided into High Income (HIC), Middle Income (MIC) and Low Income Countries (LIC). HIC include North America, Europe and Pacific OECD countries; MIC cover centrally planned Asia,[1] the former Soviet Union and Latin America; and LIC consist of Africa, the Middle East, South Asia and non-OECD Pacific. We construct the mitigation pathways based on the idea of contraction and convergence [23]. In case of 3 °C climate sensitivity HIC and MIC roughly halve their emissions compared to the baseline by 2050, whereas LIC reduce emission by 35% compared to the baseline. From 2060 we assume a global cap, and the emissions are allocated among regions in the most cost-effective way.

The diffusion of technologies is limited so that no technology can increase or decrease its market share by more than 20% in 10 years in a specific sector such as electricity or centralised heat production; nor can the installed capacity for each technology increase by more than 30% in a year. In addition the contribution from variable resources – wind and solar PV – is limited to 20% of the electricity supply for a single source and 30% of the electricity supply regarding combined output of wind and solar PV due to grid integration and balancing issues. For technologies that are considered immature the investment costs decline linearly over a 50 year period and reach the mature levels indicated in Annex A.

2.2. Performance and cost of technologies

One of the main determinants of whether nuclear power could reduce the climate mitigation cost is undoubtedly the investment cost of nuclear power. In contrast to other energy technologies, the cost of nuclear power has increased over time [24,25]. For example the investment cost in the US has risen from less than 2000 US$(2010)/kW in the 70s to close to 6000 US$(2010)/kW today [25]. The cost increase has mainly two reasons — increased safety standards that have led to higher complexity as well as fewer investments, which in turn have led to loss of knowledge in the nuclear industry [25]. The small number of recent investments makes estimating the future cost of nuclear power difficult. This increasing trend in cost can probably be reversed by better standardisation of nuclear power plants, which would enable mass production and ease the licencing process [26]. On the other hand the need for enhanced safety measures due to risks perceived by the public in light of the recent Fukushima accident and delays in construction may cause nuclear power plants to become yet more expensive. The latter has been the case for the Olkiluoto 3 reactor in Finland, where final cost estimates have almost tripled from ca 2800 to ca 7200 US$(2010)/kW [27]. Even if cost reduction potential can be realised in full it is unlikely that the investment cost of nuclear power will decline to the levels of the 70s due to increased complexity and safety measures. Mature investment cost estimates in recent model studies range from 2050 to 8850 US$(2010) [12,13,19,28,29]. In this study we chose 5000 US$(2010) for LWRs and 6000 US$(2010) for FBRs as the mature investment cost level by 2050 in the standard run. It is important to note, however, that it is not the investment cost in itself that determines the role of nuclear in the system but rather the relation to costs of other technologies. Enrichment, reprocessing, waste management and other related costs were modelled separately. For more detailed info see Ref. [14]. In addition we assume, in scenarios where nuclear power can expand, that there will be social acceptance

[1] Centrally planned Asia includes Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia and Viet Nam.

of nuclear expansion as well as political support for nuclear power employment in both developed and developing countries.

Since different nuclear technologies are in various development phases, they are allowed to enter the portfolio as available options at different times. LWR technology, which is currently employed at a large scale, is available throughout the whole modelling period. MOX fuel can be introduced in 2020 for large scale deployment. Although this technology already exists on a commercial scale, it is only utilised in countries with highly advanced nuclear sectors. Many existing LWRs can burn MOX fuel though, if licenced. Its use is therefore dependent on economics and political decisions. Given the development state of FBRs, this reactor design is allowed in the model starting from 2030. Although a few FBRs are currently in operation, the technology must be improved significantly before it can be applied on a large scale. Uranium resources are modelled in 5 grades based on the Global Energy Assessment [30]. The fifth grade corresponds to uranium from non-conventional sources such as sea water (Annex B).

Renewables are often seen as an alternative to nuclear power in a climate change mitigation context, and rapid cost reductions have taken place in recent years. Yet the mature cost level of these technologies is uncertain due to various limitations and challenges. Wind and solar PV face challenges caused by their variable nature as well as from often being located far from demand and thus requiring grid improvements. Large uncertainties exist about the availability of biomass that can be grown and used sustainably. In our study we explore a range from 100 to 300 EJ of biomass available per year with a standard level of 200 EJ/yr.

