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Energy Market Impacts of Nuclear Power Phase-Out Policies

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Sammendrag:. Fukushima-ulykken i mars 2011 økte krav til sikkerhet ved kjernekraftanlegg og holdningen til kjernekraft ble revurdert i flere land. Denne artikkelen studerer virkningen av utfasing av kjernekraft på regionale elektrisitetspriser. Vi ser på 4 scenarier med ulike ambisjonsnivåer for utfasing ved hjelp av en multisektor og multiregional generell likevektsmodell. Annen elektrisitetsproduksjon enn kjernekraft antas å følge New Policies scenarioet i World Energy Outlook (IEA, 2010). Utfasing i Tyskland og Sveits øker elektrisitetsprisene i OECD-Europa med beskjedne 2-3 prosent til å begynne med til 4-5 prosent høyere prisnivå i 2035 hvis overføringskapasitet innen regionen er tilstrekkelig. Hvis alle regioner stenger ned anlegg bygd før 2011 vil Nord-Amerika, OECD-Europa og Japan stå overfor prisøkninger på 23-28 prosent i 2035. Disse prisøkningene illustrerer langsiktige insentiver for investeringer i fornybar elektrisitet eller i forbedret teknologi for kjernekraft.	**Abstract:** After the Fukushima disaster in March 2011 safety concerns have escalated and policies towards nuclear power are being reconsidered in several countries. This article presents a study of the effect of nuclear power phase-out on regional electricity prices. We consider 4 scenarios with various levels of ambition to scale down the nuclear industry using a multiple region, multiple sector global general equilibrium model. Non-nuclear power production follows the New Policies scenario of the World Energy Outlook (IEA, 2010). Phase-out in Germany and Switzerland increases electricity prices of OECD-Europe moderately by 2-3 per cent early on to 4-5 per cent by 2035 if transmission capacity within the region is sufficient. If all regions shut down old plants built before 2011, North America, OECD-Europe and Japan face increasing electricity prices in the range of 23-28 per cent in 2035. These price increases illustrate the incentives for further investments in renewable electricity or improved technologies in nuclear power production.
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1 Introduction

An electricity dependent economy requires a reliable base-load source in the energy portfolio, which makes nuclear power without direct greenhouse gas (GHG) emissions a particularly attractive option. The nuclear power opportunity offers huge emissions reductions, and estimates indicate that a tenfold expansion of nuclear power capacity might avoid 15% of the total cumulative carbon emissions between 2000 and 2075 (van der Zwaan, 2002).

Nonetheless, nuclear power has controversial implications for safety arising from accidents, waste disposal, and risk of nuclear weapon proliferation. Thus far, the industry has had three major accidents i.e. at the Three Mile Island plant in 1979 in the U.S.A, at Chernobyl in the former U.S.S.R in 1986, and at Fukushima Daiichi Plant in Japan in 2011. According to von Hippel (2011) cited in Davis (2012), the Fukushima accident radioactive leak could cause about 1,000 cancer deaths whereas Chernobyl's accident is estimated to have caused 14,000 cancer deaths. However, the political attitudes towards nuclear power are not closely related to own experiences, as is illustrated by the current positions of Germany, Russia and Japan.

According to MIT (2003) the public opinion and professional consensus has been in favor of nuclear power although it is surrounded by extremely complicated safety and global security issues of waste disposal, safety, and proliferation. This is because the problem of climate change poses a strong pressure on demand for carbon free electricity and raises concern for energy security. Several studies report that a significant proportion of the population may reluctantly accept nuclear power for the sake of climate mitigation (Bickerstaff et al., 2008; Corner et al., 2011; Pidgeon et al., 2008; Teräväinen et al., 2011). Except in a few countries, the general trend in public opinion has for some time been greater accommodation of civilian nuclear power. That renaissance lasted until March 2011 when an earthquake and a tsunami lead to meltdown of reactors of the Fukushima Daiichi Nuclear power plant in Japan.

