THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

Nuclear power as a climate change mitigation option: A modelling approach

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Division of Physical Resource Theory

Chalmers University of Technology

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ABSTRACT

Although nuclear power can provide electricity with very low life cycle carbon emissions and thus reduce the cost of climate change mitigation, it also brings along many specific challenges: accident risk, need for radioactive waste management and nuclear weapons proliferation risk. Due to this controversial nature nuclear power, among other energy forms, has been relatively little studied in a climate mitigation context. This thesis aims to provide some insight into the possible role of nuclear power in climate change mitigation.

In the first paper we assess the impact of potential nuclear expansion and advanced nuclear cycles on climate change mitigation cost and reflect on this expansion's relation to nuclear weapons proliferation risk. We find that nuclear power can reduce the mitigation cost around 20%, and new reactor types and advanced uranium extraction methods provide a significant part of the savings (10%). To materialize those savings however the number of reactors would need to increase tenfold by 2070, which implies an increase in enrichment and/or reprocessing facilities, technologies that are directly related to proliferation risk. We show that even if reprocessing can be made proliferation safe as some scientists believe, the switch to a closed fuel cycle that does not need enrichment will take more than the remainder of this century under a cost minimising condition, and therefore proliferation risk cannot be eliminated.

In the second paper we investigate further the mitigation cost reducing ability of nuclear power by subjecting our model to numerous parameter variations and a Monte Carlo analysis. We observe that nuclear power can provide significant cost savings in almost all cases and that the expansion of nuclear power is dependent on climate policy. In addition we discovered that the capacity for carbon capture and storage plays a significant role in cases of a nuclear phase out and high climate sensitivity but is inconsequential if nuclear expansion is allowed.

Keywords: nuclear power, climate change, energy system model, nuclear weapons proliferation, sensitivity analysis, CCS

List of Publications

I. Mariliis Lehtveer and Fredrik Hedenus, "Nuclear Power as a Climate Mitigation Strategy – Technology and Proliferation Risk", *Journal of Risk Research* **Submitted for publication**

II. Mariliis Lehtveer and Fredrik Hedenus, "Will Nuclear Power reduce Climate Mitigation Cost? – Critical Parameters and Sensitivity" **Working paper**

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Göteborg, December 2013

Mariliis Lehtveer

CONTENTS

INTRODUCTION

BACKGROUND

Recent years have seen growing concern over the possible effects of climate change, as human activity has significantly changed the composition of the atmosphere. The atmospheric carbon dioxide (CO_2) concentration had increased to 390 parts per million (ppm) in 2011 from a pre-industrial level of 280 ppm, while at the same time observation of the global average temperature has identified a warming trend, which is likely the cause of severe weather events and potent changes in climate systems [1]. Scientist strongly agree that the warming effect, in turn, is caused by elevated concentrations of CO_2 and other greenhouse gasses (GHG) [1].

Considering global cumulative emissions so far, humanity has likely committed itself to a global mean surface peak warming of at least 1ºC above the pre-industrial level [2]. But as emissions continue to increase, much more drastic warming can be expected. The Intergovernmental Panel on Climate Change (IPCC) estimates that the doubling of the pre-industrial CO_2 level will lead to an average global peak warming between 1.5–4.5°C. Some future projections do not exclude scenarios in which the CO_2 concentration reaches as much as 1000 ppm by the end of the century – more than 3 times the pre-industrial level [3]. This resulting temperature change will affect weather systems and lead to alterations in ecosystems. At the same time sea levels are expected to rise due to the melting of ice in Greenland and Antarctica as well as the expansion of water as it warms [1]. These effects are likely to cause considerable social and ecological damage. Thus growing concern has emerged, and many have called for immediate action [e.g. 4].

Mitigating climate change, however, is a long term obligation. A significant share of anthropogenic CO_2 stays in the atmosphere for more than 100 years. Scientific models have estimated that if global warming is to be kept under 2°C without an overshoot and with a probability of at least 66%, GHG emissions must drop to less than 20 gigatonnes of CO_2-equivalent annually by mid-century, continue declining afterwards and eventually stabilise at zero net CO_2 emissions [5]. The global energy system, including heat and electricity production and transport, is the largest source of anthropogenic GHG emissions and therefore the main target for emission reductions. These emissions can be reduced in two ways: by either reducing energy consumption e.g. via efficiency improvements or by switching to technologies with smaller GHG emissions.

