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Nuclear power as a climate mitigation strategy – technology and proliferation risk

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Recent years have witnessed renewed interest in nuclear power in large extent due to the need to reduce carbon emissions to mitigate climate change. Most studies of cost and feasibility of stringent climate targets that include nuclear power focus on the currently available light water reactor (LWR) technology. Since climate mitigation requires a long-term commitment, the inclusion of other nuclear technologies such as mixed oxide-fuelled LWRs and fast breeder reactors may better describe the future energy supply options. These different options also entail different nuclear weapon proliferation risks stemming from uranium enrichment or reprocessing of spent fuel. To investigate this relation, we perform a scenario analysis using the global energy transition model. Our results indicate that meeting a scenario with a 430 ppm CO_2 target for 2100 is feasible without the involvement of nuclear power; however the mitigation costs increase by around 20%. Furthermore, a lasting contribution by nuclear power to climate change mitigation can only be achieved by alternative fissile material production methods and global diffusion of nuclear technologies. This in turn bears important implications for the risk of nuclear proliferation for several reasons. First, knowledge and competence in nuclear technology becomes more accessible, leading to the risk of nuclear programmes emerging in states with weaker institutional capacity. Additionally, even if the reprocessing step in a fast breeder cycle proves to be essentially proliferation resistant, the build-up of breeder reactor systems necessitates a long transition period with large-scale use of enrichment technology and its related proliferation risks. Our study does not include the costs posed on society by nuclear accident risk and by the need to upscale safeguards and regulatory capacity to deal with increased proliferation risk.

Keywords: nuclear power; energy system model; nuclear weapon proliferation

Introduction

Recent years have seen growing concern over the possible effects of climate change and the need for immediate action (e.g. World Bank 2012). At the same time renewed interest in nuclear power has been observed among both countries and researchers alike, which the disaster in Fukushima has not significantly curbed (Rogner 2013). The call for an expansion of nuclear power has been to a large extent motivated by the need to reduce carbon emissions to mitigate climate change (e.g. Vaillancourt et al. 2008; Bauer, Brecha, and Luderer 2012). The advantages of nuclear power that are often emphasised are its low lifecycle greenhouse gas (GHG) emissions and base-load power production. To compare these advantages to those of

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other technologies such as carbon capture and storage (CCS) and renewable energy sources, comprehensive model analysis is needed.

Mitigating climate change is a long-term obligation. Considering global cumulative emissions so far, we have likely committed ourselves to a global mean surface peak warming of at least 1 °C above the pre-industrial level (Tanaka and Raddatz 2011). A significant share of anthropogenic CO_2 stays in the atmosphere for more than 100 years. If global warming is to be kept under 2 °C without an overshoot and with a probability of at least 66%, greenhouse gas emissions must drop to less than 20 gigatonnes of CO_2 equivalent by mid-century, continue declining afterwards and eventually stabilise at zero net CO_2 emissions (Rogelj et al. 2011). To this point, most studies of cost and feasibility of stringent climate targets feature only currently available light water reactor (LWR) technology (e.g. GEA 2012). Yet considering the long-term commitment, technologies that are not fully developed can have a significant contribution in the second half of the century, and excluding them portrays a more limited and inflexible world, in contrast to profusely diverse energy needs and available technologies. Therefore, closed nuclear cycle technologies should also be considered.

Even though nuclear power can be an economically competitive source of electricity, it raises other specific concerns such as accident and nuclear weapon proliferation[1] risk and management of radioactive waste. Although having a civil nuclear programme does not mean that a country will automatically pursue nuclear weapons, having enrichment or reprocessing facilities provides a state with the technology to fabricate the critical component of bomb material. If nuclear power is to make a major contribution to mitigating climate change, technologies that can be enabled for weapons development are likely to spread. In this paper, we try to answer two questions rooted in the previously described situation. First, how would the climate mitigation cost be affected by use of different nuclear cycles? And secondly, what would be the potential proliferation consequences of introducing nuclear in the scale needed for a significant contribution to climate mitigation?

Background

Some investigations of the dynamics among different nuclear cycles have been made, the most prominent of recent ones being "The Future of the Nuclear Fuel Cycle" (MIT 2011). This study analysed the dynamics between conventional LWRs, mixed oxide (MOX)-fuelled LWRs and sodium-cooled fast breeder reactors (FBRs). Their analysis showed that the transition from the open fuel cycle to a closed cycle would require 50–100 years, and a scale-up of FBRs is preceded by an expansion of LWR technology. Although this report yields many interesting insights about resource use and relations between different reactor types, it does not assess nuclear power as a part of the global energy system. Since competitiveness among different nuclear technologies will also be affected by dynamics among the other parts of the energy system and the characteristics of the competing technologies, it is important to expand the system boundaries.

Other studies have been performed that assess the role of nuclear in climate mitigation in a global context (e. g. Vaillancourt et al. 2008; GEA 2012; Mori 2012). Here, we briefly discuss four studies that focus primarily on the role of nuclear energy and ask questions similar to those we pose. The main characteristics of these studies are summarised in Table 1.

Table 1. Comparison of previous studies on related topics.

