THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Modelling the Role of Nuclear Power and Variable Renewables in Climate Change Mitigation

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ABSTRACT

As the number of people on Earth and our energy needs have increased the system for providing this energy has become ever more complex and complicated and thus the need for more systematic understanding of it has grown. However, change in energy system is slow and many of the challenges that we face such as mitigating climate change need global solutions. Energy system models with long time span and global reach provide a way to analyse questions related to these challenges. This thesis focuses on capturing the role of nuclear power and variable renewables in global long term energy models.

Papers I, II and IV assess the potential role nuclear power can play in global climate mitigation as well as identify the determining factors of this contribution whereas Paper III looks at the possible effects of phase out of Swedish nuclear power on European CO_2 emissions and electricity prices. We show that nuclear power can reduce the climate change mitigation cost if allowed to remain or expand. The main factors determining the cost reduction potential are availability and cost of carbon capture and storage and cost of renewable and nuclear technologies. However, 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.

To analyse such concerns we use post analysis of model scenarios in Paper I to assess the nuclear power expansion's effect on nuclear weapons' proliferation and apply the multi-criteria model analysis (MCMA) method in Paper IV to actively include criteria such as proliferation concern and energy security into optimisation. We find that MCMA method significantly improves the analysis of attainability of multiple simultaneous goals such in large-scale energy-systems models compared to simple scenario analysis that is presented in Paper I. The approach is more intuitive and requires minimal mathematical skills on the part of the user. MCMA method also avoids infeasible or dominated solutions that are caused by the stringent constraints applied in parametric optimisation.

Paper V presents a method for capturing the effects of intermittency induced by variable renewables into the power system. Our results show that this approach manages to capture many aspects such as need for flexible generation capacity and curtailment at high penetration levels. We also find optimal electricity production mixes to vary significantly between regions due to different endowments of solar and wind resources. We show that adding electricity storage to the system will favour solar power but has only a minor effect on wind and nuclear power.

Keywords: nuclear power, variable renewables, optimisation, multi-criteria analysis, climate change, energy system model.

List of Publications

I. Mariliis Lehtveer and Fredrik Hedenus, "Nuclear Power as a Climate Mitigation Strategy – Technology and Proliferation Risk", *Journal of Risk Research*, Volume 18, Issue 3, 16 March 2015, Pages 273-290.
FH conceived the idea; ML collected the data; ML performed the modelling with contributions from FH; ML and FH analysed the results; ML wrote the paper with contributions from FH.

II. Mariliis Lehtveer and Fredrik Hedenus, "Will Nuclear Power reduce Climate Mitigation Cost? – Critical Parameters and Sensitivity", *Energy Strategy Reviews*, Volume 6, 2015, Pages 12-19.
FH conceived the idea; ML collected the data; ML performed the modelling with contributions from FH; ML and FH analysed the results; ML wrote the paper with contributions from FH.

III. Mariliis Lehtveer, Mikael Odenberger and Fredrik Hedenus "Making a Mountain out of a Molehill: Possible Phase-out of Nuclear Power in Sweden", *Working paper*.
ML conceived the idea; MO performed the modelling; ML, MO and FH analysed the results; ML wrote the paper with contributions from MO and FH.

IV. Mariliis Lehtveer, Marek Makowski, Fredrik Hedenus, David McCollum, Manfred Strubegger, "Multi-Criteria Analysis of Nuclear Power in the Global Energy System: Assessing Trade-Offs between Simultaneously Attainable Economic, Environmental and Social Goals" *Energy Strategy Reviews*, Volume 8, 2015, Pages 45-55.
MM and DM conceived the idea; ML collected the data; ML performed the modelling in MESSAGE with contributions from MS and DM; MM implemented the MCMA tool; ML and MM analysed the results with contributions from FH and DM; ML wrote the paper with contributions from MM, DM, FH and MS.

V. Mariliis Lehtveer, Niclas Mattson, Fredrik Hedenus and Martin Soini, "Using Resource Based Slicing to Capture the Intermittency of Variable Renewables", *Working paper*.
FH and NM conceived the idea; ML and MS collected and analysed the data; NM performed the modelling with contributions from ML and FH; ML, NM and FH analysed the results; ML wrote the paper with contributions from NM, FH and MS.

OTHER RELATED PUBLICATIONS, NOT INCLUDED IN THE THESIS

- M. Lehtveer. Multi-Criteria Analysis of the Role of Nuclear Power in the Global Energy System. Report for the Young Scientist Summer Program, IIASA. 2012. Supervisors: Dr D. McCollum, Dr M. Makowski.
- M. Lehtveer, D. McCollum, M. Makowski, "Multi-Criteria Analysis of the Role of Nuclear Power in the Global Energy System – Conference paper for the 21st International Conference "Nuclear Energy for New Europe", 2012, Ljubljana, Slovenia.

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Mariliis Lehtveer

Göteborg, January 2016

Contents

*Remember that all models are wrong;
the practical question is how wrong do
they have to be to not be useful.*

G. Box, 1987

INTRODUCTION

MODELLING ENERGY SYSTEMS

The use of energy is an ever-present aspect of our daily lives. We need energy to heat or cool our houses, to prepare our food, to enable us to travel etc. As the number of people on Earth and our energy needs have increased the system for providing this energy has become ever more complex and complicated and thus the need for more systematic understanding of it has grown.

Energy policy gained importance in the wake of the oil crisis in the seventies. Linear programming methods developed during the second world war were then put to use to analyse interactions inside the energy system and between this system and the general economy [1]. Affordability of energy and reliability of supply in terms of oil imports were the main driving forces in the quest to understand energy systems [1]. Today many additional challenges steer the investigation of possible ways to develop energy systems, for example mitigation of climate change, health effect of the energy system such as air pollution etc. but the old concerns remain. At the same time development of new technologies such as wind and solar power has created additional challenges to energy systems.

Yet change in the energy system is slow. Much of the infrastructure has high investment cost and a life time of decades and cannot therefore be replaced easily. Thus analysis of energy systems needs to span over a long time frame. For many of the energy challenges interdependencies among regions exist. Energy resources are not evenly distributed over the world and trade between regions can enable cost reductions; emissions from one country will affect the climate of the whole world etc. Hence global solutions are needed to effectively meet many of the world's energy challenges. Energy system models with long time span and global reach provide a way to analyse questions related to these challenges.

CLIMATE CHANGE AS ONE OF THE DRIVERS OF TRANSFORMATION IN ENERGY SYSTEM

Recent decades have seen a 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 400 parts per million (ppm) in 2015 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 [2]. Climate scientist strongly agree that the warming effect, in turn, is caused by elevated concentrations of CO_2 and other greenhouse gasses (GHG) [2].

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 [3]. 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 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 three times the pre-industrial level [4]. The 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 [2]. 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. 5].