The Fukushima disaster has been behind the recent revival or escalation of anti-nuclear power attitudes in countries such as the US, Germany, Switzerland, Italy, and Belgium although the problem of waste disposal and the earlier accidents of the Three Mile Island and Chernobyl nuclear plants have not disappeared from minds of many people. In the wake of the Fukushima accident, political decisions have altered the position of nuclear power in most of these countries. An exception within OECD is the US, where a new plant was approved in 2012 for the first time after the Three Mile Island accident in 1979 (Reuters, 2012).

The Fukushima Daiichi accident was no accident in an old reactor below critical maintenance level in a country with limited capacity for advanced technology. It demonstrated that a natural phenomenon could set aside presumably advanced security systems, and revealed that a technologically and administratively advanced society like Japan could fail in nuclear safety.

After the accident, the risk of earthquakes and tsunamis facing nuclear facilities of Japan has been reassessed and substantially adjusted upwards (Cyranonoski, 2012). The particular challenges to nuclear energy safety from impacts of climate change have also been focused, as plants are actually vulnerable to both floods and droughts (Kopytko; Kopytko and Perkins, 2011). Existing nuclear plants generally depend on cooling from water and for that reason are located near the sea or along rivers, exposed to floods and sea level rise. A recent example of a critical situation is Fort Calhoun nuclear plant at Missoury River where a serious flood took place in 2010. The plant was close to being incapable of reaching a cold shut down - now the plant is equipped with improved defenses (BEHR, 2011). They are also exposed to close-downs and production loss during heat waves (Kopytko; Linnerud et al., 2011). Upgrading to gas-cooled reactors would mitigate this risk, however, at a considerable cost.

More than a year after the Fukushima accident, only 2 of Japan's 54 reactors are back in operation, and it is highly uncertain if or when more plants will be reopened as the Japanese society at large seems to have lost confidence in nuclear power and turned to programs for renewable energy. Their nuclear program with 14 new reactors to achieve a 50 percent coverage of Japan's electricity demand has been scrapped (Science, 2011).

The situation after Fukushima has also provided opportunity for reconsidering the economy of nuclear energy, highlighting the fact that sluggish growth in nuclear energy is due to high costs and fading government subsidies. The cost of construction has escalated and cost of nuclear power is considerably higher than the cost of electricity from natural gas, even in the case of a 25 USD carbon tax (Davis, 2012). The cost issue might thus even deter new and improved technologies from being phased in. It is symptomatic that the licensing of a new plant in the U.S. is not expected to be the forerunner of an investment boom, as US experiences a bonanza in domestic gas discoveries and extraction.

Many countries have, at least temporarily, halted giving license for new reactors. Germany and Switzerland have set concrete deadlines to phase out nuclear reactors aiming at ultimately removing nuclear power from their energy portfolio by 2022 and 2034 respectively. This would remove about 30% of German's and 40% of Swiss' power capacity and might leave demand unsatisfied without resorting to other sources such as coal, natural gas, hydro power, and other renewable electricity sources. However, trade in electricity might transfer the supply shortage to a wider market beyond Germany and Switzerland.

A phase-out will affect the electricity markets, but how seriously? Kemfert and Traber (2011) explored the effect of the moratorium of seven nuclear power plants of Germany in May 2011 and found only a slight increase in prices leading to a minor reduction in electricity consumption. In the short term the decrease in supply from nuclear energy is replaced by increased production of electricity from coal and gas-fired power plants. This is feasible because all the companies (E.ON, RWE, EnBW, and Vattenfall) whose nuclear reactors were shut down in May 2011 had substantial idle capacity in coal, gas, and oil based power plants. Growitsch and Höffler (2011) use observed reactions in the market and show that Germany's moratorium, although it has no impact on spot prices of electricity, has raised future prices. The authors write that within the next 10 to 15 years, we may expect that the reduction of nuclear capacity will be compensated by fossil fuel power plants, especially hard coal and natural gas as there is a need for base load power supply, which cannot easily be satisfied with renewable energies.