Many possibilities exist for producing energy with low life time emissions such as the use of biomass, wind, solar and nuclear power. Alternatively emitted CO_2 can be captured and stored in suitable geological formations. Clearly no single technology will be sufficient to completely solve the problem, and likely expansion of many if not all is needed [6]. As a consequence concern about climate change has also renewed interest in nuclear power. The aim of this thesis is to contribute to the understanding of the possible role nuclear power can play in climate change mitigation.

OVERVIEW OF NUCLEAR POWER

Currently nuclear power provides about 14% of the global electricity supply with an installed capacity around 370 GW_e in 29 countries. Most of the capacity is placed in Europe and the US. Additions to capacity have been relatively few in the last decade, and the growth in output has been mainly achieved by improving load factors [7]. As of 2010 61 countries had asked the International Atomic Energy Agency for advice on building their first nuclear reactor, but expected additions remain low and assumedly will mostly occur in Asia [8].

Studies have shown that nuclear power may help to mitigate climate change due to its very low life cycle GHG emissions [e.g. 9]. These emissions are indirect, meaning that they are not caused by nuclear energy production directly but by activities needed for building power plants, mining and transporting uranium, etc. Most of these emissions could therefore be removed by decarbonising other sectors such as transport and power production. Nuclear power can provide base load power with low life cycle emissions and can also be up-scaled significantly. In addition nuclear power can enhance a country's energy supply security because nuclear fuel is very energy dense, meaning that a small volume of fuel contains a large amount of energy, and can thus be easily stored at the reactor site at low cost. Nuclear energy, moreover, is not highly sensitive to fuel cost, as the price of uranium comprises only about 5% of the electricity cost; therefore fluctuations in uranium ore prices will not affect the electricity price significantly.

Although nuclear power has advantages, it also comes with challenges such as high investment cost, long building times and large increments that make it unsuitable for smaller grids or less wealthy countries. In addition nuclear power has a specific set of risks attached that clearly distinguishes it from other power production options. This set includes radioactive contamination risk, radioactive waste management and nuclear weapons proliferation risk.

Nuclear power is produced by the fissioning of very heavy nuclei such as uranium-235 and plutonium-239. This process is induced by absorption of a neutron and results in the release of two or three neutrons, two fission products and an amount of energy. If the concentration of fissile material is sufficient a chain reaction can occur, producing a continuous flow of energy. In the fission process energy is released mostly in the form of kinetic energy (heat), and this energy is converted to electric power via heated water and steam turbines. Many different reactor designs have been developed to make use of nuclear energy. The most widespread is the light water reactor (LWR) that uses uranium-235 as fuel and light water as a moderating medium to slow neutrons to suitable speeds to cause fission and also for transferring heat for the production of steam. Other media can be used for moderation, such as heavy water and graphite, and heat transfer, such as molten salts and metals.

Fissioning of heavy nuclei results in isotopes that are not stable and will continue decaying over a long period of time, releasing radioactivity with each incident. Also created by neutron absorption are new elements that are unstable due to their size and decay over time into more stable elements. This process takes tens of thousands of years for some isotopes and poses a threat to living organisms via direct radiation damage or increased risk of cancer. Radiation can also make vast areas of land uninhabitable for decades as is the case with the Chernobyl Nuclear Power Plant accident, which contaminated 3000 km^2 [10]. The causes for radiation release can vary from design errors and operation mistakes to force majeure and deliberate intervention during safety procedures. Since the first generation of nuclear power plants reactor designs and operating practices have been improved by inclusion of more passive safety measures and learning via simulations, yet constant vigilance and also active security measures are needed [e.g. 11].

Related to radioactive contamination risk is the waste disposal issue. Due to its high radioactivity for thousands of years, spent nuclear fuel must be isolated from the biosphere or converted into a less dangerous form. Since current transmutation technologies still require the resulting product to be stored for at least 1000 years, building long term repositories seems inevitable. Yet there has been little progress. Siting such repositories has proven to be difficult due to opposition from local inhabitants and various non-governmental organizations. Although geological disposal is widely believed to be adequately safe, definite proof of its reliability over tens of thousands of years cannot be given. At a preliminary stage, locating a long term repository seems to have been more successful among countries that have used a consultive approach such as Finland and Sweden [7].