Study	Nifenecker et al. (2003)	Vaillancourt et al. (2008)	Tavoni and Van der Zwaan (2011)	Mori (2012)
Model	–	World-TIMES	WITCH	MARIA
Scope of analysis	Global, 4 regions	Global, 15 regions	Global	Global, 23 regions, focus on Asia
Time horizon	2000–2100	2000–2100	2005–2050	1997–2100
Climate target	Less than 3 GtC emissions per year	450, 550 ppm	450, 550 ppm	CO2 price \$10, 20 and 50; 550 ppm
Advanced nuclear reactors	Yes; breeder reactor, thorium cycle	Yes; high-temperature gas-cooled reactor, fusion reactor	Breeder reactor is assumed to become competitive at \$300/kgU but not explicitly analysed	Yes; breeder reactor, MOX
Proliferation discussed	No	No	General mention	No
Main question	What are the limitations to the expansion of nuclear power under high development scenarios?	What is the penetration rate of nuclear power in climate mitigation context?	What is the relative importance and mutual behaviour of nuclear power and CCS?	What is the cost of phasing out nuclear power under different global warming policies?
Main findings relevant to this paper	Main limitation is resource constraint. Therefore, in large-scale expansion breeders will predominate in the electricity system. Renewables might lessen the share of nuclear if they become competitive.	In all scenarios, nuclear reaches 50% or more of electricity production by 2100. Fusion reactors will enter under stringent climate constraint but are price sensitive. Gas-cooled reactors will not become competitive.	Without growth constraints and under climate mitigation constraint, nuclear renaissance is observed. Technological and economic improvements of CCS are needed to replace significant share of nuclear power.	The higher the carbon price the earlier nuclear power is expanded. With high carbon price FBRs will play a significant role in the later half of the century. CCS and nuclear power are substitute mitigation technologies.

Nifenecker et al. (2003) performed a simple scenario analysis based on an assumed maximum share of nuclear energy in electricity production in 2030 and 2050 to explore the limits of possible nuclear expansion. In their scenarios most uranium resources will be used by 2050, and breeder reactors or uranium extraction from seawater is needed to support continued growth. Breeding with both plutonium and thorium is considered, and since both cycles need the initial creation of fissile material by LWRs, the dynamics are assumed to be similar. Although the paper discusses stockpiling both plutonium and uranium-233, there is no discussion about the associated proliferation concerns. Vaillancourt et al. (2008) analysed the penetration rate of nuclear power and found that it has the potential to supply more than half of global electricity production by the end of the century. A technology-rich model with advanced nuclear cycles was used for this analysis, but the potential effects in terms of proliferation were not analysed. Tavoni and Van der Zwaan (2011) focused on the relation between CCS and nuclear power. They concluded that under climate mitigation constraint, nuclear power will grow if not inhibited by explicit constraints and that further improvements of CCS technology are needed for the replacement of a significant amount of nuclear power. Proliferation was mentioned as a concern but was not discussed in detail, nor were the advanced nuclear cycles analysed. The most recent study, by Mori (2012), combined advanced nuclear cycles and a global energy system perspective, but the question posed dealt with a phase out of nuclear power instead of an expansion. Due to that focus the proliferation risk was not analysed.

As can be seen, none of the previous studies combined the global energy system perspective with analysis of advanced nuclear cycles and explicit discussion proliferation concerns. This paper aims to fill that gap.

Method

We perform this analysis using the global energy transition (GET) model first developed by Christian Azar and Kristian Lindgren (Azar, Lindgren, and Andersson 2003; Hedenus et al. 2010). GET is a cost minimising "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 for the next 100 years with an objective of meeting both a specified energy demand and 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 variables. In addition, resource estimates are included as well as various restrictions on technologies such as a limit for intermittent electricity supply. Resource estimates are based on the GEA (2012). 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 with a stabilisation level of 480 ppm CO_2-eq by 2100 (GGI Scenario Database), whereas the transportation demand scenarios are based on (Azar, Lindgren, and Andersson 2003). The demand is exogenously given and does not vary among scenarios. The discount rate in the model is 5% per year. More information about the model framework can be found in Hedenus et al. (2010).

We use the three-region version of GET, version 8.0, featuring improved representation of the nuclear cycles. The world is divided into blocs referred to as high-income (HIC), middle-income (MIC) and low-income countries (LIC). HIC contain North America, Europe and Pacific OECD countries; MIC cover centrally planned Asia, the former Soviet Union and Latin America; and LIC consist of Africa, the Middle East, South Asia and non-OECD Pacific. To better represent a probable

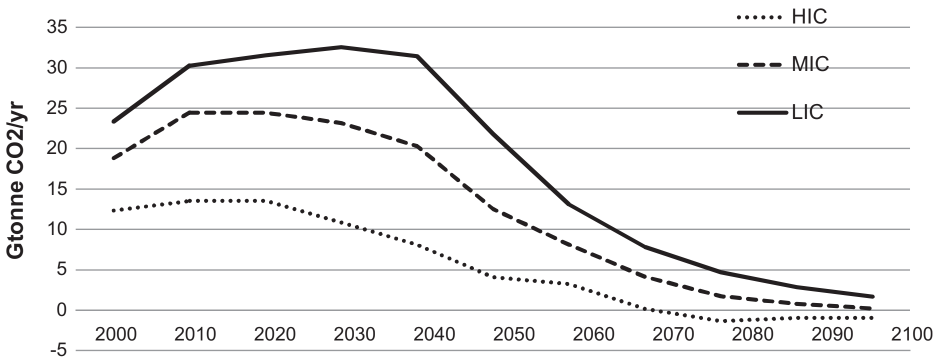

Figure 1. CO_2 emission trajectories by regions. Emissions are shown cumulatively.

abatement path, HIC start to reduce emission by 2020, whereas MIC reduce emissions by 20% and LIC by 10% by 2030 compared to the baseline scenario. Later on, the emissions in MIC and LIC are assumed to decline at a slower rate than in HIC (Figure 1). From 2060, we assume a global cap, and the emissions are allocated among regions in the most cost-effective way.