Similar to FBRs, Concentrated Solar Power (CSP) is a technology that still requires further improvements to become competitive. It also needs favourable atmospheric conditions to function and can therefore be implemented in a much more restricted area than solar PV. On the other hand CSP can be equipped with energy storage, thereby enabling power production during night, which results in a significantly higher capacity factor than solar PV can achieve. In our model we have coupled CSP with a 12–15 h thermal storage capacity based on a two tank molten salt system [31]. To take into account the more demanding nature of CSP in terms of solar radiation, which limits the possible locations, and its variable nature as well as the limitations of storage, the share of CSP in electricity production was limited to 30% in HIC and MIC and to 50% in LIC. A global grid could perhaps remove those limitations [32] but is unlikely to materialise due to political disincentives and security risks. Even if realised, this type of grid would require large amounts of investments that are dependent on the exact setup and therefore not easily captured with our model.

CCS is an abatement technology that can be used in cycles utilizing either fossil fuels or biomass, but relatively large point sources of CO_2 are required. The infrastructure and regulations for capturing carbon are not yet in place, and therefore the final cost is unclear [15]. In the model we assume that 95% of the generated CO_2 can be captured. Furthermore the efficiency of a power plant is reduced by 10 percentage points [15], and a cost for the transport and storage of the captured CO_2 in the amount of 10 US$(2010) per ton of CO_2 is added. Bioenergy can be used with CCS when co-fired with coal; thus biomass with CCS is limited to 20% of the coal that is used with CCS. This assumption is made due to many technical difficulties connected to the transport and capture of CO_2 from purely biomass burning plants. In the industrial sector CCS can only be used at large industrial plants, meaning that no more than 50% of industrial heat production can be coupled with CCS. For similar reasons CCS use in residential-commercial heat production is limited to 70%. The level of storage capacity of CO_2 is assumed in our baseline to be 2000 $GtCO_2$, which is the likely minimal technical potential of storage capacity level in geological formations estimated by the Intergovernmental Panel on Climate Change's (IPCC) special report on CCS [15]. This is our baseline assumption due to various restrictions. Some sites will not be economically attractive or are not usable under current conditions such as being part of a nature reserve. Additionally, like nuclear power CCS faces problems in the siting of depositories due to negative public opinion. Therefore it is unlikely that the technical potential will be fully realised.

Although gas and coal resources are better explored than many other resources, the uncertainty in extraction cost increases as we move to less accessible and unconventional deposits. We model 2 grades of coal and gas and 3 grades of oil resources based on extraction costs to better describe the change in resource costs. More info can be found in Annex B.

To better compare the different electricity sources, we calculate the levelized cost of electricity for the year 2070 from standard model runs, at which point all technologies have reached maturity. The levelized cost includes investment, fuel, operation and maintenance and waste disposal costs (Fig. 1). It is interesting to note that nuclear technologies are not the cheapest; instead wind and coal with CCS will be chosen first on cost bases.

2.3. Scenarios

To analyse the contribution of nuclear to climate change mitigation we look at three nuclear scenarios. The first, called *advanced nuclear*, allows use of FBRs as well as LWRs and sets no restrictions to nuclear expansion or technology use other than the limits mentioned in the previous section. The second scenario called *conventional nuclear* assumes that only technologies that are commercially available today will be used in the future. Thus FBRs are not permitted to enter the energy mix, and uranium extraction from alternative sources such as seawater is not allowed, diminishing the resource base for producing nuclear power. The third scenario called *no nuclear* assumes that due to various challenges related to nuclear power, a global phase out occurs. No new reactors will be built after 2020, and all existing reactors will be retired by 2040. Also the baseline, i.e. the scenario without carbon constraint but otherwise unchanged, was solved for each scenario to assess the mitigation cost.

To further investigate the role of nuclear we varied different parameters in the model as shown in Table 1. The 50% variation was chosen to capture the high uncertainty of the future outcomes of chosen parameters (also described in section 2.2.). Choosing a low variability would not capture the uncertainty and thus result in solutions similar to our standard runs. Also widely different estimates of future costs of those parameters are given in the literature from source to source but also from year to year (IEA, International Renewable ENergy Agency (IRENA), US Energy Information Administration etc.). Therefore there seems to be no commonly accepted range of possible values for these parameters. Only one parameter was varied at a time, and the others were kept at the constant level

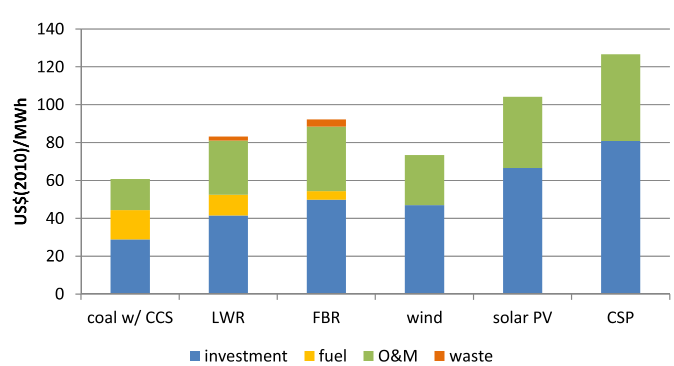

Fig. 1. Mature levelized cost of electricity for different sources at 2070 (excluding CO_2 tax and scarcity rents of non-renewable sources and carbon storage) based on standard model runs.