Nuclear weapons proliferation risk stems from two processes in the nuclear fuel cycle. Enrichment of uranium to increase the share of the fissile isotope uranium-235 and reprocessing of spent fuel to separate fissile material, especially plutonium-239, have historically been utilized for accruing weapons grade materials. Uranium that is found in nature consists mostly of uranium-238, which is not easily fissioned. Only 0.7% of natural uranium is uranium-235, which for water moderated reactors must be increased through enrichment to a sufficiently high concentration to sustain a chain reaction. If U-235 is too dilute free neutrons will be absorbed by non-fuel materials and fail to cause new fissions, thereby halting the chain reaction. The usual concentration of uranium-235 in reactor fuel is between 3–5%. Nuclear weapons exploit the same chain reaction but instead of constant power output rely on explosive increase. To achieve this uranium-235 must be enriched to much higher concentrations, typically 90% or more. The problem from the nuclear weapons proliferation point of view is that the same process can be used for both making reactor fuel and nuclear weapon material. The latter simply requires more time and political determination.

Spent reactor fuel contains a significant amount of fissile material — about 1% of uranium-235 that does not undergo fission and about 1% of plutonium created by neutron absorption. These materials can be separated and used as fuel for other reactors through reprocessing, in which the fuel is dissolved and various isotopes are partitioned. This is an expensive process that requires the uranium ore price to increase from around US $80 today to about US $300–500 per kg to be economically attractive compared to burning uranium once and then disposing of the resulting waste [e.g. 12, 13]. Additionally the separated material can also be used for weapons production. Smaller quantities of plutonium are needed to produce a nuclear weapon, although it is significantly more difficult to handle than uranium, and therefore a much higher technology level is needed for producing a plutonium based weapon. The most widely used LWR technology is considered mostly proliferation safe if the fuel is not reprocessed. Spent fuel has high radioactivity that makes it difficult to handle and separate fissile materials. Also proliferation risk stemming from enrichment is believed to be politically manageable via multinational agreements or a UN governed enrichment facility [14], yet there has been little movement on this issue.

As a measure to reduce the amount of waste and burn plutonium, mixed oxide fuel (MOX) consisting of both uranium and plutonium oxides has been proposed. This fuel can make use of the fissile material separated from spent fuel or previously extracted plutonium under military programs. However, this approach has not been economically interesting and also poses proliferation concerns, as plutonium could be separated before recycling into MOX fuel and possibly diverted.

Misled assumptions during the early years of the nuclear age about uranium resource scarcity sparked research in breeder reactors — reactors that can create more fuel than they consume. For this to happen, a surplus of free neutrons that can be absorbed in uranium-238 for conversion into plutonium is necessary. Alternatively thorium could be used to create another fissile isotope, uranium-233, and therefore the resource base would be even further increased. The surplus of neutrons is achieved by disposing of a moderator and using coolants that have low neutron absorption characteristics such as molten salts and metals. This, however, makes the technology technically more complex. 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 [15]. Uranium-233, additionally, has never been used for commercial electricity production. Therefore its use necessitates new reactor designs and testing. Similarly to MOX fuel reprocessing is an integral part of the breeder fuel cycle, and therefore the risk for nuclear weapons proliferation is notable. However, if reprocessing can be made proliferation resistant as some scientist believe [16], this fuel cycle renders enrichment obsolete in the long term.

METHOD

MODELLING ENERGY SYSTEMS

Using models is much more common than most people think. In fact we use models every day while making decisions. We consult not the real world but our mental images of that world, our ideas of relations that hold in this world and the believed consequences of our actions. As Sterman [17] puts it: “Mental models are the filters through which we interpret our experiences, evaluate plans, and choose among possible courses of action. The great systems of philosophy, politics, and literature are, in a sense, mental models.” But those mental models are often opaque for others or even for the person himself. They can contain contradictory beliefs and biases in addition to limitations in the number of factors they can take into account [18]. As a result our decisions are often incorrect or suboptimal. In theory computer models can improve our decisions by making the assumptions explicit, including more factors and infallibly calculating the logical consequences of the given assumptions [17].

The first steps to use models to study energy and environment related issues were taken in the early 70s by Meadows et al. and resulted in publication of “The Limits to Growth” [19]. Innovative numerical approaches to energy, resource and environmental economic analysis were also taken by Nordhaus [20] and Manne [21] for example. Many models have been developed since, and although they have increased in size and complexity as the available computing power has increased, the underlying theory and conceptual modelling approach has not changed much.

Energy-Environment-Economy (E3) models are used for various purposes. Hedenus et al. list the five most common aspects addressed by energy systems models in a climate context:

- Cost of climate stabilization
- Feasibility of climate targets
- Burden sharing and timing
- Role of technologies

- Exploration of possible futures depending on population growth, economic development, etc.

Many mathematical approaches are used today to investigate climate related questions. The models range from dynamic optimization models like MERGE [22], MESSAGE [23] and GET [24] to policy simulation models like TIMER [25]and general equilibrium based models like IGSM [26].