To further align the model with the real world, efficiency differences were introduced between regions, meaning that the same technologies in LIC are less efficient than in HIC. These differences will converge to the HIC level over time. We also assume that most climate mitigation enabling technologies have not reached their maturity, and therefore the investment costs will decline over time and reach the mature level by 2060. The diffusion of technologies is limited so that no technology can increase or decrease its market share in a specific sector such as electricity or centralised heat production by more than 20% in 10 years; nor can the installed capacity for each technology increase by more than 30% in a year.

Performance and cost of technologies

The main characteristics of the primary supply technologies with low carbon emissions are presented in Table 2. Hydro power is not shown because it has limited expansion possibilities, and its use is maximised at 30 EJ/year globally even without a carbon constraint. Our costs for nuclear technologies are based on the MIT study (2011). We assume that reactor costs given in this study are at the mature level, while the starting costs are somewhat higher, as shown in Table 2. The enrichment,

Table 2. Main characteristics of different electricity production options.

Technology	Starting cost per kW ($2010)	Mature cost per kW ($2010)	Load factor	Efficiency
Coal with CCS	3000	2500	0.8	35%
CSP	12,750	7000	0.7	N/A
LWR	7000	5000	0.8	33%
MOX	7000	5000	0.8	33%
FBR	8500	6000	0.8	41%
Wind	2100	1450	0.25	N/A
Solar PV	4500	1400	0.17	N/A

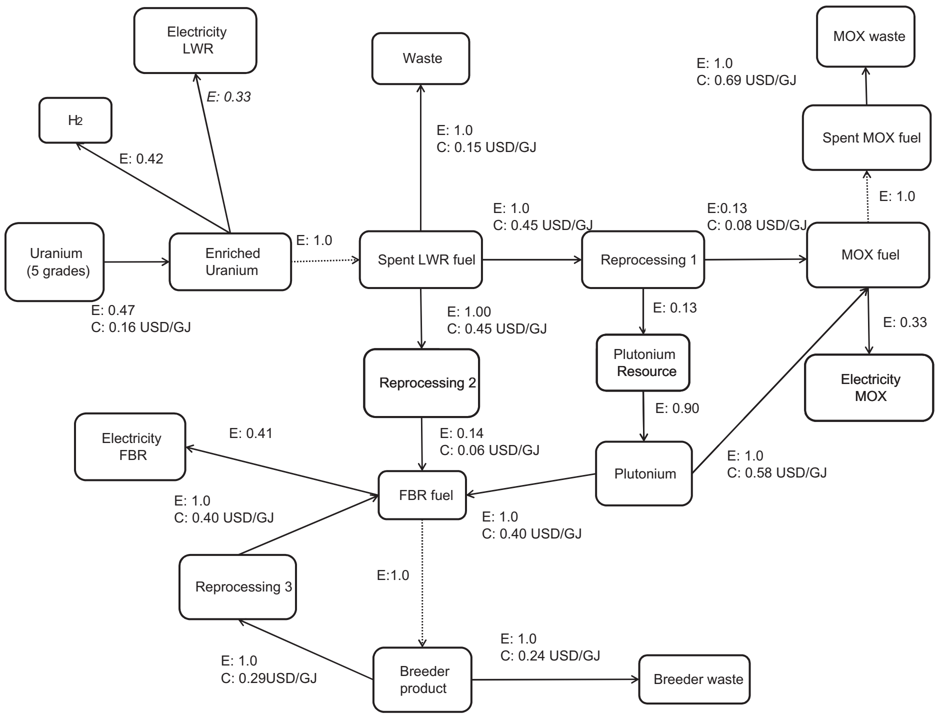

Figure 2. Nuclear cycles in GET 8.0. E signifies efficiency and C cost in USD (2010). Costs are input normalised.

fuel fabrication, reprocessing and waste disposal costs are also taken into account but modelled separately from reactor costs (Figure 2). Wind, concentrated solar power (CSP) and photovoltaic (PV) solar power costs are in line with the International Renewable Energy Agency's (IRENA) cost analysis (2012a, 2012b, 2012c).

The current version of the model includes three different nuclear cycles – LWR, MOX fuel and FBR. In the case of the LWR cycle, natural uranium ore is converted via enrichment into fuel containing 4.5% uranium-235, burned in a reactor once and then disposed permanently. This nuclear cycle is also called the open or once-through cycle. Following its period in a reactor, on the other hand, the remaining fissile materials in fuel, mostly plutonium, can be extracted through reprocessing methods and mixed with uranium-238 to create a second type of usable fuel – MOX fuel. In our model, we assume that MOX fuel is burned only once and then disposed, though technically, albeit at a greater cost, the fuel can be dissolved and isotopes separated for the manufacture of further fuel resources. Extracted plutonium can also be used to start up another reactor type, the FBR, which is designed to produce fissile material that can be used as fuel in FBRs or MOX-fuelled reactors. Nuclear cycles that include reprocessing like the MOX and FBR cycles are often called closed cycles. The FBR, however, needs fuel with a much higher concentration of fissile material; 14% is assumed in the MIT study (2011). As an alternative to plutonium, we assume that uranium enriched to 20% (highly enriched uranium [HEU]) could be used to operate these reactors based on Cochran et al. (2010). This, however, has been tested on a very limited scale. The cost of HEU is assumed to be six times higher than the cost of normal LWR fuel, mainly because of increased intensity in the enrichment effort. The difference in the share of U-235 and plutonium is due to differences in their atomic properties of neutron production as well as fission and absorption probabilities.