Table 1
Parameter variations.

Parameter	Optimistic	Standard	Pessimistic
CCS	2 times the standard storage capacity; 0.5 times the investment cost of adding carbon capture to a power plant; 0.5 times the storage cost	Standard carbon storage capacity and costs	0.5 times the standard storage capacity; 1.5 times the investment cost of adding carbon capture to a power plant; 1.5 times the storage cost
Renewables	0.5 times the standard cost for wind, solar PV and CSP; 1.5 times the standard penetration limit for CSP, 1.5 times the standard biomass potential	Standard costs and biomass potential	1.5 times the standard cost for wind, solar PV and CSP; 0.5 times the standard penetration limit for CSP, 0.5 times the standard biomass potential
Gas and coal cost	0.5 times the standard cost for high cost coal and gas	Standard costs	1.5 times the standard cost for high cost coal and gas
Cost of nuclear technologies	0.5 times the standard investment cost	Standard costs	1.5 times the standard investment cost
Demand	Standard demand $\times$ $(1-0.05)t$ where $t(2020) = 1$ and t is measured in decades	Standard demand	Standard demand $\times$ $(1 + 0.05)t$ where $t(2020) = 1$ and t is measured in decades

that we refer to as standard. Each parameter variation was tested in all three nuclear scenarios. Also the baseline was solved for each variation with the same parameter values. We define abatement cost as the difference in the net present value of the total energy systems cost between a carbon constrained scenario and the baseline. Not included in this analysis are many externalities such as air pollution caused by coal power plants or policies to support renewable electricity generation that in the real world are likely to affect the development of the energy system in addition to cost. Therefore the baseline case should not be seen as a prediction of the future energy system without a carbon price but rather as the cost optimal solution to the given constraints.

The allowable amount of emissions to maintain the global average surface warming under 2 °C depends on the climate sensitivity. With higher climate sensitivity faster cuts in GHG emissions are needed. We test two different carbon emissions pathways corresponding to climate sensitivities of 2 °C and 3 °C warming per doubling of atmospheric CO_2 from the pre-industrial level. The emission trajectories are based on a GET version with a simple integrated climate model [33]. Although the IPCC gives a likely range for climate sensitivity of 1.5–4.5 °C per doubling of atmospheric CO_2, a climate sensitivity above 3 °C per doubling of atmospheric CO_2 is not explored because to reach the 2 °C target in this case would require a massive and unlikely emission reduction compared to the baseline before 2050. Also to meet a 2° target with very high climate sensitivities, BioEnergy with CCS (BECCS) must probably be applied at a large scale [33], which is outside the scope of this study. Global emission trajectories corresponding to different sensitivities are shown in Fig. 2.

In addition to uncertainties involved in future developments of energy technologies discussed in the previous section, the future demand is largely unpredictable. It is possible that improvements in energy efficiency will occur much faster than expected or that consumption will increase faster than anticipated. To investigate how this may affect the potential role of nuclear we vary the demand as shown in Table 1.

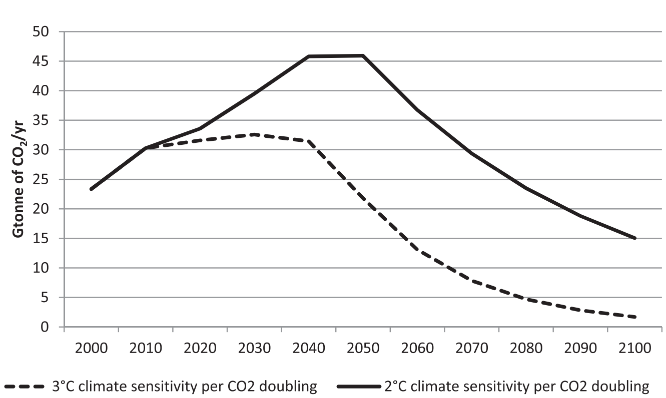

Fig. 2. Global CO_2 emission trajectories for meeting the 2 °C target with different climate sensitivities.

The limits on the expansion rate of technologies and market share changes were also varied but did not produce significant changes in our results and were therefore omitted from further analysis.