Dynamic E3 optimization models are well based in mathematical theory. In general the objective is to maximize aggregated welfare or minimize aggregated cost under a given set of assumptions and constraints such as available energy resources, allowed emissions, need to meet the demand etc. Some of these models capture the effect of climate policies on the whole economy via subsequent price changes e.g. MERGE; others cover only a part of the total economy e.g. GET. Modelling only a part of the whole economy allows for a more detailed description of relations within that sector and easier interpretation. This approach can also be theoretically justified if the partial market is small in relation to the whole economy.

GET MODEL

We perform energy system analyses by using the Global Energy Transition (GET) model first developed by Azar and Lindgren [24] and further improved by Hedenus et al. [27]. 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 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. In our analysis we use the three region version of GET, version 8.0, featuring improved representation of the nuclear cycles. In addition to the LWR fuel cycle also MOX and fast breeder reactor (FBR) options have been added. The regionalised version is used to allow more realistic carbon trajectories but also to analyse restricting the spread of nuclear technologies.

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 stabilization level of 480 ppm CO_2-eq by 2100 [28], whereas the transportation demand scenarios are based on [24]. The demand is exogenously given. The model also has perfect foresight and thus finds the optimum for the whole study period. Scarce resources such as oil and biomass are allocated to sectors in which they are used most cost effectively.

Some central aspects of the energy system are not captured in GET. First, as demand for different sectors is 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 thus be interpreted as a cost optimal solution under a central world government or as an ideal market with ideal policy instruments. 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 are 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. The 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 world energy system in a rather stylised manner. These limitations must be kept in mind while interpreting the results.

PREVIOUS STUDIES

The question of what role can nuclear power play in mitigating global warming is more than two decades old [29], yet no definitive answer has been reached. Most studies that have attempted to estimate the role of nuclear power in climate mitigation have been qualitative. Pasztor [29] discusses waste, nuclear weapons proliferation and public acceptance issues and concludes that these challenges make nuclear expansion unlikely in the short term and therefore its ability to mitigate climate change is limited. Mez [30] finds that nuclear power expansion on a scale needed to mitigate climate change is unlikely due to a lack in industrial capacity to provide such a number of power plants. He also argues that increased emissions from mining and transporting uranium ore due to the need to use lower grade resources will offset the direct emissions reductions. This claim, however, is based on the questionable assumption that mining and transport sectors cannot be decarbonised.

In contrast Sailor et al. [31] find that nuclear power can play a significant role in climate change mitigation and that there are no insurmountable technical barriers to nuclear expansion. Van der Zwaan [32] finds the life cycle emissions of nuclear power to be on par with renewables and claims further reductions to be likely as the carbon intensity of the electricity portfolio declines. Socolow and Glaser [13] argue that nuclear power will not necessarily benefit from global climate policies. Although such policies would handicap fossil fuels, they promote renewable energy and efficiency. It has been shown that even stringent climate targets can be achieved without nuclear power expansion [e. g. 33, 34, 35]. Therefore nuclear power is not essential to climate change mitigation, yet it can provide significant cost reductions [35-37]. It is clear that for a meaningful assessment of the role of nuclear power, it must be placed in the context of the global energy system.

Few studies have attempted to analyse nuclear power from a systems perspective. Vaillancourt et al. [38] studied the penetration of nuclear power with the technology rich World-TIMES model under two different climate scenarios and under various constraints on nuclear power development. They find significant expansion of nuclear power throughout the century in all cases. Renewables are claimed to need further cost reductions to penetrate the market in a significant quantity. More recent studies by Mori using the Integrated Assessment Model (IAM) MARIA [36] and by Bauer et al. using IAM ReMIND-R [37] reported losses up to 1.9% of GDP by 2100 resulting from early retirement or a phase out. In addition Mori finds CCS and nuclear power to be substitute mitigation technologies, whereas renewables cannot completely compensate for restrictions on nuclear technology. Tavoni and van der Zwaan [12] also analyse the relation between CCS and nuclear power under a climate mitigation condition. Similarly to Vaillancourt et al. they observe nuclear expansion and conclude that for large scale replacement of nuclear power by CCS, further cost reductions are necessary.

Research studies

Paper I

Aim

Our first paper aims to answer two questions related to nuclear power's role in climate change mitigation. First how is climate change mitigation cost affected in scenarios of nuclear power expansion and increased availability of advanced nuclear cycles? Secondly since there is a connection between nuclear power and nuclear weapons manufacturing possibility, how does this expansion relate to nuclear weapons proliferation risk?