The breeder reactor concept has generally only been tested on a limited scale, but breeding ratios above unity, the production of a greater amount of fissile material than consumed, have been achieved in many countries and reactor types (Cochran, et al. 2010). In our model, due to the lack of extensive data related to FBR fuel economy, we assume a breeding ratio of 1 and base our costs on sodium cooled reactors. Other advanced nuclear reactor types have also been investigated, but none have sufficiently reliable cost estimates or have been technically developed to the extent of the sodium cooled FBR (GIF 2012; IRSN 2012).

Since different nuclear technologies are in various development phases, they are allowed to enter the portfolio as available options at different times. LWR technology 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 and is used in some countries, it is only utilised in countries with highly advanced nuclear sectors, though many existing LWRs can burn MOX fuel if licenced. Its use is therefore more dependent on economics and political decisions. Given the development state of this reactor design, FBRs are 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. The schematic representation of nuclear cycles in GET can be seen in Figure 2.

Similar to FBRs, CSP is a technology that still needs further improvements to become competitive. It also needs favourable atmospheric and climatic 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 also during night, which results in a significantly higher capacity factor than solar PV can achieve. To take into account the more demanding nature of CSP in terms of solar radiation, its share in electricity production was limited to 30% in HIC and MIC and to 50% in LIC.

CCS is an abatement technology that can be used in cycles utilising either fossil fuels or biomass, but relatively large point sources are required. There are energy efficiency losses and increased capital costs for carbon capture technologies and, furthermore, additional costs for transport and storage of the captured CO_2. Bioenergy can be used with CCS when co-fired with coal; thus, biomass used with CCS is limited to 20% of the coal that is used with CCS. This assumption is made because of many technical difficulties connected to transport and capture of CO_2 from purely biomass burning plants. In the industrial sector, CCS can only be used at large industrial plants. The level of storage capacity of CO_2 is assumed to be 2000 $GtCO_2$, which is the likely minimal storage capacity level in geological formations estimated by the Intergovernmental Panel on Climate Change's (IPCC) special report on CCS (IPCC 2005).

Weaknesses of the method

Some central aspects of the energy system are not captured in GET and in many other models. First, as demand for different sectors are fixed, no reduction due to rising energy prices takes place, nor any other effects on the overall economy that we would expect to see in the real world. The model also fails to describe actual agent behaviour; including preferences, risk perception and lack of information. The results of the model can be interpreted as a cost-optimal solution under a central world government. Real world solutions are bound to be less efficient, but the model results can still provide direction to mitigation efforts. Furthermore, even though oil is a vital energy carrier, the actual behaviour of the oil market and prices is not captured in the model. The reason for the difficulty in modelling oil prices in a linear programming model like GET is that the extraction cost of oil is low, and other technologies such as synthetic fuel from coal set a price ceiling. Our model aims to describe the long-term equilibrium dynamics and not short-term price volatility, and therefore the cost of oil is based on extraction costs scarcity rent and carbon price. Finally, taxes and policies for local pollutants or energy security are not incorporated. Thus, the GET model represents the energy system in a rather stylised manner. These shortcomings must be kept in mind while interpreting the results.

Nuclear weapon proliferation

The risk of nuclear weapon proliferation from civilian use of nuclear energy stems mainly from two different stages of the nuclear fuel cycle – enrichment and reprocessing. These processes can create fissile material for use in nuclear weapons, and once created, these materials therefore need to be safeguarded against diversion.

Enrichment is a process that increases the share of the fissile isotope uranium-235 from 0.7% in natural uranium, which is composed mostly of uranium-238, to 3–5% to be used in LWRs as fuel. The same process can be used for creating weapons-grade material simply by enriching uranium to much higher levels. The commonly accepted limit of weapon usable material, or HEU, is 20% enriched uranium-235, and material containing more than 90% is called weapons grade. There is no technical fix for proliferation risk stemming from enrichment, and political controls are needed.

In the context of reactor fuel production as opposed to military applications, the purpose of reprocessing is to separate from spent reactor fuel the fissile plutonium that accumulates during reactor operation for further use as a fuel. The separated plutonium can also, however, be used for making weapons and for this purpose is needed in smaller quantities than HEU. Plutonium for purely weapon purposes is typically produced in smaller dedicated reactors with shorter operating periods in the range of a month, which creates a high yield of Pu-239, the most suitable plutonium isotope for creating weapons. During normal LWR operation, on the other hand, other isotopes such as Pu-238 and Pu-240 are formed in significant quantities. These isotopes makes bomb manufacturing more problematic due to high heat generation and spontaneous fissions. These characteristics make the material difficult to handle and may cause the bomb to detonate prematurely, decreasing the yield of the weapon significantly (Kessler 2011). Therefore, the main barrier against proliferation is controlling the plutonium isotope composition. According to Kessler (2007), 6–8% of Pu-238 is sufficient to make material non-weapon usable.