2.4. Expected cost analysis

To give an estimate of the cost reduction enabled by nuclear power we perform an expected cost analysis examining five different levels of carbon storage capacity corresponding to 0, 1000, 2000, 3000 and 4000 $GtCO_2$ as well as the cost of CCS, CSP and nuclear technologies corresponding to 50%, 75%, 100%, 125% and 150% of the standard cost level. Calculated in all three nuclear scenarios, expected cost is defined as the average abatement cost of all possible combinations of these variables.

2.5. Monte Carlo analysis

To investigate the robustness of our results we perform a Monte Carlo analysis, in which we solve the model for a large set of randomised key parameters presented in Table 1 for emissions trajectories corresponding to two different climate sensitivities — 2 °C and 3 °C warming per atmospheric CO_2 doubling from the pre-industrial level. We created 1000 sets of these parameters and used them in solving all scenarios. This allowed us to maintain comparability among scenario results. Since uncertainties for all parameters are substantial, we used a uniform distribution ranging between 0.5 and 1.5 times the original parameter value for all varied parameters with exceptions as follows. CCS storage capacity was varied between 0 and 4000 G tonnes of CO_2 to include the case in which CCS will not enter the energy system due to political or technical reasons. The maximum potential share of CSP in electricity production was also varied, between 15 and 45% for HIC and MIC and between 25 and 75% for LIC with uniform distribution. The demand was varied among three trajectories specified in scenario analysis of parameter variations. For all cases the corresponding baseline scenario was also solved to allow a fair comparison of mitigation costs.

3. Results and discussion

We present here and in the following sections the results for climate sensitivity of 3 °C per doubling of atmospheric CO_2 if not stated otherwise. In our standard model runs electricity is mostly produced from coal when no carbon constraint is specified (Fig. 3). Additionally hydro power is expanded to its maximum potential.

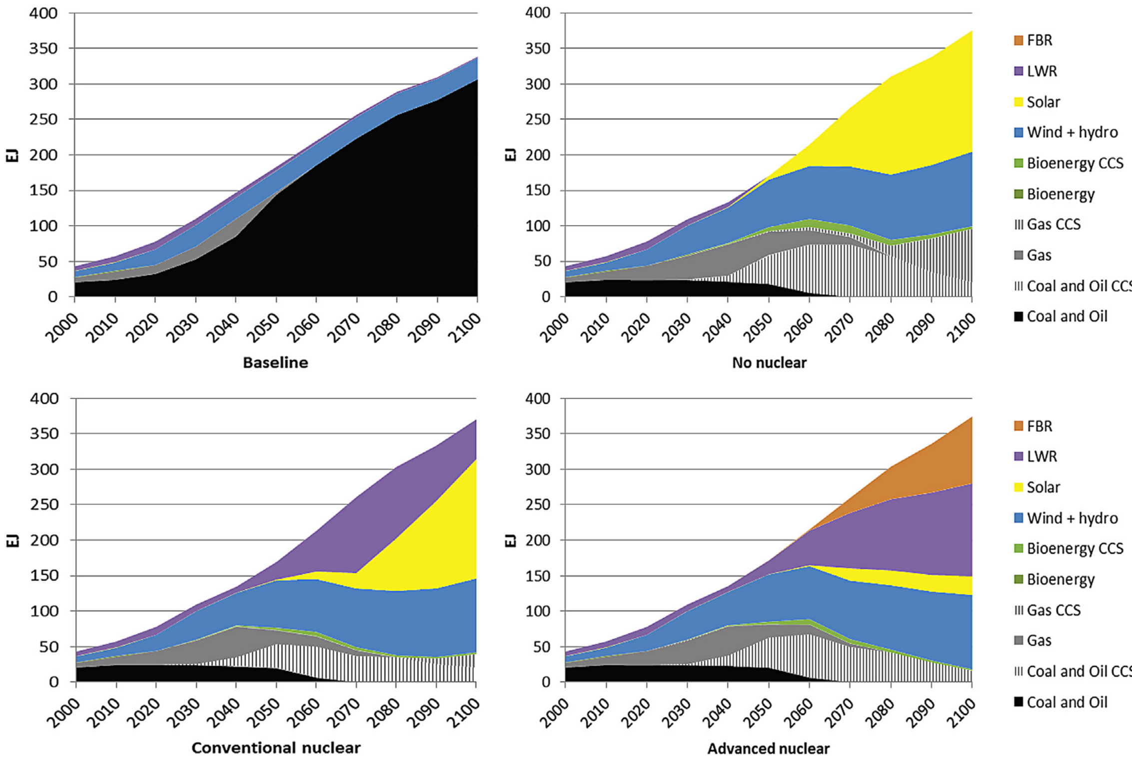

Fig. 3. Electricity supply in standard scenarios with 3 °C climate sensitivity per doubling of atmospheric CO_2.