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 [6]. 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 or even negative GHG emissions.

THE ROLE OF POWER SECTOR IN THE ENERGY SYSTEM

The power sector in the energy system plays a special role in various ways. First of all, the demand for electricity is expected to increase substantially over the current century due to electrification of new regions as well as an increases in population and general consumption as well as income growth [7]. Another driver for increasing electricity demand is the electrification of other energy sectors such as transport and heating and cooling. Therefore providing electricity in a sustainable, clean and affordable manner will become increasingly important.

Many possibilities exist for producing energy with low life cycle emissions such as the use of biomass, wind, solar, hydro and nuclear power. Alternatively emitted CO_2 can be captured and stored in suitable geological formations. Yet no single technology will be sufficient to completely solve the problem, and likely expansion of many is needed [8]. As a consequence, concern about climate change has also renewed interest in nuclear power as a proven low emitting technology. At the same time the cost of variable renewable technologies – wind and solar PV – has been significantly reduced making them another set of possible substitutes for fossil power.

The power sector also has a specific feature that the demand and supply must equal at any given point of time to maintain the frequency in the system and thus the functioning of the system. While electricity storage methods exist such as pumped hydro storage, batteries, compressed air energy storage, flywheels etc. their low long term efficiency due to losses and limited geographical availability of the most efficient options means that having strategical long term reserves of electricity is in general not possible.

Typical electricity system today is built to follow the demand by employing different types of power plants. The base load is typically covered by power plants with high investment but low running costs such as coal or nuclear power plants. They are run at a nearly constant rate close to their maximum possible output level. Most of the rest of the demand is covered by load following power plants with intermediate cost profile and peaks are provided by peak load plants with low investment but high running cost typically fuelled by gas.

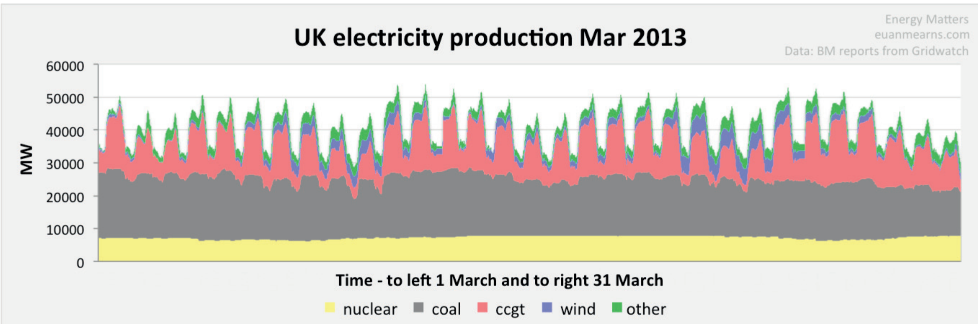

Figure 1. Electricity supply in UK during March 2013. CCGT stands for combined cycle gas turbine. Source: Energy Matters, euanmeans.com

Overview of nuclear power

Currently nuclear power provides about 11% of the global electricity supply with an installed capacity around 370 GW_e in 30 countries. Most of the capacity is placed in Europe and the US. Additions to capacity have been relatively few in the last decades, and the growth in output has been mainly achieved by improving load factors [9]. 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 [10].

Studies have shown that nuclear power may help to mitigate climate change due to its very low life cycle GHG emissions [e.g. 11]. These emissions are indirect, meaning that they are not caused by nuclear energy production directly but by activities needed for building power plants, mining, transporting and enriching 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 [12]; therefore fluctuations in uranium ore prices will not affect the cost of generating electricity from nuclear significantly.

Although nuclear power has several 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 contrast to other energy technologies, the cost of nuclear power has increased over time [13, 14]. 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 [14]. 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 [14]. 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 [15]. 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 [16]. Even if the 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. 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 heavy nuclei such as uranium-235 and plutonium-239. This process is induced by absorption of a neutron in a nucleus 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), which is then 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 [17]. 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. 18].

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 organisations. Although geological disposal is widely believed to be adequately safe, definite proof of its reliability over tens of thousands of years cannot be given due to the time needed to conduct such experiments. 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 [9].

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 utilised 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. 19, 20]. The separated material can also be used for weapons production. Smaller quantities of plutonium are needed to produce a nuclear weapon, although it is 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 [21], 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 plutonium previously extracted under military programs. However, this approach has not been economically interesting and also poses proliferation concerns, as weapons usable plutonium could be separated before recycling into MOX fuel and possibly diverted. Plutonium for purely weapon purposes is typically produced in smaller dedicated reactors with shorter operating periods than power reactors 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 [22].

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 [23]. 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 [24], this fuel cycle renders enrichment obsolete in the long term.

OVERVIEW OF VARIABLE RENEWABLES IN THE POWER SYSTEM

Wind and solar PV show a great potential with large resource base and significantly reduced costs over last decade. According to the Global Energy Assessment wind power has a practical potential of providing 250-1200 EJ/yr and solar PV of 12 300 EJ/yr taking into account the technical limitations, land-use conflicts and transmission [25]. Recent years have also seen great expansion in both solar and wind capacity installed (figure 2) with largest growth taking place in Asia [26]. In 2014 wind power met more than 20% of electricity demand in several countries, including Denmark, Nicaragua, Portugal, and Spain. Yet the share of wind and solar power combined in global electricity production remains currently under 5% [27].

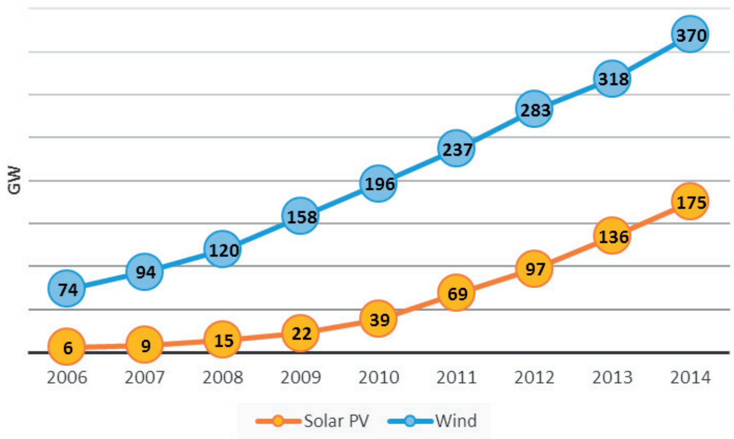

Figure 2. Total installed capacity of solar PV and wind power 2006-2014 [26].