One of the most studied breeder designs, FBRs with blankets of U-238, produce plutonium with a very low share of Pu-238 (0.01%) (Meiliza, Saito, and Sagara 2010), which poses a major proliferation concern. Meiliza, Saito and Sagara (2010) argued that mixing minor actinides into the blanket could increase the share of Pu-238 to as much as 18%, which would impair bomb manufacturing through the mechanisms described earlier. No general agreement, however, on the proliferation resistance stemming from plutonium's isotopic combination has been reached. For example, Marka (1993) claimed that the technical difficulties involving reactor-grade plutonium are of the same type as for constructing a bomb from weapons-grade plutonium. Kessler et al. (2008) in turn argued that only nuclear weapon states have the technical capacity to construct bombs with spent nuclear fuel, and therefore diffusion of reprocessing technology to non-nuclear weapon states should not cause proliferation concerns.

To provide an extra measure against possible material diversion and use for weapons, alternative reprocessing methods have been proposed that would simultaneously extract other transuranic elements together with plutonium, making the separation of plutonium more difficult (IAEA 2008). Von Hippel (2001) claimed that even with these technologies, a cessation of reprocessing will always be more proliferation resistant because plutonium can be separated from the reprocessing product with extra effort and because of the protection that highly radioactive fission products provide against material diversion. Nevertheless, it has been assumed that some nuclear cycles that include reprocessing can provide an early warning of weapon assembly intentions and can thus be employed with a high level of confidence if a robust safeguards regime is in place (Yim 2006).

To summarise, although several different methods for making reprocessing of plutonium more proliferation resistant have been proposed, we still do not know to what extent these proposed technologies will be used in the future and if they will succeed in their goal of making nuclear weapon acquisition difficult.

Scenarios

In this paper, we compare six climate mitigation scenarios that have different availability of nuclear cycles and resources (Table 3). All scenarios reach the 2 °C target with an assumed climate sensitivity of 3 °C, which corresponds to a CO_2 concentration level of approximately 430 ppm CO_2 by 2100. The emission trajectory was generated with GETClimate, which is a GET version with an integrated climate model (Azar, Johansson, and Mattson 2013).

The first scenario, called full nuclear, represents a world in which a full commitment to exploit all nuclear cycles at a global scale has been made. It assumes that public acceptance is not a problem and that all nuclear technologies are available for large-scale global adoption as specified in our methodology section. In the second scenario called optimistic FBR, we take this worldview even further and assume that technological advancement of FBRs will be greater than expected such that a breeding ratio of 1.2 can be achieved with a mature cost that is 500 USD lower than in the standard scenario. Also, using HEU for starting FBRs is allowed in this scenario. In the third and fourth scenarios, no HIC and no LIC, we limit the spread of nuclear technology regionally by forbidding the building of nuclear power plants in HIC and LIC after 2020, respectively. The motivation for restricting nuclear in HIC is an unfavourable public opinion to nuclear in many of these countries, especially after the Fukushima accident. The prime example is Germany, whose government decided to phase out nuclear after the accident. The constraint in the no LIC scenario is motivated by proliferation concerns. This region contains a large number of countries with unstable political institutions that may not be able to guarantee the safety of nuclear material or may assist militant actors seeking to acquire nuclear weapons.

Table 3. Scenarios.

Scenario	Nuclear cycles allowed after 2020	Regions where nuclear power is allowed	Additional constraints and/or changes
Full nuclear	LWR, MOX, FBR	All	None
Optimistic FBR	LWR, MOX, FBR	All	Breeding ratio 1.2 Mature cost of FBR $5500/kW HEU start-up allowed
No HIC	LWR, MOX, FBR	MIC, LIC	None
No LIC	LWR, MOX, FBR	HIC, MIC	None
Limited technology	LWR, MOX	All	No uranium production from seawater or other alternative resources
No nuclear	None	All (until 2020)	None

Thus, the fourth scenario represents a case when technology is not made available for such countries. The fifth scenario explores limited technological development. In this scenario called limited technology, uranium extraction from seawater or other alternative sources is not available and resource base therefore reduced. It is also assumed that FBRs will never become a feasible electricity production option and only LWR and MOX options that exist today can be used in the future. In the last scenario we assume that due to the risks associated with nuclear power, a global phase out will take place. Specifically, building new nuclear power plants will be forbidden across the world after 2020, and the use of existing plants for electricity production will cease after 2040. This scenario is called no nuclear.

Results

Costs

We define the abatement cost as the difference between the given scenario's cost and the cost of the baseline scenario in which there are neither carbon constraints nor restrictions on nuclear power deployment. Figure 3 shows the abatement cost for different scenarios in comparison with the no nuclear scenario. As can be seen, even though reaching the climate target without employing nuclear power is possible, the abatement costs increase considerably. Our results indicate that allowing nuclear to expand would reduce the mitigation cost by around 22% compared to the nuclear phase out scenario. Employing advanced nuclear technologies like the FBR and seawater uranium extraction can reduce the cost even further than merely expanding the fleet of LWRs, as demonstrated by the difference between the full nuclear and limited technology scenarios. Limiting regional availability has an effect that is around 3–4% on cost, slightly more so when nuclear is not allowed in developing countries. However, this effect is relatively small compared to not allowing any nuclear expansion.

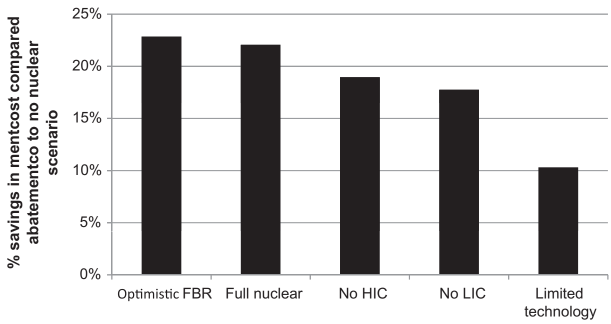

Figure 3. Savings in abatement costs for scenarios over period of 2000–2150 compared to no nuclear scenario.