The huge uncertainty and difference in policies between countries can be illustrated by the fact that in the USA a new nuclear plant got approval from the Nuclear Regulation Commission for the first time in 30 years, whereas Japanese experts question both the safety and need for nuclear power after the Fukushima disaster (Normile, 2012a, b). Hence, there is huge uncertainty about future regional supply of nuclear power, about the prices of alternative feedstock for electricity production and also about the climate effect if fossil fuels are filling the gap in electricity supply. It is important, however, to distinguish between the political statements and what might be expected. The Nuclear Regulatory Commission of the USA approved a new plant, but the head of the commission voted against the decision (4-1) due to safety concerns. But most importantly the economic situation now favours gas-fueled electricity, as gas reserves are plentiful both within US and globally. Currently, the gas price is low and might stay that way due to huge reserves in Iran and Qatar (USGS, 2013).

It is likely that nuclear power will see investors demanding higher risk premium and increased subsidies from governments to cope with increasing costs of stricter safety regulation and earlier retirement of plants. A new energy law proposed by the British government in December 2012 seeks to reduce the uncertainty by introducing a guaranteed minimum price for all carbon free power production (The Economist, 2012). The costs of decommissioning and safe disposal of used fuel will also be highlighted during the upcoming close-downs. In Japan, the cost of decontaminating the Fukushima plant will cost US$ 126 billion according to the Tokyo Electric Power Company, twice the clean-up fund established by the government (Nature, 2012).

The position taken by Germany and Switzerland points to the potential tension between a need for climate mitigation and a desire for a society free from nuclear power. Temporary halt or phasing out of nuclear reactors would entail more electricity generation from the other sources to meet a given demand. Subject to the constraint on capacity, the substitution follows a merit order of marginal costs of generating electricity from different sources.

van der Zwaan (2002) suggests that the consequences of phasing out nuclear power plants on the energy market are relevant for the maximum emission reductions the world can achieve. Nonetheless, the issue of potential impacts of nuclear phase-out on energy markets is under-researched. This paper explores the energy market impacts of alternative scenarios of phasing out nuclear power towards 2035. The central question we raise is: how are the electricity prices affected by phasing out nuclear power plants? We approach this question by using the GRACE model, a global CGE, which deals explicitly with 5 different technologies in electricity production. We introduce 4 different scenarios of nuclear power phase-out and trace the effects on regional electricity prices assuming electricity supply from other types of feedstock will follow trajectories in the New Policies scenario of World Energy Outlook (IEA, 2010).

2 Model and phase-out scenarios

The GRACE model developed at CICERO (Aaheim and Rive, 2005) is a multi-sector, multi-region, recursively dynamic global computable general equilibrium model. An updated version of GRACE is described and applied in a more recent application (Rive, 2010). It has 7 regions (North America, OECD-Europe[1], Japan, Russia, China, India and Rest of the world). The depiction of each region's economy includes activities of 15 aggregated production sectors, which are listed in Table A1_1 in Appendix 1. All sectors except the electricity sector produce one composite good (or service) by one single technology.

The model version GRACE developed and used for this study is calibrated around the GTAP v7 database with 2004 as base year (Badri and Walmsley, 2008). The GTAP v7 database is a global database of input-output tables, which has been used for a wide variety of agricultural, trade, and environmental economics analyses[2]. In this study, we consider CO2 emissions from fossil fuels combustion from an auxiliary database provided by GTAP (Lee, 2008).

GRACE's parametric values of the elasticity of substitution are from the MIT EPPA model (Paltsev et al., 2005). Detailed description about the structure of the model, calibration of the parameters, and specifications of preferences and technologies of GRACE are reported in Rive and Mideksa (2009).

The GRACE model depicts electricity production as a nested CES function where the electricity is generated by five technologies: coal-fueled, oil-fueled, gas-fueled, nuclear, and other non-fossil technologies combined (hydro, solar, wind, and bio).The data on electricity production by technology are taken from World Energy Outlook (IEA, 2006) and costs from Table 3.13 in OECD/NEA (2005). These data are used for calibration to make input and output values for each generation technology consistent with the GTAP data on the electricity as described in Appendix 2.

We consider four different phase out scenarios, which we call "Phase out: concrete plan", "Phase out: very old reactors", "Phase out: old reactors", and "Comprehensive phase out".

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[1] Eastern Europe except Russia is part of Rest of the world.