However, both of these technologies are characterised by a feature that causes problems to the current set up of energy system – intermittency. Electricity demand depend on several factors such as daily habits of people, the structure of economy and presence of energy intensive industries. These factors are rather well predictable on aggregate scale and also do not usually change rapidly. Therefore demand fluctuations are predictable with relatively good accuracy over long periods (several years). In the traditional electricity system different power plants are available most of the time and can be dispatched based on their running cost. Knowing the demand thus also allows to predict the running times and profitability of different power plants in this kind of a system rather well. The outputs of wind and solar PV, however, are highly dependent on availability of wind and solar radiation which can vary greatly over both short and long time scales (daily and seasonal variations) and are not well predictable over long time periods. Yet they tend to be employed when available due to near zero running costs. While employing some amount of solar can help balancing daily variations in demand, employing large amounts of intermittent renewables quickly starts to reduce the intermediate and baseload available for other plants and thus also their running times and profitability. Since wind and solar patterns are not well predictable and the effect on the other plants also depends on the amount of intermittent sources in the system and their distribution. Therefore the electricity price and running times of traditional base load plants and consequentially also their profitability becomes more difficult to foresee. Thus including the effect of intermittency into the analysis of future energy systems can significantly change the optimal solution but it is yet unclear to what direction this change will incline.

OBJECTIVE OF THIS THESIS

This thesis addresses following research questions rooted in the situation presented in previous sections:

- What is the techno-economical potential of nuclear power in climate mitigation and what are the main determinants of this potential?
- How to analyse non-monetary goals such as proliferation risk with large scale energy models?
- How to represent intermittency of variable renewables in a large scale energy model in an effective way?

SCOPE AND RELATED WORK

THE ROLE OF NUCLEAR POWER IN CLIMATE CHANGE MITIGATION

Several attempts have been made to assess the possible role of nuclear power in climate mitigation. Some studies in that direction have been qualitative. For example Pasztor [28] 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 [29] 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. [30] 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 [31] 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 [20] 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. 7, 32, 33]. Therefore nuclear power is not essential to climate change mitigation, yet it can provide significant cost reductions [33-35].

Some studies have attempted also taken a systems perspective and use large scale energy models to assess the possible role of nuclear power in climate mitigation. Vaillancourt et al. [36] 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 [34] and Bauer et al. [35] 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 [19] 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 [37]. 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 [38]. Yet no systematic exploration of a large number of factors that can possibly affect the role of nuclear power within the 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 thesis focuses on two questions related to the role of nuclear power in climate change mitigation. First, what is the global techno-economical potential of nuclear power in reducing the climate change mitigation cost? Secondly, what are the main determinants of the size of the cost reductions enabled by nuclear power? Paper I analysis the potential role of availability of different nuclear cycles via scenario analysis. Paper II looks deeper into the factors influencing the potential mitigation cost reductions via both scenario and Monte Carlo analysis. Paper III analyses the effect of phase out of Swedish nuclear power on European emissions and electricity prices via scenario analysis. The technological scope of two first paper includes conventional LWR cycles as well as MOX fuel and FBR cycles. Also uranium extraction from sea water and other unconventional resource bases are included. In paper III only LWRs are modelled. The geographical scope is the whole world with regional separation by current income levels to high, medium and low income countries in Papers I and II and Europe for Paper III. The time frame analysed is 21st century and mitigation targets 430ppm CO_2 in Paper I and meeting the 2°C target with 2°C and 3°C climate sensitivity per atmospheric CO_2 doubling in Paper II. Paper III spans over years 2015-2045 and includes current policies for GHG reductions.

Representing non-monetary goals in large scale energy models

While having affordable energy is one of the goals while developing an energy system there are also other concerns that must be taken into account such as energy security and health and climate effects of the system. These effects, however do not always come with an obvious price tag and cannot therefore be directly included into the objective function of the model. Including non-monetary goals as constraints is a common practise in energy system modelling. For example the concern for climate is usually included as a carbon budget that technologies cannot exceed. Another common way is to perform a post analysis of energy system developments produced by modelled scenarios and assess their impact on non-monetarised aspects.

However, as other energy-related goals besides affordability and climate mitigation have increased in importance, multi-criteria analysis methods have been explored to more fully understand the relations between different objectives and their achievability. Thus far these studies have been mainly limited to a national or power plant scale (e.g. [39-41]). A notable exception is the IIASA Energy – Multi Criteria Analysis (ENE-MCA) policy tool [42]. This tool explores an ensemble of over 600 possible futures generated through parametric single criteria optimisations, in which the parameters represent different levels of constraint for the other criteria. The results of the optimisations are treated as discrete alternatives. Of several thousands of optimisations, only roughly 600 resulted in Pareto-optimal alternatives i.e., the majority of generated alternatives were dominated, therefore not worth further analysis. One alternative is dominated by another, if the latter has a better value for at least one criterion, and equally good values of all other criteria. ENE-MCA supports multiple criteria analysis of these alternatives, thus enabling the assessment of the co-benefits of simultaneously achieving goals related to climate, health, and energy security and the discovery of synergies between climate and energy security [43]. Yet that study only deals with the discrete alternatives generated through the parametric optimisation and thus fails to explore the entire space of Pareto-optimal solutions. To do the latter a multi-criteria model analysis (MCMA) is necessary.

This thesis investigates the inclusion of non-monetary goals in two ways. In Paper I post modelling scenario analysis is used to assess the proliferation risks in different scenarios. In Paper IV MCMA method is used to include energy security and proliferation concerns into decision making. Both papers investigate the developments under climate mitigation scenarios (430ppm CO_2 in Paper I and 450 and 600 ppm CO_2 in Paper IV).

CAPTURING INTERMITTENCY IN LARGE SCALE ENERGY MODELS

Long-term energy models representing multiple sectors and regions are often used to investigate the questions related to long term developments such as decarbonisation of the energy system. These models typically make a cost-effective choice among large number of technologies and optimise investment decisions over many time periods and over vast geographic area. This makes these models computationally demanding and simplifications in temporal, geographic and technical detail are necessary to maintain reasonable running-times. Typically time steps of 5-10 years are modelled in such models [44]. However, supply from wind and solar varies on much shorter time scales and is thus difficult to capture in this type of models.

Traditionally, models such as GET [45] often circumvent this problem by simply limiting the amount of variable renewables to 25-30% of electricity production; a level that is widely viewed as possible to integrate into current systems without significant additional costs. This approach limits the role that variable renewables can play in scenarios designed to investigate possible pathways to global climate mitigation, and therefore model results can be misleading. Different approaches have been tried by various modelling groups to avoid this artificial restriction and incorporate intermittency related effects into long-term energy models. For example, Sullivan et al. use additional constraints to capture the capacity credit provided by different penetration levels of intermittent renewables as well as technology dependent flexibility coefficients to account for the increased need for back-up capacity and flexible generation as the penetration of variable renewables increases [46]. Another approach is to interlink long-term capacity expansion models with short-term dispatch models [47]. However, this method requires considerable effort to set up both models and ensure the convergence of their results, as well as extensive additional computational resources.