Future composition of electricity production

In all scenarios, the share of coal and oil without carbon capture will diminish significantly by 2050 (Figure 4). It is largely replaced by new capacity with CCS. The year 2100 also sees a reduction of the share of CCS technologies in all scenarios due to more stringent emission goals except for the no nuclear scenario, in which the share stays similar to 2050 (Figure 5). In cases of a phase out of nuclear power or its limited availability, the role of solar energy is significantly enhanced. Similarly to hydro power, wind power is developed in all emissions-constrained scenarios and will reach levels above 70 EJ of electricity production by 2100. The introduction of FBRs is preceded by upscaling of LWRs. This is due to the need for providing FBRs with initial material. In all scenarios in which FBRs are allowed, they will be employed on a significant scale in the second half of the century reaching 16–27% of electricity supply by 2100. Although HEU start-up is allowed in the optimistic FBR scenario, it is not economically attractive, and a slightly larger share by FBRs is achieved via the increased breeding ratio. MOX fuel never becomes economically attractive.

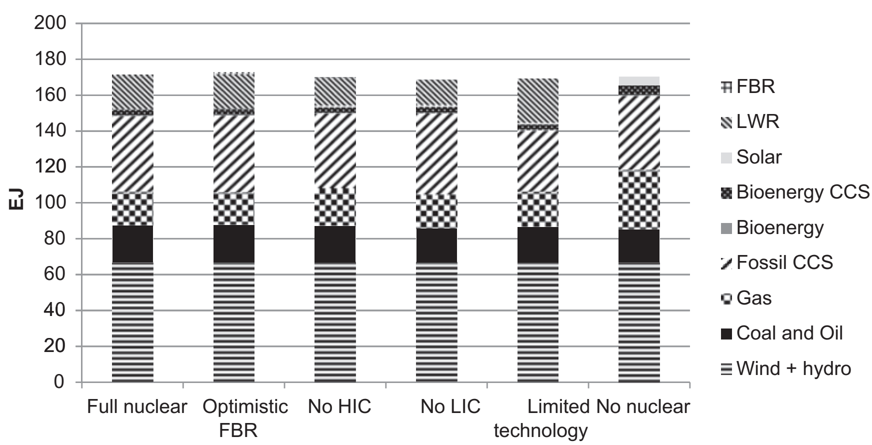

Figure 4. Electricity supply composition in 2050.

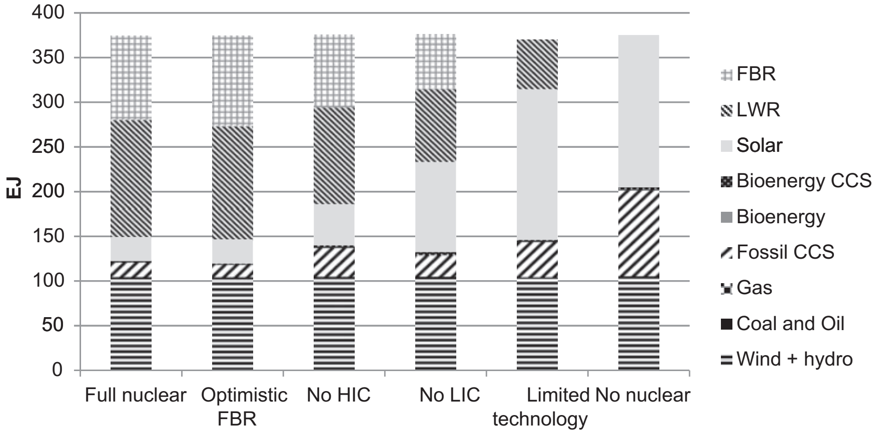

Figure 5. Electricity supply composition in 2100.

The expansion of the number of nuclear facilities

All scenarios except a complete nuclear phase out see a significant increase in the number of reactors needed (Figures 6 and 7).[2] Currently about 400 nuclear reactors operate for electricity production in the world (Rogner 2013). In these scenarios, the number of nuclear reactors increases twofold by 2050 if 1 GW of electricity capacity is assumed per reactor. By the end of the century more than a 20-fold increase is reached in some scenarios. Expansion on this scale is only thinkable with universal political support.

If FBRs do not become available and uranium resources are limited, then the number of reactors decreases again after an initial expansion. This indicates that for a long-term large-scale climate mitigation contribution from nuclear power, either advanced reactors or novel uranium extraction methods are seemingly required. Similar dynamics can be observed also on a regional level (Figure 7). Due to the stronger increase in electricity demand in LIC, the expansion of nuclear reactors is most prominent in this region.

Given the expansion of the nuclear fleet, the enrichment facilities providing fuel for LWRs must also increase in number (Figure 8). This increase will be relatively

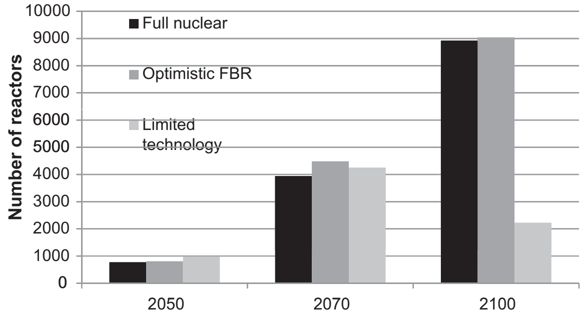

Figure 6. Number of reactors assuming 1 GW_e capacity per reactor.