[2] See examples at the GTAP website: https://www.gtap.agecon.purdue.edu/models/research.asp.

Scenario 1 (SN1): Phase-out concrete plan

The "phase out: concrete plan" adjusts for reduction in nuclear power generation capacity for which there is a nationally agreed time line of phase out. Germany and Switzerland are so far the only countries with a concrete plan to phase out their reactors in a nationally agreed time line. The Japanese government announced that it will end the use of nuclear power before 2040, but this plan is not formally incorporated in the national energy strategy and put on hold before an election during the first half year of 2013 (WNN, 2012). Table A1_2 in Appendix 1 presents the technologies and time line of phasing out Germany's nuclear reactors and the associated loss of capacity from the electricity grid.

As can be seen from Table A1_2, Germany has two different types of reactors, i.e. boiling water reactor (BWR) and pressurized water reactor (PWR). Of the total capacity, about 40% were withdrawn from the power grid in March 2011 immediately after the Fukushima accident. The closure time line suggests that closure will resume in 2015 and by 2022, all of the 9 remaining reactors of Germany will be disconnected from the power grid. The other country with a concrete horizon for turning off its reactors is Switzerland. Closure of these reactors will begin in 2019 and the last closure will occur in 2034 (Table A1_3).

Scenario 2 (SN2): Phase-out very old reactors

The scenario "phase out: very old reactors" focuses on the very old reactor technologies Light water graphite moderated reactors (RBMK/LWGR) and Gas Cooled Reactors (GCR), These technologies are still in operation in the United Kingdom and Russia although the U.K. did turn off its gas cooled reactors (GCR) between 2004 and 2011. SN2 assumes that these very old reactors are phased out by 2015 from both the U.K. and Russia. GCR reactors were part of the first generation of prototype reactors to be commissioned for use in electricity production, and their operation identified both strengths and weaknesses of the design. The strengths have been taken aboard in the later Advanced Gas Cooled Reactor design (AGCR, further considered in scenario SN4), but the early GCR reactors have now reached the end of their operational life cycles. Light water graphite moderated reactors, notably used in Russia/former Soviet Union are regarded as early generation-II reactors, but have a number of known security issues. The most notable problems are instability at low operating power and a tendency to increase power output rather than reduce it if inhomogeneities (e.g. steam bubbles) occur in the coolant or moderator. In addition to being early reactor types with issues that have been addressed in later designs, the "very old reactors" of Russia and UK phased out in this scenario have been operating for quite a number of years. System fatigue and wear and tear on the reactor buildings can therefore be expected.

Scenario 3 (SN3): Phase-out old reactors

The "Phase out: old reactors" involves phasing out all plants built before 1975 in a uniform manner by 2035 (the same absolute reduction annually within each region). This group of reactors is mainly early adoptions of the Boiling Water Reactor (BWR) and Pressurized Light

Water Reactor (PWR) designs. These are generation-II designs, building on experience from the first round of prototype reactors, and similar to the bulk of reactors operating today. However, the designs of BWR and PWR reactors have also improved with time and the first ones commissioned can be assumed to have the oldest security and operating systems. While most operating reactors have been retrofitted with later advances in security technology, these first operational reactors will also be experiencing system damage (mechanical system fatigue, weakening of the reactor vessels) due to long term operation and radiation exposure.

Scenario 4 (SN4): Comprehensive phase-out

The last scenario "comprehensive phase out" is shutting down old reactors. According to this scenario, reactors built before 1975, 1976-1980, 1981-1985, 1986-1990, and during 1991-2010 are assumed to be phased out by 2015, 2020, 2025, 2030, and 2035 respectively. China's plants are built more recently and only starts to phase out after 2030. This phase-out will include a number of technologies, both the ones considered in scenarios SN2 and SN3, and more modern designs such as the Advanced Gas Cooled Reactor (AGR) and Canadian Deuterium-Uranium Reactor (CANDU). Such later types have distinct advantages over the early LWR and BWR designs, building on experience from operating early reactors. Most operating reactors have also been retrofitted with later advances in security technology, so there is no clear mapping between the year of first operation and current level of security for this group. However, the main consideration here is the number of years the reactor has been operational. Long term exposure to high levels of radiation, as experienced by the inner components of an operational reactor, will weaken most materials. All reactors are therefore commissioned with a certain lifetime in mind and a natural path towards comprehensive decommissioning would therefore be to follow this general pattern.