The infeed from wind and solar is not the only source of variability in the power system – the demand for electricity is also fluctuating over time. To capture the variability of demand in large energy system models, a time slice approach is often used. This involves implementing a coarse load duration curve for electricity demand, in which hours with similar levels of demand are grouped together (typically day/night, week-day/week-end, and seasons). Recently, attempts have been made to extend this approach also to variable renewable sources. For example, Ludig et al. investigate the effect of increased time resolution of demand based slicing on capturing the variability of renewables and find that it helps to better capture the variability of demand and solar infeed, but does not adequately represent the variability of wind infeed [48]. Nahmmacher et al. propose an approach for selecting representative days and summarise other attempts in that direction [44]. They find 6 representative days with 3 hour resolution to be sufficient to reflect the characteristic fluctuations in input data. Yet this approach results in 48 time slices that may make it inapplicable for large scale energy models due to high computational requirements.

In this thesis we propose another solution for representing variability of wind and solar PV in large scale energy models based on resource based slicing.

Limitations of the thesis

The analysis carried out in this thesis assume a perfect market where resources are allocated most cost effective manner. Thus it does not look into the possible distribution of welfare nor at micro level incentives that may hinder the implementation of such cost optimal solution. Moreover, main part of this thesis includes only technical and economic aspects of research questions and does not discuss social and political feasibility.

Method

Typology of long term energy system models

First steps to analyse energy and environment related issues with computer models were taken in early 70s. Ground breaking publication “The Limits to Growth” that was issued in 1972 looked into dynamics resulting from interactions among world population, industrialisation, pollution, food production and resources depletion [49]. Several other studies followed soon after [50]. Although a vast amount of models has been developed and improved since, most of them rely on the conceptual approach developed in 70s [50].

Energy models are commonly divided into simulation and optimisation models although the division is not always clear cut and models can have characteristics of both types. The first set aims to predict the modelled system’s likely evolution thus they do not necessarily try to optimise the system. Due to the detail needed those models also tend to be on national or regional scale, although also global simulation models exist. Examples of this type of models include IMAGE with a global scope [51] and PRIMES with a regional focus [52].

Large bottom up optimisation models have been the standard of energy modelling. These models usually have rich detail of technical components but require simplifications in other areas such as geographic detail or time resolution to keep the solving time in feasible range and the model trackable. Examples of this family include MERGE [53], MESSAGE [54], ReMIND-R [55] and GET [56]. Optimisation models are well based in mathematical theory. In general the objective is to maximise aggregated welfare or minimise aggregated cost under a given set of assumptions and constraints such as available energy resources, allowed emissions, need to meet the demand etc. Optimisation models are used for various purposes but mainly for trying to answer “what if?” questions about future development of the system. Hedenus et al. [50] list the five most common aspects addressed by energy systems models in a climate context:

- Cost of climate stabilisation
- Feasibility of climate targets
- Burden sharing and timing
- Role of technologies
- Exploration of possible futures depending on population growth, economic development, etc.

The distinction between simulation and optimisation models is not always clear and may depend on the model set-up or research question asked.

Energy models can either encompass the whole economy – general equilibrium models like GEM-E3 [57] – or only some sectors of economy such as energy or electricity – partial equilibrium models like GET [56]. Modelling only a part of the whole economy allows for a more detailed description of relations within chosen sectors and easier interpretation. On the other hand this approach also only captures the effects of price changes, resource base and policies applied in these chosen sectors and may thus misrepresent some dynamics. In contrast general equilibrium models capture the changes in all sectors. Partial models can also be soft-linked to form integrated assessment models that change information between different sectors and thus capture the interactions among sectors. One example of such models is MESSAGE-MACRO [58].

MODELS USED IN THIS THESIS

Several energy systems models with varying scope were used in this thesis, but all of them fall into the category of partial equilibrium optimisation models. A more detailed description of each model is provided below.

GET MODEL

Global Energy Transition (GET) model was first developed by Azar and Lindgren [56] and further improved by Hedenus et al. [45]. 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 over 100 years' time span 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 with 5%/yr discount rate. In order to do this, the model evaluates a number of technologies for converting and supplying energy based on data related to costs, efficiencies, load factors and carbon emissions among other variables. The time step considered by GET model is 10 years.

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 [59], whereas the transportation demand scenarios are based on [56]. 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.

In our analysis we use both the three region version as well as 10 region version of GET, with improved representation of the nuclear cycles. In addition to the LWR fuel cycle also MOX and fast breeder reactor (FBR) options have been added.

ELIN model

The ELIN (ELectricity INvestment) model that covers the EU-27 as well as Norway and Switzerland and is a bottom up long-term dynamic optimisation model with perfect foresight that describes the power sector. The objective of this model is to minimise the cost of the power system of Europe. The time horizon of the ELIN model is 2010–2050 with each year modelled separately. The intra-annual time resolution of the ELIN model is 16 time steps, including two daily load segments (night and day) for weekdays and weekends as well as four seasons. The fundamentals and the original formulation of the ELIN model are more thoroughly described in [60, 61].

MESSAGE model

MESSAGE is a global systems engineering optimisation model with 11 regions and a 100 year timespan with 10 year time step. It is based on a linear programming solution framework that optimises by minimising the total discounted energy system costs over the entire model time horizon with perfect foresight. A global 5%/yr discount rate is used. The model includes energy resources, energy extraction, conversion, and end use sectors: thermal, electricity and feedstock demand for industry; thermal and electricity for residential and commercial buildings; transport and non-commercial biomass. MESSAGE is most commonly used for energy system planning, energy policy analysis and scenario development. For example, MESSAGE has been used extensively in the development of previous Intergovernmental Panel on Climate Change (IPCC) scenarios [62] and for the GEA report by IIASA [7].

MULTI-CRITERIA OPTIMISATION

Humanity faces a complex array of energy related challenges, for which there are no universal solutions. Some of our energy goals can work against each other. A typical example here is the use of coal power that is impeding our climate change mitigation efforts but may at the same time be beneficial for developing economies due to its low cost and resulting affordability of electricity. Some other goals are synergetic such as reduction of greenhouse gas emissions and health effects due to particle pollution [43]. Two approaches of analysis are typically used in such cases. First, the analyst can focus on a single goal (most often minimising systems cost) and include other criteria as constraints. This approach leads to many runs of single criterion parametric optimisations each corresponding to a set of constraints on the other criteria, resulting in several possible future scenarios. The second approach is to apply the linear aggregation of criteria in which each criterion is given a weight and then attempts to modify the weights to represent changing preferences for trade-offs between criteria. Both approaches, however, have limitations such as counterintuitive solutions or missed opportunities for improvement discussed e.g., in [63]. Thus a more sophisticated method for analysing multiple simultaneously attainable goals are needed.