Methodology

To answer these questions we look at six different scenarios representing different possible future energy systems. 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 all nuclear technologies are available for large scale global adoption. 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 US $500 lower than in the standard scenario. Also, using highly enriched uranium (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 after 2020 the building of nuclear power plants in regions of high income countries (HIC) and low income countries (LIC) 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 in 2011. 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 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. Thus the fourth scenario represents a case in which 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 the resource base is 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 universally after 2020, and the use of existing plants for electricity production will cease after 2040. This scenario is called *no nuclear*. In addition to looking at the resulting energy mix, we also calculate an estimate for the necessary number of enrichment and reprocessing facilities based on data from current facilities.

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

Table 1. Scenarios.

MAIN FINDINGS

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 (Figure 1).
- New nuclear technologies such as FBR and alternative uranium extraction methods provide about half of these cost reductions.
- 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 tenfold 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 and poses a proliferation risk (Figure2).

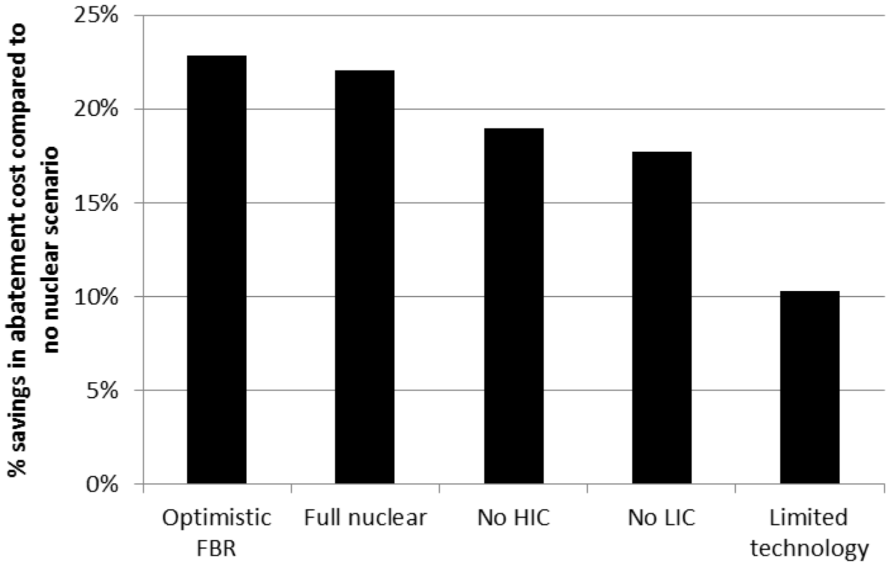

Figure1. Savings in abatement costs for scenarios over period of 2000–2150 compared to the *no nuclear* scenario.

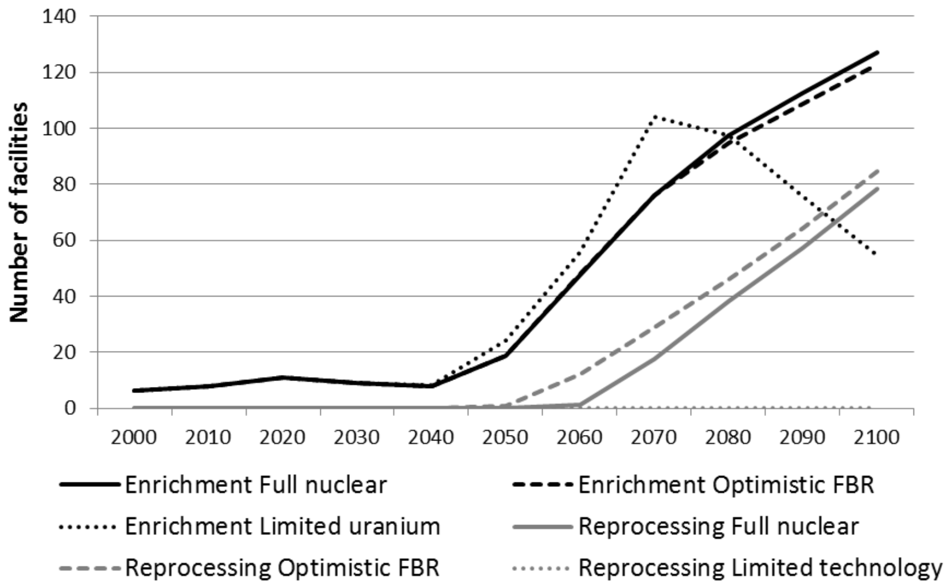

Figure 2. Number of enrichment and reprocessing facilities needed assuming capacity 600 t of LWR fuel per year for enrichment and 5000 tHM/yr for reprocessing.