Implementation

As a background to our nuclear phase-out scenarios we use an economic baseline scenario (BAU) which is calibrated to reproduce the regional GDP growth and associated energy market development as depicted in the New Policies scenario of World Energy Outlook 2010 (IEA, 2010). The New Policies scenario was established before the Fukushima disaster and is still reflecting the emerging trust in nuclear power as a source of electricity as well as a climate mitigation option.

The New Policies scenario accounts for national pledges to reduce GHG emissions, and for plans to phase out subsidies to fossil energy, i.e. a cautious redirection of the energy system where fossil fuels remain dominating (IEA, 2010). As a result the BAU share of fossil fuels will decline from 81 per cent in 2008 to 74 per cent in 2035.

In our phase-out scenarios, we assume that the regional capacity in other power generation than nuclear will stay unchanged in line with the New Policies Scenario. Hence our study mimics a situation where fossil based electricity production continues as the main pillar for future electricity supply, but where fossil based capacity is constrained to hold back CO2 emissions, thus withstanding a pressure for more fossil electricity after nuclear plant closures. Our time horizon is towards 2035, a period over which CCS (Carbon capture and storage) is not expected to mature and achieve widespread implementation, thus unable to give relief to the climate burden of fossil combustion.

Although the non-nuclear electricity supply is frozen the consumers might switch from electricity to other energy carriers when the price of electricity is increasing. Hence, as the nuclear capacity and thus total capacity in power production is reduced, our study captures the switch from use of electricity to fossil energy as consumers and producers are not constrained in their choices between electricity and other energy like fossil fuels or bioenergy. As a consequence the upward pressure on the electricity price is somewhat relieved.

For Russia we assume that 5 GW of very old reactor capacity and additional 5 GW of more recent plants built before 2011 are already phased out in the BAU scenario.

There is practically no trade in electricity between regions as defined in our model. Hence the regional price effects are strongly related to the history of investments in nuclear power and thus to what extent the existing capacity in nuclear power plants in the region is vulnerable to our phase-out scenarios, which basically target generations of technologies built during different time periods.

Notice that all the scenarios allow for investments in new nuclear power capacity if this is built into the BAU scenario. Even in the “comprehensive phase-out “there might be new investments after 2010 along with the ongoing process of shifting down all older plants.

3 Results

Figure 1 shows the decline of nuclear power capacity in OECD-Europe (EUR) after the political decisions of Germany and Switzerland have been implemented in SN1. The capacity falls markedly from 2020 and creates a difference between BAU and SN1 capacities around 16-17 per cent during 2025-2030 as illustrated in Figure 2.