A comprehensive multi-criteria analysis involves exploration of subsets of Pareto optimal solutions, also known as efficient or non-dominated solutions. A solution is Pareto optimal if and only if there is no other solution with a better value of at least one criterion and at least equally good values of all other criteria. The whole set of efficient solutions for non-trivial problems is typically huge and complex; therefore its analysis is impractical. Moreover, users are typically interested in analysis of those Pareto subsets that have desired trade-offs between criteria values. The latter observation justifies interactive multi-criteria analysis methods that provide users with effective controls to explore diverse Pareto subsets. In this thesis we apply one such method to a large scale global energy systems model.

A class of such methods is called the reference point method where the *point* stands for a vector composed of criteria values. The method used in this thesis, called the aspiration–reservation based approach, is an extension of the reference point method, and is described in detail in [64]. In this method the analyst defines interactively two points called Aspiration (A) and Reservation (R). The values defining the A–point are composed of the criteria values the user wants to (simultaneously) achieve while the R–point contains the worst acceptable values. The pair of A/R–points is used for defining parameters of the so-called scalarising achievement function, maximisation of which provides a Pareto solution. Full discussion of the method and its properties is beyond the scope of this paper this introduction. Therefore let it only be mention that if the A–point is not attainable i.e., there is no solution having criteria values at least as good as the values defining the A–point, then the provided solution is the closest in the sense of a distance measurement defined by the A/R–point to the A–point; if the A–point is attainable then the provided solution is better. Upon analysis of the obtained solution the user decides which criterion or criteria he/she wants to improve i.e., tighten the corresponding component of the R–point and optionally also set a more ambitious component of the A–point. Optionally, the user may set less ambitious values of the A/R–points of the criteria that should be compromised for the desired improvement. It should be kept in mind that due to the definition of the Pareto solution, improvement of a criterion value is possible only by worsening value of at least one other criterion

This method has several advantages over multi-criteria analysis of discrete alternatives generated through parametric optimisation (as in [43]). Firstly, the user specifies her/his preferences in a natural way using the A/R values. There are no restrictions for the A/R values (except the obvious one, that the A has to be better than the R), and therefore it is easy to experiment with various combinations of the desired criteria values and modify the values while learning their attainable combinations. Secondly, the method provides the Pareto set limited by the best and worst criteria values. These points are called Utopia and Nadir, respectively, and imply for each criterion the range of values worthy to consider. Thirdly, each optimisation run provides a Pareto solution. Therefore the method is much more efficient than parametric optimisation, which provides a majority of dominated solutions as well as many infeasible solutions.

Overview of the research studies

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

Aim

The aim of this paper is to answer two questions related to nuclear power's role in climate change mitigation. First, how is climate change mitigation cost affected by enabled 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 use GET model to look at six different scenarios representing different possible future energy systems meeting the 430 ppm CO_2 climate target. 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 can be expected to reduce the cost of reaching a stringent climate target compared to a global decommissioning of nuclear power (Figure3).
- 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 due to the need to provide fuel for FBRs and poses a proliferation risk (Figure 4).

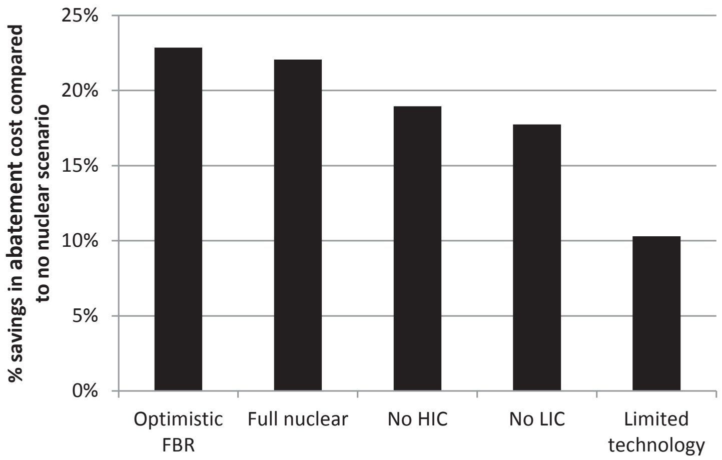

Figure 3. Savings in abatement costs for scenarios over period of 2000–2150 compared to the *no nuclear* scenario.

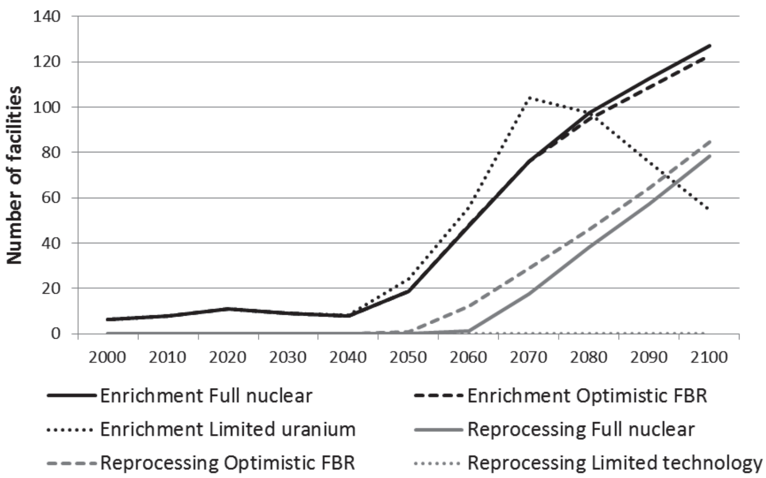

Figure 4. Number of enrichment and reprocessing facilities needed assuming capacity 600 t of LWR fuel per year for enrichment and 5000 tHM/yr for reprocessing.

Paper II - Will nuclear power reduce climate mitigation cost? – Critical parameters and sensitivity

Aim

Many studies have shown that nuclear power can reduce mitigation cost [e.g. 19, 34-36], but the robustness of the solution and its dependency on other factors in the system is rarely investigated systematically. In this paper we estimate the effect of allowing a large scale expansion of nuclear power on the climate mitigation cost as well as try to 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

Methodology

In this paper we analyse further three scenarios defined in previous paper to analyse the contribution of nuclear to climate change mitigation: *full nuclear, limited technology* and *no nuclear*. To 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 policies but rather as the cost optimal solution for a given system without carbon constraints. 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 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 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 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. Still, from our rather stylised modelling on the economic benefit side, 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 of renewable technologies, nuclear technologies and availability and cost of CCS have the largest effect of nuclear powers potential to reduce climate mitigation cost out of analysed factors (figure 5).
- 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 1–78% 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 (figure 6).
- 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.
- 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.