PAPER II

AIM

Many studies have shown that nuclear power can reduce mitigation cost [e.g. 12, 36-38], but the robustness of the solution and its dependency on other factors in the system is rarely investigated systematically. In this paper we analyse the effect of changes in various technology costs, efficiency improvements on the demand side, carbon storage availability, biomass availability and climate sensitivity on nuclear power expansion and on its ability to reduce climate change mitigation cost.

METHODOLOGY

To analyse the contribution of nuclear to climate change mitigation we look at three nuclear scenarios. The first, called *full nuclear*, sets no restrictions to nuclear expansion or technology use. The second scenario called *limited technology* assumes that only technologies that are 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.

To further investigate the role of nuclear we sequentially varied different parameters in the model as shown in Table 2, while all others were kept at the usual level that we refer to as standard. Each parameter variation was combined with three nuclear scenarios. Also the baseline was solved for each variation with the same parameter values but without any carbon constraint. 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 in a given system. It should also be kept in mind that many externalities are not included in this analysis such as air pollution caused by coal power plants or policies to support renewable electricity generation.

Parameter	Optimistic	Standard	Pessimistic
CCS	2 times the standard storage capacity; 0.5 times the investment cost of adding caron capture to a power plant; 0.5 times the storage cost	Standard capacity and costs	0.5 times the standard storage capacity; 1.5 times the investment cost of adding caron 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, 1.25 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, 0.75 times the standard biomass potential
Fossil fuel 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 cost	Standard costs	1.5 times the standard cost
Demand	Standard demand x $(1 - 0.05)^t$ where t(2020)=1 and t is measured in decades	Standard demand	Standard demand x $(1+0.05)^t$ where t(2020)=1 and t is measured in decades

Table 2. Parameter variations

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 for emissions trajectories corresponding to two different climate sensitivities, – 2°C and 3°C. All parameters in Table 2 are varied between their optimistic and pessimistic values with uniform distribution except for CCS storage capacity, which is varied from 0 to 4000 Gtonnes of CO_2, and demand, which was varied among three trajectories specified in scenario analysis. For all cases the corresponding baseline scenario was also solved to allow a fair comparison of mitigation costs.

MAIN FINDINGS

To decide whether to support large scale expansion of nuclear power, the observed cost savings must be weighed against increased risks of radiation releases from reactor operation and waste storage accidents in addition to nuclear weapons proliferation. To make this assessment economic as well as moral considerations are necessary. To perform this analysis is not in the scope of this paper, and therefore further analysis is needed. Still, from our rather stylized modelling on the economic benefit side, we conclude that:

- Nuclear power probably needs strong climate policies to be competitive at a large scale.
- The relative cost benefit of expanding nuclear power for climate mitigation ranges from 1-72%, with median value of 26 % for 3°C climate sensitivity in our Monte Carlo analysis (Figure3).
- Nuclear power is not the most cost effective option before 2050, being surpassed by wind and hydro power. Therefore most of 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 costs. The cost savings are typically 10-13 percentage points lower if FBRs and alternative uranium extraction methods are not available. However, the cost benefits provided by expansion of nuclear power compared to phase out are never completely eliminated.
- Availability of CCS storage has a small effect on mitigation cost when nuclear power is available but plays a significant role in case of a phase out and high climate sensitivity (Figure 4).
- Constraining nuclear power tends to enhance the penetration of solar power but does not necessarily result in solar expansion.

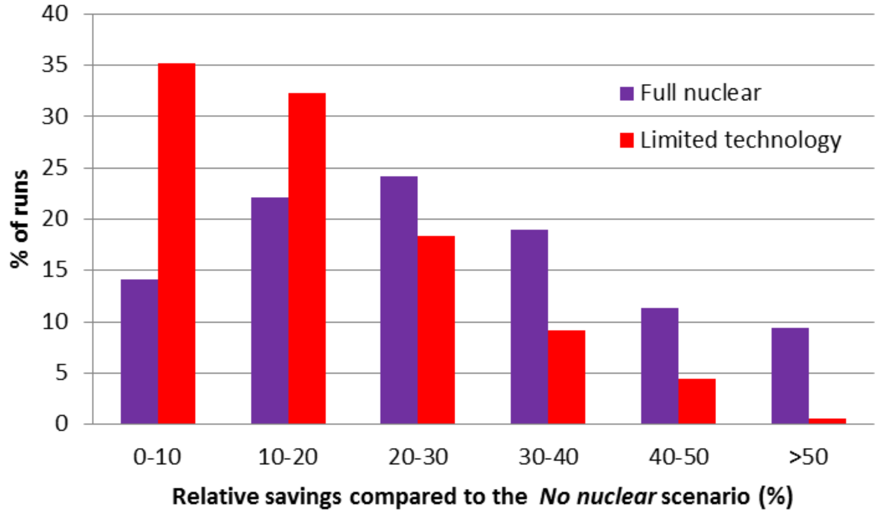

Figure 3. Relative savings compared to the *no nuclear* scenario in case of 3° climate sensitivity.