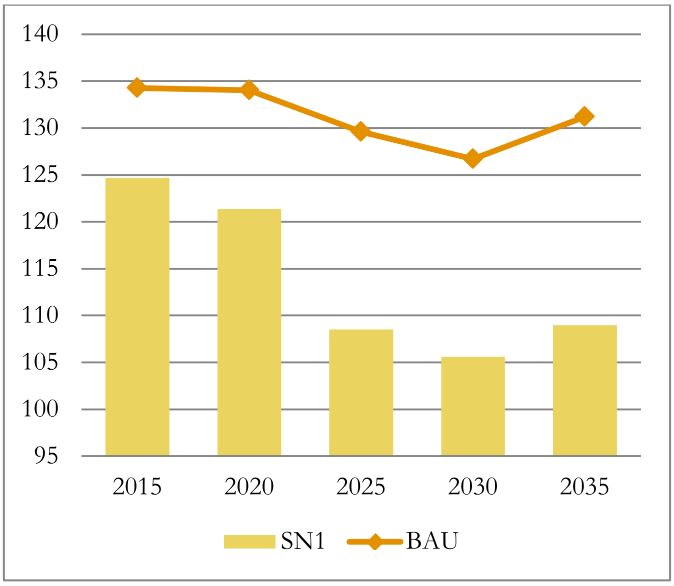

Figure 1. Nuclear power capacity of OECD-Europe in SN1. GW

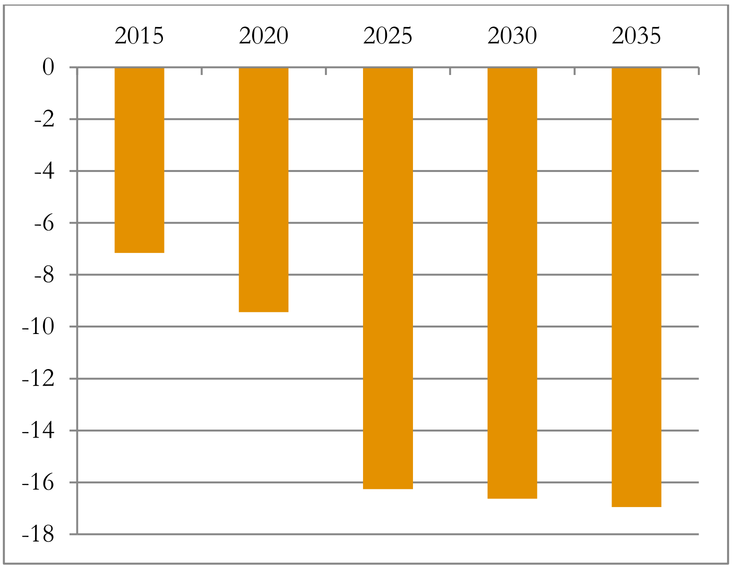

Figure 2. Nuclear power capacity in EU. Deviation from BAU. Percent.

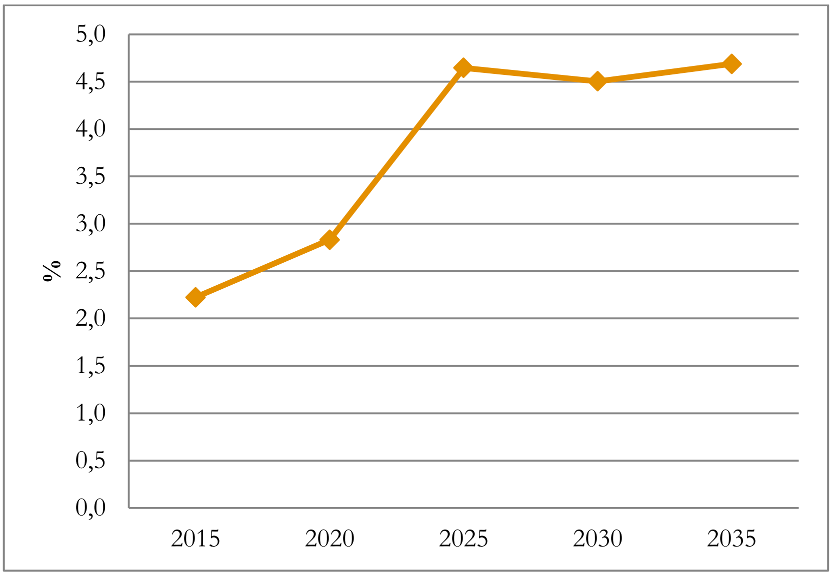

Figure 3 Purchasing prices of electricity in EUR in SN1. Deviation from BAU. Per cent.

Figure 3 shows the effect on the electricity price of OECD-Europe (EUR) over time in the case of nuclear phase-out in Germany and Switzerland (SN1). The price level increases by a modest 2-3 per cent during 2015-2020, before reaching a level around 4.5 per cent above the baseline price level during 2025-2035. Although the economy in OECD-Europe keeps growing the growth rate falls below 2 per cent per year during last part of the time horizon. The upward pressure on the electricity price levels off, as the growth in demand to a large extent is offset by energy efficiency improvement at 1.5 per cent annually in households and industries except the energy sectors. Further, the higher energy costs generate shifts in production and trade, shrinking energy intensive industries and encouraging more import of energy intensive goods. However, in SN1 the effect on the steel market is marginal. The production of steel in EUR is reduced by less than 1 per cent in 2035 compared with in BAU. A third of this fall in supply is compensated by import growth, whereas the export is reduced by 0.8 per cent. Hence, the German and Swiss policies are not having a large effect on the cost of using electricity as long as there is transmission capacity and trade options within EUR. Enhanced growth in the capacity of power production based on fossil or renewable energy is not taken into account in our scenarios. In the short term a switch to more fossil based electricity can thus be expected to modify the price increase. In the longer term we assume that climate policy will constrain the switch to fossil energy as governments have signaled more investments in renewable technologies and increase supply of renewables beyond what is included in the New Policies scenario.