Nuclear power is employed on a very small scale — 1% of the electricity supply in 2070. We here and afterwards present the average of the period 2060—2080 as 2070 for easier reference. In carbon constrained scenarios, wind power is expanded in addition to hydro power, but this development is limited due to our exogenous constraint on variable resources.

When nuclear expansion is allowed, the share of nuclear electricity in the supply is considerable, reaching slightly more than one third by 2070. Even though FBRs can be built starting from 2030, they do not become economically competitive before 2050. This is partially due to the availability of other lower cost mitigation options in earlier periods such as wind and hydro and emissions trajectories that allow for more emissions in earlier periods, but also because the time dependent investment costs decline. In case of a phase out of nuclear power the role of solar power is greatly enhanced. It reaches 32% of the total electricity supply by 2070 in the *no nuclear* scenario compared to only 5% in the *advanced nuclear* scenario.

Although the share of nuclear power in electricity production is similar in both nuclear scenarios in 2070, they develop very differently in the latter part of the century. In the case of limited technology options and resources, the *conventional nuclear* scenario, nuclear power is gradually phased out and replaced by solar power as uranium resources are depleted by the end of the century. In the *advanced nuclear* scenario, expansion will continue for both LWR and FBR technologies. This means that the number of reactors will roughly grow tenfold compared to today's level if future reactors are assumed to have one GW_e capacity on average. A similar expansion is also observed by Vaillancourt et al. [13], who assessed the penetration level of nuclear power with the World-TIMES model. Their model, however, finds a significant expansion of nuclear power in the baseline as opposed to the near phase out in our model due to exogenous assumptions that set a lower limit to nuclear penetration. A tendency for expansion under CO_2 emission constraints is also observed by Mori [16], Tavoni and van der Zwaan [12] and the EMF 27 study [19].

In the *no nuclear* scenario the discounted mitigation cost over the whole study period is 9 trillion US$(2010). This abatement cost is reduced by 20% if all nuclear technologies are allowed to expand and by 10% if only current technologies are available. These results are in line with the EMF27 study that found nuclear power can reduce climate mitigation costs up to 30% [19]. In light of our levelized cost analysis (Fig. 1) it may seem surprising that nuclear power can reduce climate mitigation cost, but it is important to remember that the levelized costs given do not include all systemic effects. Although wind power is cheaper than nuclear power, it is constrained due to its variable nature and can only provide 20% of the electricity supply. Coal power with CCS has also a lower levelized cost, but is subject to many limitations. First of all the carbon storage capacity is limited, which sets also a limit to CCS use. In addition CCS is not a zero-emissions technology, as only 95% of the produced CO_2 is captured. As the emissions budget decreases over time, the CO_2 price increases, raising in turn the levelized cost of coal power with CCS. Finally resource scarcity plays a role. As the cheapest resources are used first, the model turns to more expensive resources in the other half of the century. This is true for both nuclear and coal power, but since fuel cost represents a much greater fraction of the levelized cost of electricity from coal, it is more greatly affected. To test the significance of the capture ratio we ran our model with 100% capture efficiency. The result was a postponement by a decade of the phase out of CCS in the electricity sector. We therefore conclude that the other two factors play a much more important role in the levelized cost development of coal with CCS.

Our analysis is subject to several limitations. First we look at the energy system in isolation from other parts of the global economy; therefore the effects of changes in other sectors resulting in price, resource availability or demand changes are not considered. De Cian, Carrara and Tavoni show that phasing out nuclear power can result in higher R&D investments for renewables and their higher deployment than in cases of continued use of nuclear power. As a result the costs of renewables may be reduced, offsetting some of the benefits from keeping nuclear in the portfolio [34]. Furthermore the energy system is represented in a highly stylized manner that omits the increased requirements upon electricity grids resulting from an increased share of renewables that is likely to be located further from demand and more dispersed than current production units or caused by the large unit size of nuclear power plants. Nor do we account for increased balancing costs. Including these costs can make nuclear more competitive according to a study by the Nuclear Energy Agency (NEA) [35] or not have a significant effect for variable electricity penetration up to 25% [36]. Finally, weighing the risks of nuclear power against its benefits and providing a full cost benefit analysis is beyond the scope of this paper.