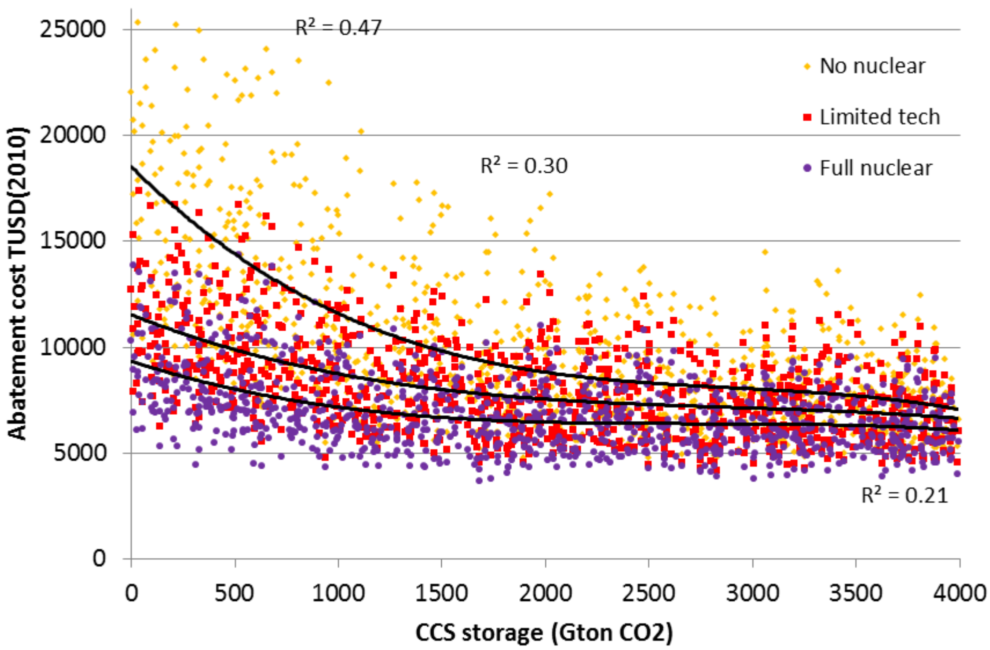

Figure 4. Relation of abatement cost to carbon storage capacity in case of 3° climate sensitivity.