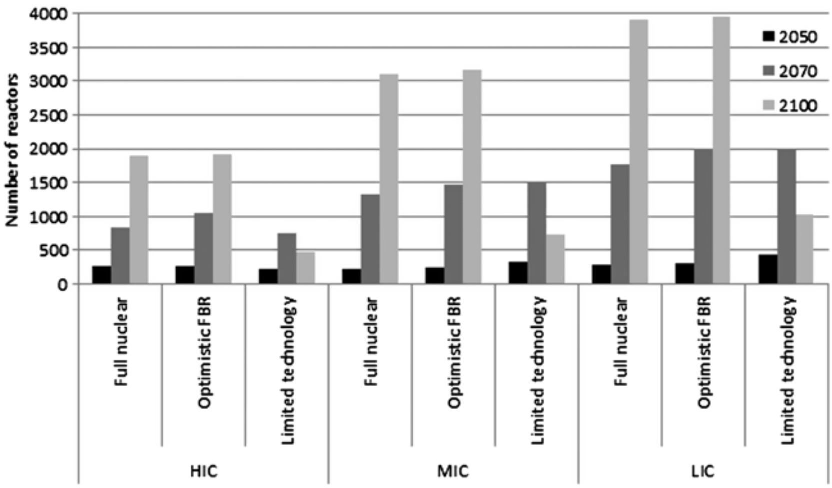

Figure 7. Regional distribution of reactors assuming 1 GW_e capacity per reactor.

small by mid-century. It would suffice if 5 of the 12 current facilities are upgraded to the capacity of the largest existing commercial enrichment plant, which has a capacity of producing 1780 tonnes of 4.5% enriched LWR fuel per year (NFCIS 2013). Using the aforementioned plant as a reference we find that in our nuclear scenarios 25–35 enrichment plants would be needed globally by 2070, making probable at least a doubling of the current number. Due to political issues, some countries may want to operate their own plant rather than participate in a shared facility. In this case, the number of enrichment plants can be even higher. Using the current commercial average plant capacity, which is 600 tonnes of LWR fuel production per year (NFCIS 2013), our scenarios project about 75 enrichment facilities globally by 2070 for the full nuclear and optimistic breeder scenarios. This number increases more significantly in the limited technology scenario and reaches 105 average size facilities by 2070. By 2100, however, this number is reduced to 55 in the limited technology scenario as the world exhausts its uranium resources. In both the full nuclear and the optimistic FBR scenarios, the number increases throughout, reaching about 125 average size facilities. Although both of these scenarios see an expansion of FBR technology, the need for start-up fuel causes the continued use of the LWR cycle. This is also true for the optimistic breeder scenario. Although some of the start-up material is provided by the FBRs themselves and HEU fuelling is allowed, LWR spent fuel stays economically preferable for expansion. HEU is not used due to high costs associated with enrichment and increased resource requirements.

Similarly, the number of reprocessing plants increases in all nuclear scenarios, except the limited technology scenario where reprocessing is not allowed. The number of reprocessing plants will stay low by mid-century because closed fuel cycles are employed later. Using the current average processing capacity of the five commercially operating reprocessing plants in the world, 1000 tonnes of heavy metal per year (NFCIS 2013), we calculate that 90–145 reprocessing plants would be needed by 2070 in scenarios in which FBRs are allowed. By 2100, 400–425 plants would be needed. This large increase is caused by the technology shift to the closed fuel cycle triggered by the depletion of low cost uranium. Since reprocessing is

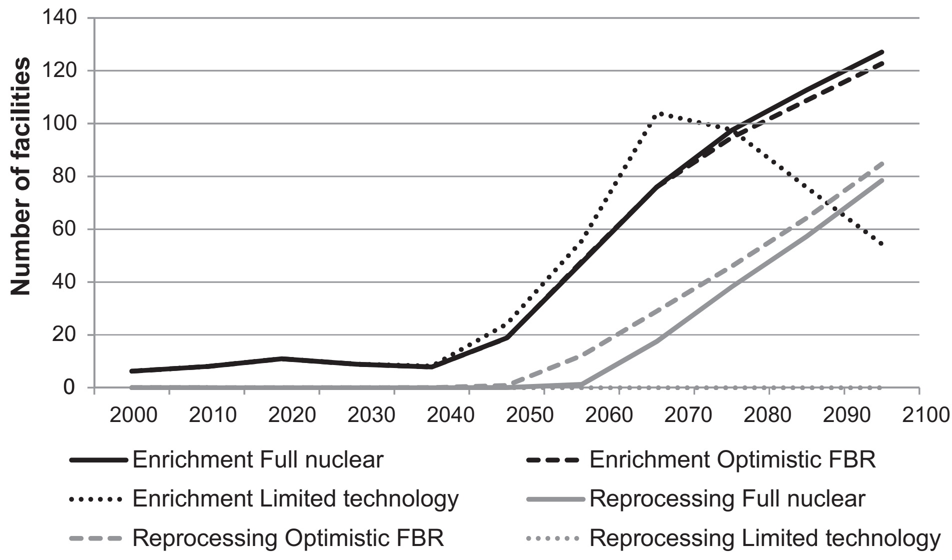

Figure 8. Number of enrichment and reprocessing facilities needed assuming capacity 600 t of LWR fuel per year for enrichment and 5000 tHM/year for reprocessing.

currently uncommon in the nuclear industry, we can assume that significantly larger plants could be built in relation to the upscaling of nuclear power. In Figure 8, we assume that future plants are on average five times larger than the current average plant. But since the same political incentives apply as in the case of enrichment, a large number of plants is not implausible.