4. Uncertainties

4.1. Sensitivity analysis

We analyse the sensitivity of our main result — i.e. that nuclear has the potential to reduce mitigation costs — with respect to changes in a wide range of parameter values (see Table 1). We find that carbon mitigation costs savings are possible if nuclear technologies are made available, but the size of these savings varies considerably. The possible savings are highest when renewable technologies prove to be more expensive and biomass availability lower than expected or when the cost of nuclear is reduced. Also the EMF27 study shows a significant effect of biomass limitations upon climate change mitigation costs [18]. At the same time low cost renewables or significantly more expensive nuclear technologies will reduce the savings considerably, down to a cost reduction of only 4% enabled by nuclear technologies in the low cost renewables case. The remaining small savings in cost are enabled by the use of existing nuclear power plants until the end of their lifetime of 40 years in the first half of the century instead of a phase out by 2040. Gas and coal cost and demand variation have a small effect on cost savings enabled by nuclear.

These patterns are observed in both nuclear scenarios (see Figs. 4 and 5), although overall savings made possible by the availability of nuclear power are more limited in the *conventional nuclear* scenario. Not employing FBRs and alternative uranium extraction technologies reduces the relative savings in climate mitigation costs between 6 and 18 percentage units. In the optimistic renewables case, FBRs and advanced uranium extraction methods provide very little additional relative savings compared to the *conventional nuclear* scenario (~1 percentage unit).

In case of low nuclear costs a significant share of nuclear power is achieved in the baseline: 14% of electricity supply by 2070, slightly higher than today's share [8]. In other cases the share of nuclear in the baseline is minimal (~1%). Most mitigation scenarios show at least 20% nuclear electricity in 2070. MOX fuel does not become economically attractive in any scenario. A similar result regarding MOX has been shown in other more detailed studies, e.g. Ref. [29].

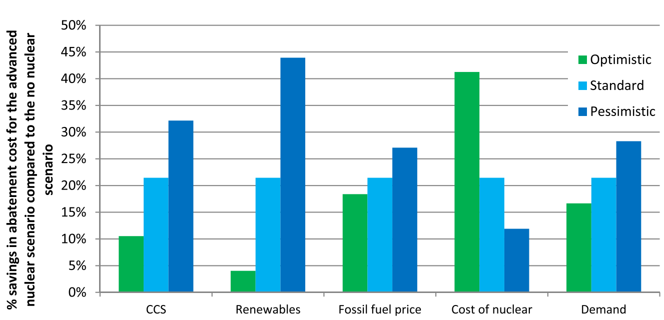

Fig. 4. Relative savings in abatement cost for *advanced nuclear* scenario compared to the *no nuclear* scenario.

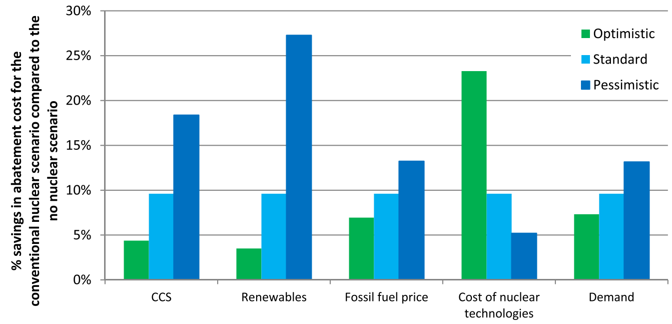

Fig. 5. Relative savings in abatement cost for the *conventional nuclear* scenario compared to the *no nuclear* scenario.

4.2. Expected cost analysis

Our expected abatement cost calculation results are presented in Fig. 6. They show that the expected cost of mitigating climate change is significantly higher in a world without nuclear power compared to a future with nuclear power. Most of the cost savings are provided by conventional nuclear technology, and developing advanced technologies such as FBRs and alternative uranium extraction methods will result in about 1 trillion US$(2010) expected savings at net present value.

More interestingly the cost savings enabled by nuclear power are about 15 percentage units greater in the expected cost analysis than in our base result. The reason behind this is the asymmetrical effect of the pessimistic and optimistic costs of renewables and nuclear technologies on mitigation cost that can be also seen on Figs. 4 and 5. If the portfolio of low emitting technologies is very limited, meaning that CSP or CCS becomes expensive, or there is limited carbon storage potential together with a nuclear phase out, the mitigation cost will be very high. If we allow another large scale power source to enter the electricity supply, this risk of high cost is significantly reduced, as the probability that all three option have a high cost is lower than the probability that only two options (renewables and CCS) have a high cost. This is not specific to nuclear power; adding a technology to the mitigation portfolio given uncertain future prospects will reduce the expected cost of climate mitigation.