REFERENCES

1. IPCC, *Working Group I Contribution to the IPCC Fifth Assessment Report (AR5) Climate Change 2013: The Physical Science Basis* 2013.
2. Tanaka, K. and T. Raddatz, *Correlation between climate sensitivity and aerosol forcing and its implication for the "climate trap".* Climatic Change, 2011. **109**(3-4): p. 815-825.
3. *Emissions Scenarios - IPCCs Special Report*, N. Nakicenovic and R. Swart, Editors. 2000.
4. *Turn Down the Heat: Why a 4°C Warmer World Must Be Avoided*. 2012, World Bank.
5. Rogelj, J., et al., *Emission pathways consistent with a 2°C global temperature limit.* Nature Climate Change, 2011. **1**(8): p. 413-418.
6. Pacala, S. and R. Socolow, *Stabilization wedges: Solving the climate problem for the next 50 years with current technologies.* Science, 2004. **305**(5686): p. 968-972.
7. von Hippel, F., et al., *Chapter 14 - Nuclear Energy*, in *Global Energy Assessment - Toward a Sustainable Future*. 2012: Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. p. 1069-1130.
8. Jewell, J., *Ready for nuclear energy?: An assessment of capacities and motivations for launching new national nuclear power programs.* Energy Policy, 2011. **39**(3): p. 1041-1055.
9. Sovacool, B.K., *Valuing the greenhouse gas emissions from nuclear power: A critical survey.* Energy Policy, 2008. **36**(8): p. 2940-2953.
10. UNSCEAR, *Sources and Effects of Ionizing Radiation*. 2000, UN Scientific Committee on the Effects of Atomic Radiation.
11. IAEA, *Boiling Water Reactor Simulator with Passive Safety Systems: Ures Manual*. 2009: Vienna, Austria.
12. Tavoni, M. and B. van der Zwaan, *Nuclear Versus Coal plus CCS: A Comparison of Two Competitive Base-Load Climate Control Options.* Environmental Modeling and Assessment, 2011. **16**(5): p. 431-440.
13. Socolow, R.H. and A. Glaser, *Balancing risks: Nuclear energy & climate change.* Daedalus, 2009. **138**(4): p. 31-44.
14. IAEA, *Multilateral Approaches to the Nuclear Fuel Cycle*. 2005.
15. Cochran, T.B., et al., *Fast Breeder Reactor Programs: History and Status. Research Report 8*. 2010, International Panel on Fissile Materials.
16. Yim, M.S., *Nuclear nonproliferation and the future expansion of nuclear power.* Progress in Nuclear Energy, 2006. **48**(6): p. 504-524.
17. Sterman, J.D., *A Skeptic's Guide to Computer Models*, in *Managing a Nation: The Microcomputer Software Catalog*, G.O.e.a. Barney, Editor. 1991, Westview Press: Boulder, CO. p. 209-229.
18. Kahneman, D., P. Slovic, and A. Tversky, *Judgement Under Uncertainty: Heuristics and Biases*. 1982, Cambridge, UK: Cambridge University Press.
19. Meadows, D.H., et al., *Limits to Growth*. 1972, New York: Universe Books.
20. Nordhaus, W.D., *Allocation of Energy Resources.* Brookings Paper on Economic Activity, 1973. **3**: p. 529-570.
21. Manne, A.S., *ETA: A Model for Energy Technology.* The Bell Journal of Economics, 1976. **7**(2): p. 379-406.
22. Manne, A., R. Mendelsohn, and R. Richels, *MERGE. A model for evaluating regional and global effects of GHG reduction policies.* Energy Policy, 1995. **23**(1): p. 17-34.
23. Messner, S. and M. Strubegger, *User's Guide to MESSAGE III*. 1995, IIASA: Laxenburg, Austria.

24. Azar, C., K. Lindgren, and B.A. Andersson, *Global energy scenarios meeting stringent CO2 constraints - Cost-effective fuel choices in the transportation sector.* Energy Policy, 2003. **31**(10): p. 961-976.
25. De Vries, B., et al., *Greenhouse gas emissions in an equity-, environment- and service-oriented world: An IMAGE-based scenario for the 21st century.* Technological Forecasting and Social Change, 2000. **63**(2-3): p. 137-174.
26. Sokolov, A.P., et al., *The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation*, in *Joint Program Report Series*. 2005.
27. Hedenus, F., et al., *Cost-effective energy carriers for transport - The role of the energy supply system in a carbon-constrained world.* International Journal of Hydrogen Energy, 2010. **35**(10): p. 4638-4651.
28. IIASA, *GGI Scenario database*.
29. Pasztor, J., *What role can nuclear power play in mitigating global warming?* Energy Policy, 1991. **19**(2): p. 98-109.
30. Mez, L., *Nuclear energy-Any solution for sustainability and climate protection?* Energy Policy, 2012. **48**: p. 56-63.
31. Sailor, W.C., et al., *A nuclear solution to climate change?* Science, 2000. **288**(5469): p. 1177-1178.
32. van der Zwaan, B., *The role of nuclear power in mitigating emissions from electricity generation.* Energy Strategy Reviews, 2013. **1**(4): p. 296-301.
33. Gea, *Global Energy Assessment - Toward a Sustainable Future*. 2012, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.
34. Rogner, M. and K. Riahi, *Future nuclear perspectives based on MESSAGE integrated assessment modeling.* Energy Strategy Reviews, 2013. **1**(4): p. 223-232.
35. Lehtveer, M. and F. Hedenus, *Nuclear Power as a Climate Mitigation Strategy – Technology and Proliferation Risk.* Journal of Risk Assesment, 2013.
36. Mori, S., *An assessment of the potentials of nuclear power and carbon capture and storage in the long-term global warming mitigation options based on Asian Modeling Exercise scenarios.* Energy Economics, 2012. **34**(SUPPL. 3): p. S421-S428.
37. Bauer, N., R.J. Brecha, and G. Luderer, *Economics of nuclear power and climate change mitigation policies.* Proceedings of the National Academy of Sciences of the United States of America, 2012. **109**(42): p. 16805-16810.
38. Vaillancourt, K., et al., *The role of nuclear energy in long-term climate scenarios: An analysis with the World-TIMES model.* Energy Policy, 2008. **36**(7): p. 2296-2307.