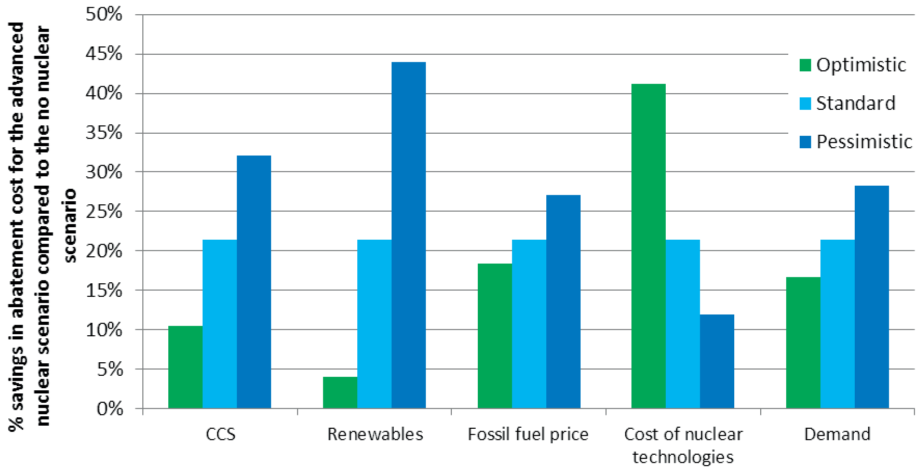

Figure 5. Relative savings in abatement cost for *advanced nuclear* scenario compared to the *no nuclear* scenario.

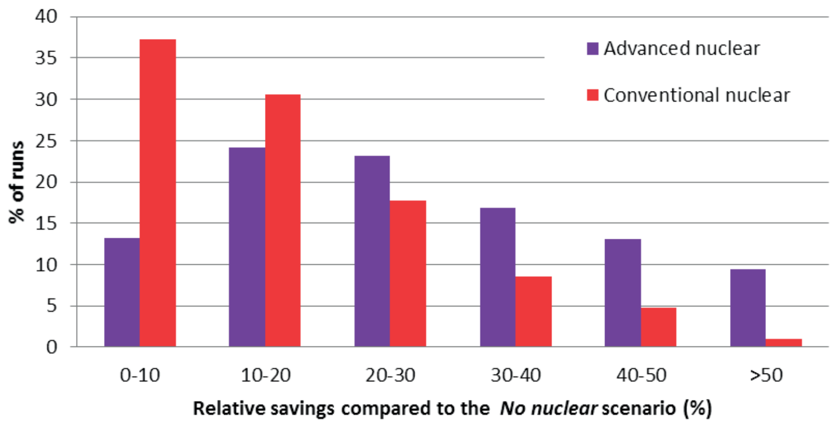

Figure 6. Relative savings compared to the *no nuclear* scenario in case of 3° climate sensitivity.

Paper III - Making a mountain out of a molehill: Possible phase-out of nuclear power in Sweden

Aim

In their article "Environmental and health impacts of a policy to phase out nuclear power in Sweden" Qvist and Brook claim that a phase-out of nuclear power in Sweden would result in up to 1.9-2.1 Gtonnes of added CO_2 emissions as well as up to 50 000-60 000 extra energy-related-deaths [65]. Both of these claims are based on the assumption that electricity from nuclear power plants is either totally or in large part replaced by electricity from coal power plants. We argue that the authors oversimplify a complex question and do not distinguish what is replaced in the production margin today from what would be on the investment margin over several decades. Further the authors totally neglect the policies in place in the EU today that heavily influence marginal production of electricity.

Methodology

The model setup used here can in short be described as reflecting the current European ambitions described in the EU roadmap scenarios, yet adapted to include the adopted policy regimes for 2020 as well as 2030 with targets on renewables, CO_2 limitations and energy efficiency. This means that the analysed scenario yields reduced emissions within the electricity sector by 30% by 2020 compared to 1990 levels (a proxy of the outcome of the overall energy system target of 20% reduction) and 50% by 2030 (cf. 40% overall target) and finally a virtual decarbonisation by 2050 for electricity generation, i.e., 99% reduction. Targets for renewables are based on national targets and prognoses in national renewable allocation plans, which also have been used for extrapolation until 2050. The targets on energy efficiency are included via the exogenously set demand development.

To evaluate a likely replacement mix for Swedish nuclear power in the case of a phase-out, we use the European energy system model ELIN. We compare two scenarios. The first assumes a lifetime of 60 years for Swedish nuclear power plants and allows for reinvestment, whereas in the second scenario nuclear power has a lifetime of 45 years and no reinvestment options are available resulting in a gradual phase-out of Swedish nuclear power from 2017 till 2030.

Main findings

- Electricity from nuclear will be replaced by natural gas, wind and coal with CCS instead of mainly coal as assumed by Qvist and Brook.

- Due to the EU emissions trading system this will at most lead to a modest increase of 200 Mtonnes in CO_2 emissions due to the current surplus of emission permits. The reason for an increase is that the emission cap is redundant to at least 2020 due to other policies, especially efficiency targets limiting demand.
- The number of energy-related-deaths is estimated at a maximum of 3000.

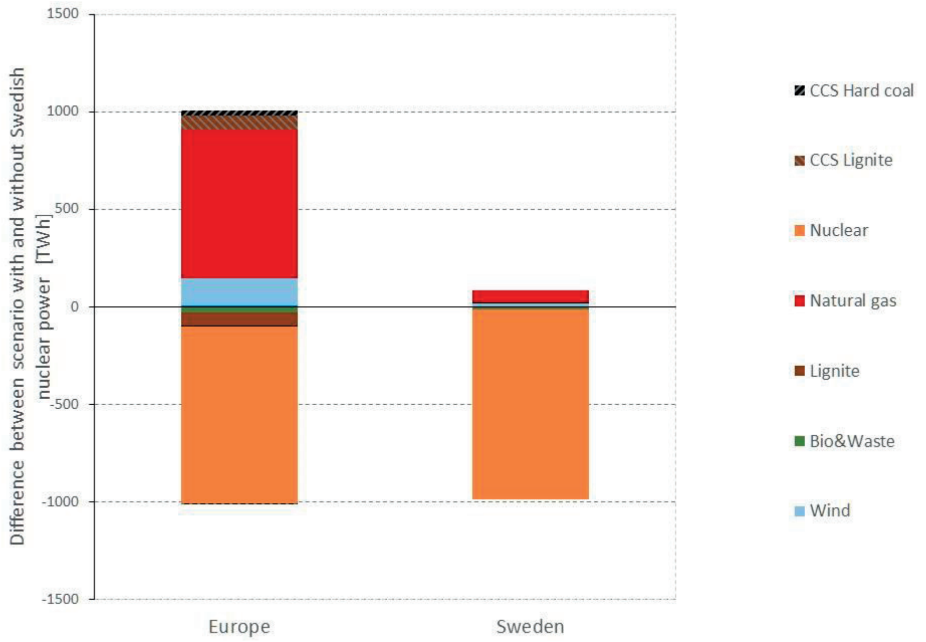

Figure 7. Cumulative difference in electricity production 2015–2045 on European and Swedish levels. The low level of replacement in the Swedish case is due to decreased export of electricity.