4.3. Monte Carlo analysis

Our results from the Monte Carlo analysis confirm the insights from the scenario analysis. Nuclear power enables mitigation cost reduction in all cases, but these relative reductions are more restricted in the conventional nuclear case (Fig. 7). As can be seen the distribution of cost savings enabled by nuclear power is more dispersed in the case of

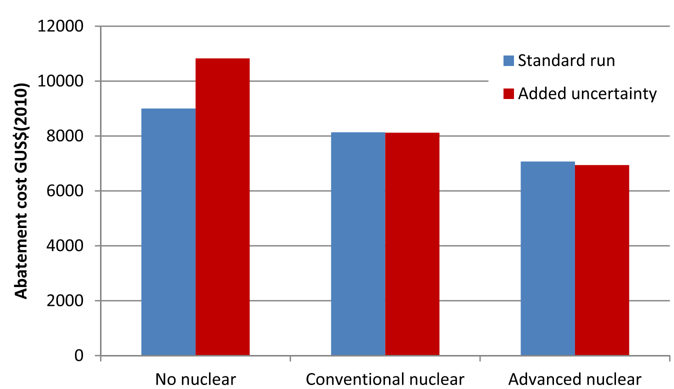

Fig. 6. Standard and expected abatement cost for different scenarios in billions of US$(2010).

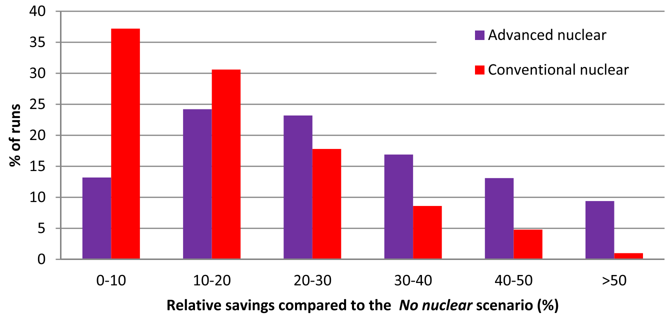

Fig. 7. Relative savings compared to the *no nuclear* scenario in case of 3 °C climate sensitivity per doubling of atmospheric CO_2.

the *advanced nuclear* scenario, peaking around 20% and with almost one tenth of runs providing relative savings higher than 50%. In the case of the *conventional nuclear* scenario the distribution is much more skewed towards lower values. The relative savings are less than 10% in one third of the cases in the *conventional nuclear* scenario compared to only one seventh in the *advanced nuclear* scenario. In cases in which many low emitting technologies prove to be expensive or limited by other constraints, nuclear power plays an important role. Without FBRs and alternative uranium extraction methods, however, nuclear expansion is curtailed by uranium resource scarcity, and therefore conventional nuclear technologies can offer more limited benefits. This result shows that although investing in advanced nuclear technologies such as FBRs and advanced uranium extraction methods may not be very attractive from an expected cost point of view in which the expected cost was reduced only a further 10 percentage units, it can be an important risk hedging strategy to avoid the risk of very high mitigation costs.

4.4. The role of carbon storage capacity

To further analyse the role of carbon storage capacity in relation to nuclear power we calculate the abatement cost for the nuclear scenarios combined with abundant or no storage availability. The results are presented in Fig. 8, showing that nuclear power can almost halve the abatement costs if there is no carbon storage available but has essentially no effect if storage capacity is abundant. Similarly to expected cost analysis, having nuclear reduces the risk of having to turn to very high cost technologies such as renewables with storage and backup electricity generating technologies and thus lowers the cost when carbon storage capacity is scarce. In a case of abundant storage capacity, CCS as a lower cost technology replaces much of nuclear, and therefore the availability of nuclear technologies is not significant. A small cost reduction in the nuclear scenarios is achieved by operating existing reactors until the end of their economic lifetime of 40 years instead of phasing them out by 2040 and also by expanding nuclear power starting from 2090 when the emission constraint is stringent. These results are also confirmed by Monte Carlo analysis.

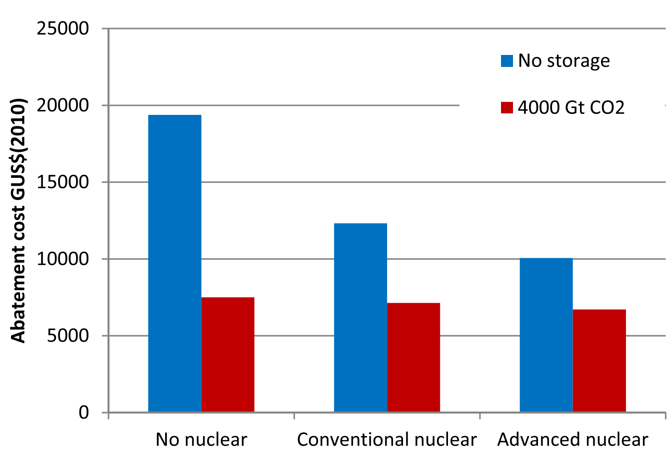

Fig. 8. Abatement cost for different carbon storage capacities and scenarios.