Discussion

Our scenarios see a large increase of nuclear facilities in all scenarios in which nuclear power is allowed. This result, however, depends heavily on cost assumptions of nuclear reactors and other main technologies. Still, sensitivity analysis (not presented here) shows that nuclear expansion can be expected in this cost-minimising framework for a rather large interval of technology costs.

Nevertheless, if a nuclear expansion of this magnitude is realised, increased risk of nuclear weapons proliferation could result. First, it must be acknowledged that no inevitable connection exists between using civil nuclear power and acquiring a nuclear bomb. Many countries in the world possess long-standing civil nuclear programmes and technical capabilities to manufacture a bomb but no nuclear weapons ambitions. There are many competing theories of why states decide to acquire a nuclear weapon. Some emphasise security reasons (e.g. Mearsheimer 1990; Paul 2000), others focus on norms and prestige issues (e.g. Sagan 1999; Rublee 2009). In reality both of these reasons may play a role. Once the decision has been made, however, having the technical capability and fissile material will shorten the time it takes to assemble a nuclear weapon considerably (Sagan 2011). In a world containing states with the political ambition to build atomic weapons, the presence of a civil nuclear programme makes it easier both to obtain a bomb and to hide a bomb construction effort from the international community. Also, the presence of technology and nuclear material may lead to proliferation to a sub-national group, even though the likelihood may be small due to the technical and economic obstacles.

As mentioned before, the proliferation risk stems from two processes in the nuclear cycle, enrichment and reprocessing. For nuclear power to play a major role in mitigating climate change, it must be employed at a large scale globally throughout the century, and therefore the geographical spread will likely increase. This means also that more countries will have access to materials required for producing a nuclear bomb, making more probable the pursuit of nuclear weapons and sale of sensitive materials, technology or knowledge to other countries or groups interested in nuclear weapons. These problems can be significantly alleviated with centralised and United Nations' controlled fuel production facilities and depositories or even centralised and internationally controlled electricity production. Even though both ideas are far from new, they have found limited political support (Leventhal, Tanzer, and Dolley 2002; IAEA 2005).

Employing nuclear power at a large scale and in many countries also means that related material flows will increase. Even without a dedicated weapons material production programme, states can stockpile these materials by diversion of small amounts that are difficult to track. Without strict security measures and safeguards, a world with more sources enables diversion of materials from different facilities.

Increases in either the quantity or location of nuclear facilities entails that more people will be employed in power, enrichment and reprocessing plants, but also in factories providing components for plants, meaning that nuclear-related knowledge will be more widespread than today. This could create a broad market of people with the crucial knowledge for manufacturing a nuclear weapon (Langewiesche 2008).

The risks associated with reprocessing depend largely on the plutonium isotopic composition and the method used. Creation of various mixtures unsuitable for making a bomb is theoretically possible. Proliferation resistance of reprocessing also depends on how easily the process can be converted to extract weapon-usable materials. The use of LWR technology, however, requires enrichment and therefore will remain a proliferation concern in any case. Our analysis show that even in the most optimistic fast breeder scenarios, enrichment is prevalent at a much higher level than today. Thus, even if a fast breeder system renders enrichment obsolete in the long term, the transition period of large-scale enrichment facilities extends for more than 100 years. Thus, even if it is possible for reprocessing to become proliferation resistant, our results show that strong proliferation concerns remain with the FBR system during a long transient period. Also worth considering is that if a swift switch to the FBR cycle was to occur, many people associated with the enrichment cycle would likely lose their job, creating the conditions for an extensive supply of knowledge and skills that can be bought by countries or groups interested in creating a nuclear weapon.

Conclusions

From our model analysis of nuclear energy as a mitigation strategy, we can draw the following conclusions:

- Nuclear power is likely to reduce the cost of reaching a stringent climate target compared to a global decommissioning of nuclear power.
- A large-scale mitigation effort through nuclear power requires either uranium

extraction from seawater or FBRs; otherwise nuclear expansion is likely to be limited by resource constraints by the end of the century.

- To harvest the aforementioned benefits of nuclear, the number of reactors and enrichment facilities must increase approximately 10-fold by 2070.
- Even in a future with large-scale FBR employment with proliferation resistant reprocessing, large-scale enrichment capacity remains at the beginning of the next century.

These results are subject to several limitations. In addition to constraints related to the modelling approach discussed in the methodology section, large uncertainties exist in relation to the cost of new technologies as well as the time they become commercially available. Although we have addressed some of these uncertainties, we have not captured all future possibilities. In the next 100 years new technologies that change the cost structure of the energy system may emerge, creating a renewed need for scenario analysis. Alternatively the cost of nuclear technologies might prove to be significantly different than assumed here.

Furthermore, our study does not include the costs posed on society by nuclear accident risk and by the need to increase safeguards and regulatory capacity to deal with increased proliferation risk. These costs are likely to reduce the projected economic benefits from nuclear power but require further analysis to be quantified.

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We would like to thank Christian Azar, Kristian Lindgren and Niclas Mattson for their insightful comments and suggestions and also E.ON for funding this research project.

Notes

1. In this article, we use the terms nuclear weapons proliferation and proliferation synonymously.
2. From here on we omit the results of no HIC and no LIC scenarios from graphs for better visual clarity. The results of these scenarios are always between the results of limited uranium and full nuclear scenarios.

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