Paper IV - Multi-criteria analysis of nuclear power in the global energy system: Assessing trade-offs between simultaneously attainable economic, environmental and social goals

Aim

Global energy studies require comprehensive analysis of several criteria that are partly in conflict, partly synergetic. Therefore interactive multi-criteria tools can help in analysis of possible trade-offs and synergies among energy sources and technologies. Nuclear energy is a prime candidate for such analysis, given the diverging views on this technological option from the vantage point of different stakeholders, requiring analysis in a holistic context. In this study we combined the MESSAGE model with a novel multi-criteria model analysis (MCMA) tool. The main aim of this paper was to investigate the applicability of this approach to multi sector multi region models.

Methodology

Our analysis builds on the MESSAGE version used in the GEA report, specifically the GEA-Mix setup with its intermediate levels of future energy demand. The conventional version of the model makes use of two nuclear technologies with different cost and availability profiles, both utilising light water reactors (LWRs) with a once-through cycle. For the study the fast breeder (FBR) fuel cycle and mixed oxide (MOX) fuel option have also been implemented.

To investigate the benefits and risks of nuclear power in an integrated, holistic framework, we combined MESSAGE with a novel MCMA tool. More specifically, we extended the MESSAGE model specification by adding variables and constraints representing nuclear power technologies as well as the definitions of criteria. In order to assess the role of nuclear power we implemented seven criteria: energy affordability, climate change mitigation, energy security, CCS failure risk, proliferation risk due to enrichment and reprocessing and radioactive waste creation. We used the MESSAGE for generating the Mathematical Programming System (MPS) format files corresponding to the single-criterion optimisation linear programming problem, and then, instead of sending this MPS to the traditional optimiser, we provided it to the interactive MCMA tool. The tool uses the MCMA method described in the method section of this thesis and provides for a set of Pareto solutions corresponding to the preferences specified by the user.

Main findings

The following conclusions can be drawn from our analysis:

- Climate targets are needed to make nuclear power competitive at the modelled cost level.
- Nuclear power plays an important role in climate change mitigation if energy security and affordability goals take precedence.
- The optimal amount of nuclear power in the energy system depends strongly on the stakeholders' preferences.
- Focusing on both climate-mitigation and energy-security goals lessens the need for CCS and therefore also of technology risk arising from the availability of underground carbon storage. This is because the majority of current energy trade consists of fossil fuels; limiting it or limiting emissions will thus reduce the use of fossil fuels and also the need for imports, and also storage of carbon.
- Taking into account the proliferation risk stemming from enrichment in combination with climate targets limits the total amount of nuclear power but enhances the use of FBRs. Assigning importance to limiting reprocessing as well, however, allows nuclear power to be reduced without significant changes in other criteria values.

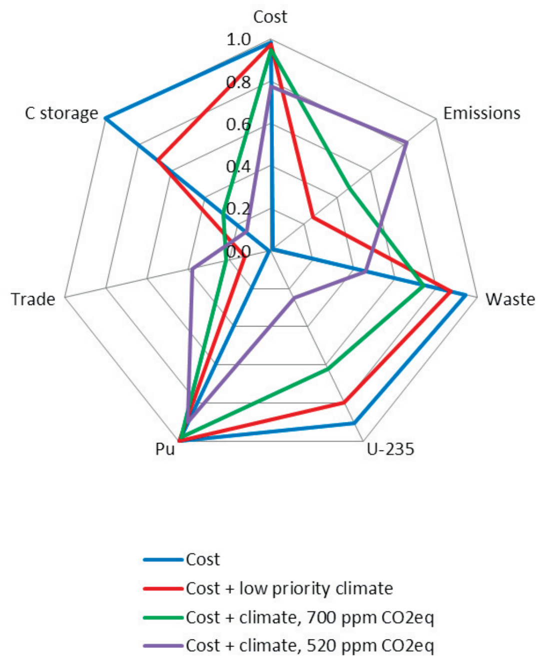

Figure 8. Selected results from varying the importance on cost and climate criteria. The range between Utopia and Nadir values has been normalised, and Utopia and Nadir values have been assigned 1 and 0 accordingly.

Paper V - Using resource based slicing to capture the intermittency of variable renewables

Aim

As the share of variable renewables – wind and solar PV – is expected to grow significantly in coming decades, it has become increasingly important to account for their intermittency in large scale energy models that are used to explore long term energy futures. In this paper we propose and evaluate one method for doing so, namely, resource based slicing.

Methodology

In the model version developed in this paper, GET 9.0., the world is divided into 10 regions. By analysing the global wind speed and solar insolation data we derive load factors for 10 different wind and solar situations in 10 world regions and then use this data as an input for GET model. Furthermore, to take into account the start-up and ramping costs of thermal technologies as well as other uses of hydro reservoirs than power production, we impose a constraint that these technologies if employed must run at least a certain percentage of their maximum output during the whole optimisation period. We complement our analysis by modelling four time durations of storage using transfer matrix approach explained in detail in [66].

Main findings

- Our preliminary results show that this approach manages to capture many aspects introduced by variable renewables such as need for flexible generation capacity and curtailment at high penetration levels.
- Optimal electricity production mixes to vary significantly between regions due to different endowments of solar and wind resources.
- Adding electricity storage to the system will favour solar power but have only a minor effect on wind and nuclear power.
- However, our approach is aimed at large integrated assessment type models, and the simplistic implementation is unable to capture all intermittency related issues

Figure 9. Electricity production mix in different slices for Europe (left) and Africa (right) in 2100 with electricity storage enabled and with the 450 ppm CO_2 scenario. The width of the slice represents the share of hours that fall into this category.

DISCUSSION

METHODOLOGICAL APPROACH

Energy policies, especially related to infrastructure can have a very long lasting effect and potentially also lock us into unsustainable paths. Therefore such decisions should be carefully considered. Although it is impossible to foresee all the consequences of any given policy, significant insight can be gained via systematic analysis. Models can be useful tools in this process. 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 [67] 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 [68]. 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 [67].

Models used in this thesis enable us to construct internally consistent scenarios that fulfils several criteria such as a 2° C temperature target and lowest possible energy system cost, under various constraints and estimates for cost developments for energy conversion technologies, climate sensitivities etc. Although it is unlikely that the cost optimal path will be followed due to the lack of a global government as well as other considerations we have besides the cost such as energy security etc., knowing it can still give us an idea of what is technologically possible, where the major bottle necks and trade-offs in the system are and also a ballpark figure of aggregated costs. These models also enable us to explore alternative futures. After all, we only have one Earth and thus the number of real experiments we can perform on it is limited.