4.5. Effects of 2 °C climate sensitivity per atmospheric CO_2 doubling

We also investigate the role of nuclear under the assumption of a low climate sensitivity (2 °C per doubling of atmospheric CO_2). We find that the reduction in mitigation cost is around 20% for both 2 °C and 3 °C climate sensitivities in our base result when all nuclear technologies are available. However, since the mitigation cost with 2 °C sensitivity per doubling of CO_2 is about one-third of that with 3 °C sensitivity, the savings in absolute numbers are much lower. Monte Carlo analysis shows a greater ability of nuclear power to lower the climate mitigation cost percentagewise than in the 3 °C sensitivity case, with the distribution of cost reduction peaking at around 30% for the *advanced nuclear* scenario and 20% for the *conventional nuclear* scenario. The average savings in absolute numbers nevertheless drop from 3.4 trillion US$(2010) to 0.8 trillion US$(2010).

5. Conclusions

We have analysed the role and economics of nuclear power in meeting a global 2 °C temperature target. The analysis was performed with a cost minimizing systems engineering model of the global energy system called GET. We conclude that:

- Expanding currently commercially available nuclear technologies results in 10% savings in climate mitigation costs in our base result. The savings reach 20% when advanced nuclear technologies such as FBRs and alternative uranium extraction methods are also available.
- However, taking into account the uncertainty of the cost of the main mitigation technologies and carbon storage availability shows that allowing nuclear expansion reduces the expected carbon mitigation cost by 35% compared to a phase out scenario if advanced technologies are available and 25% if only conventional technologies are available. Therefore developing nuclear power can be seen as insurance against high climate mitigation costs.
- The cost savings of expanding the advanced nuclear technologies depend on other developments in the energy system. In an extensive Monte Carlo analysis the savings range from 1 to 78% with median values of 25% when advanced technologies are available and 13% if conventional technology is used compared to a phase out of nuclear power.
- Building new nuclear power plants is not a cost effective option before 2040, being more expensive than wind and hydro power and coal with CCS. Therefore almost all the cost savings enabled by nuclear power occur in the second half of the century.
- Limiting available nuclear technologies to the currently used LWRs and conventional uranium extraction methods decreases the relative savings in mitigation cost. The cost savings are typically 10 percentage units lower if FBRs and alternative uranium extraction methods are not available. However, the cost benefits provided by expansion of nuclear power compared to a phase out are never completely eliminated.
- The economic benefit from nuclear is very small when the carbon storage capacity is large and the technology available but significant when CCS does not become available at a large scale.

To decide whether to allow for a large scale expansion of nuclear power, the observed cost savings must be weighed against increased risks of accidental radiation releases from reactor operation, waste storage and nuclear weapons proliferation. To make this decision economic as well as non-economic factors should also be considered.

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List of annexes

Annex A
Key parameters in the GET model.

Technology	Starting cost per kW ($ 2010)	Mature cost per kW ($ 2010)	Load factor	Efficiency
Coal PP	1800	1800	0.8	45%
Coal with CCS	3000	2500	0.8	35%
Gas turbine	800	800	0.8	55%
Gas with CCS	2000	1500	0.8	45%
Concentrated solar power (CSP)	12,750	7000	0.7	N/A
Light water reactor (LWR)	7000	5000	0.8	33%
Fast breeder reactor (FBR)	8500	6000	0.8	41%
Wind	2100	1450	0.25	N/A
Solar PV	4500	1400	0.17	N/A

Annex B
Resource costs and potentials in GET model.

	Cost per GJ of primary energy	Amount in EJ (Annual for biomass and total for other sources)		
		HIC	MIC	LIC
Biomass grade 1	2.5	40	20	61
Biomass grade 2	4	23	28	29
Coal grade 1	1.5	7000	4000	2000
Coal grade 2	3	14,000	40,000	10,000
Oil grade 1	4	1600	3900	6500
Oil grade 2	6	2700	1000	1000
Oil grade 3	10	6500	4300	300
Gas grade 1	2.5	1000	4500	4500
Gas grade 2	7	2000	7000	7000
Uranium grade 1	0.07	1479	250	750
Uranium grade 2	0.14	863	798	168
Uranium grade 3	0.23	566	300	477
Uranium grade 4	0.4	3000	3000	3000
Uranium grade 5	1.3	50,000	50,000	50,000

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