Although a lot can be learned from optimisation models there are also caveats that should be kept in mind while analysing the results. For one thing we do not know the future development of costs and other characteristics of different technologies nor the demands for different energy forms. Yet the models used here project these trends over decades up to a century. Thus these models can only give a temporary understanding of the system and its possible developments and the scenarios developed should be re-evaluated when significant new information emerges.

Also, if the problem is feasible these types of models will provide a solution – a set of values for all the variables in the system. This solution, however, can be only slightly different from another solution in respect of objective function value but vastly different in respect of variable values. One way to overcome this problem is to actively include other relevant criteria for the study as was done in Paper III. Also other methods to overcome this problem exist but they are not discussed here due to limited scope of this thesis.

The models also fail to describe actual agent behaviour, including preferences, risk perception and lack of information. Thus these models also cannot consider social feasibility of developed scenarios and analysis of this type of enablers and barriers is needed to design the policies in the most effective way. Yet the scenarios developed in our models capture many technical, environmental and economic aspects and thus provide a bench mark for directing efforts.

ROBUSTNESS OF THE RESULTS

All models include parameters whose values will determine the results. This is especially true for large scale energy models where such parameters representing costs of different technologies, availability of resources etc. can amount to thousands. At the same time the optimisation method commonly used finds the least cost or maximum welfare solution under given constraints. This means that a technology with only slightly different cost than its main competitor can over take the whole system. To understand how robust received model results are extensive sensitivity analysis of crucial parameters is needed.

For most of the papers in this thesis some sensitivity analysis was performed. This is especially true in respect to the Paper II that grew out of sensitivity analysis for Paper I and where the role of nuclear power in determining the climate change mitigation cost was extensively explored. However, Paper IV does not allow for parameter sensitivity analysis due to the method used. During the multi-criteria analysis only the criteria values can be varied and the rest of the model, including its parameter values, remains fixed. Therefore the sensitivity analysis of parameters should be performed before entering the multi-criteria analysis phase to get an understanding of the basic dynamics of the model. Also the Paper III lacks sensitivity analysis due to the format. This paper was written as a response to another article with the main aim to demonstrate the shortcomings of the method used there and thus the exact result was not of major interest. However, to develop this response into a full paper also the robustness of obtained results needs to be assessed.

However, the sensitivity analysis of parameters only captures the uncertainty within the model. It is also possible that the model is not constructed correctly and does not capture all the relevant dynamics. To alleviate this concern model comparison exercises can be useful as they enable modellers to compare results from vastly different model set-ups and explore the determining dynamics of models. Yet this process in time and resource consuming and thus not often prioritised over comparison of results. GET has not been a part of such model comparison exercise but the results obtained are compared to outcome of model comparison studies such as EMF27 [38]. MESSAGE model that is also used in this thesis is, however, a frequent participant of such exercises. However, the results obtained with GET model are in the range provided by recent EMF27 model comparison study [38].

COMPARISON OF OBTAINED RESULTS WITH OTHER SIMILAR STUDIES

Our finding that nuclear power is likely to reduce climate mitigation cost is also confirmed by various other studies e.g. [19, 36, 38] and the reduction potential reported in these studies is in the similar range to ours. Nifenecker [69] also finds that for large scale expansion of nuclear power alternative uranium resources or breeder reactors will be necessary. Similarly Mori [34] finds that FBRs can potentially play an important role in climate mitigation but are not employed until the second half of the century. Their deployment is also more cost sensitive that LWR reactors.

CONTRIBUTION OF THIS THESIS

THE ROLE OF NUCLEAR POWER IN CLIMATE CHANGE MITIGATION

This thesis finds that nuclear power can reduce the climate change mitigation cost if allowed to expand. In addition to traditional scenario analysis also extensive sensitivity analysis is performed to determine the main factors contributing to abatement cost reductions that has been lacking in the literature before. We identify the costs of nuclear technologies, renewable technologies and the availability and cost of carbon capture and storage as the main determining factors in abatement cost reductions. Developing advanced nuclear technologies such as fast breeder reactors and alternative uranium extraction methods is likely to further reduce the climate change mitigation cost. However, 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.

REPRESENTING NON-MONETARY GOALS IN LARGE SCALE ENERGY MODELS

This thesis uses post analysis of model scenarios to assess the nuclear power expansion's effect on proliferation and multi-criteria model analysis (MCMA) method to actively include criteria such as proliferation and energy security into optimisation. To our knowledge MCMA method has not been applied to large scale energy models before; thus the contribution in this area is mainly methodological. We find multi criteria model analysis significantly improves the analysis of attainability of multiple simultaneous goals in large-scale energy-systems models compared to simple parametric scenario analysis. The approach is more intuitive and requires minimal mathematical skills on the part of the user. MCMA method also avoids infeasible or dominated solutions that are caused by the stringent constraints applied in parametric optimisation.

CAPTURING INTERMITTENCY IN LARGE SCALE ENERGY MODELS

This thesis presents a relatively simple and flexible method for representing the effects of intermittency induced by variable renewables into the power system thus adding to the methodological tool kit to treat intermittency in large integrated assessment type of models. Our preliminary results show that this approach manages to capture many aspects introduced by variable renewables such as need for flexible generation capacity and curtailment at high penetration levels. We show that adding electricity storage to the system will favour solar power but have only a minor effect on wind and nuclear power. However, our approach is aimed at large integrated assessment type models, and the simplistic implementation is unable to capture all intermittency related issues. As always, the suitability of the method depends on the research question one wants to answer.

Further research

The research presented in this thesis can be further developed in several ways. One more general area to explore is the near cost optimal solutions to this type of models. First steps in this direction were taken in Paper IV by actively including other criteria than cost into optimisation but other methods could be used to further this quest. A rational for doing so is that social barriers are likely to exist that interfere with implementation cost optimal solutions. Moving away from cost efficiency can thus enable us to find more socially feasible solutions that are still relatively cost effective.

Also the multi-criteria model analysis method applied in Paper IV can be further applied to investigate synergies and trade-offs among additional or different goals in energy systems than presented in this thesis. However, more work to develop suitable indicators and to test them is needed. The current set up could be further improved to better investigate energy security aspects. In the current version total net energy imports was used as an indicator for energy security but in reality energy security concerns tend to centre more on oil or gas imports depending on a region. For example in USA oil is seen as a main energy security concern whereas in Europe gas imports from Russia are viewed as a possible threat. Therefore regional indicators for oil and gas would better capture the real trade-offs.

This thesis also presents a solution for incorporating the effects of intermittency resulting from employment of variable renewables into a large scale energy model. Further work is needed to improve and test this approach. However based on our preliminary results, we believe that this approach opens up a way to address several new research questions. One of them is the role of storage in the future energy system. It is often believed that cheap storage can solve the intermittency problem but in fact it may not be a cost effective solution for the future energy system due to low utilisation or limited transfer possibilities.

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