Kemfert and Traber (2011) study the short term effect of the sudden moratorium on 8 nuclear plants in Germany in 2011 based on a model for the German electricity market[3]. They conclude that the surplus capacity in coal and gas-fired plants compensate for the close downs, and that the electricity price in Germany will only increase slightly with an increase of 1.5 per cent for households before tax. Germany generates more electricity than the country consumes, and the export surplus might dwindle and impose price increases in other parts of the Europe. However, if trade options within the region is unconstrained, our study shows that the short to medium term effect on the electricity price in OECD-Europe as a whole will also be moderate. It is reasonable to assume that in the future the transmission capacity will facilitate trade even better than today. Incentives for investments in electricity trade will increasingly come from the potential benefits of trade, but also from an increase in power exchange as increasing shares of renewable electricity demands exchange or storage capacity to serve the market timely.

The time horizons of Kemfert and Traber (2011) is short and thus different from our study, Also, their study is based on a partial model of the German electricity market, whereas we model electricity demand within the whole regional economy and capture the indirect effects via energy substitution, trade and reallocation of investments in production capacity across sectors and regions over time.

An aspect which is not factored in by scenario SN1 in our study is that the overhaul of nuclear energy policies in other European countries might lead to delays in investments in new nuclear power plants and additional upwards pressure on the price level that is neither reflected in the New Policies Scenario (our baseline) nor captured by any of our scenarios.

For OECD-Europe as a whole, the electricity demand in the New Policies scenario stagnates during the whole period 2010-2035 (IEA, 2011), and so does the supply of nuclear power.

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[3] Two of the 8 plants were already out of operation at the time of the moratorium.

Post-Fukishima-ambitions to develop more renewable energy are not included in the New Policies scenario, only taking official policy measures already decided on before the disaster into account. More rapid phasing-in of renewables might modify our estimate of a price increase even further and reduce incentives for further investments in any kind of power production. For example, Germany introduced a comprehensive energy strategy (die Energiwende) to increase renewable energy in June 2011. After the Fukushima accident extended programs for renewables have also been presented in other countries. France launched a considerable program for wind power development in July 2011, with a 10 billion Euro program to build 1200 wind turbines with a capacity of 6 GW (de Saint Jacob, 2011). A new and ambitious bill to make the power sector greener is suggested by the British government (The Economist, 2012). The bill is supposed to guarantee an attractive long term price to encourage renewables to compensate for the shut-down of old nuclear and dirty coal plants. New nuclear power might also benefit from this price floor supposed to be above market price.

However the current economic crisis in Europe challenges the ability to implement such ambitious investment programs. Nuclear plants have high investments costs up front and long planning and construction horizon. Hence nuclear power is likely to be among the more affected by the economic crisis. It adds to the challenge that governments might also be stricter in requiring that the nuclear industry covers its full decommissioning and storage costs. The nuclear phase-out in Germany and Switzerland will further clarify the cost of decommissioning to the industry, the governments and the public. Germany is the only country with some experience when it comes to decommissioning of nuclear plants. The decommissioning of 6 reactors in Greifswald in former East Germany had a total cost of 3.2 billion Euros. However, decommissioning of only one rector of the Chernobyl type in Lithuania alone will require expenditures of 2.9 billion Euros. These costs do not include expenditure for final disposal of waste (EER, 2011) and risk might not be appropriately covered by these estimates. In Japan, the cost of cleaning up after Fukushima is estimated to US$ 126 billion – twice as big as the government fund established for this purpose (Nature, 2012).

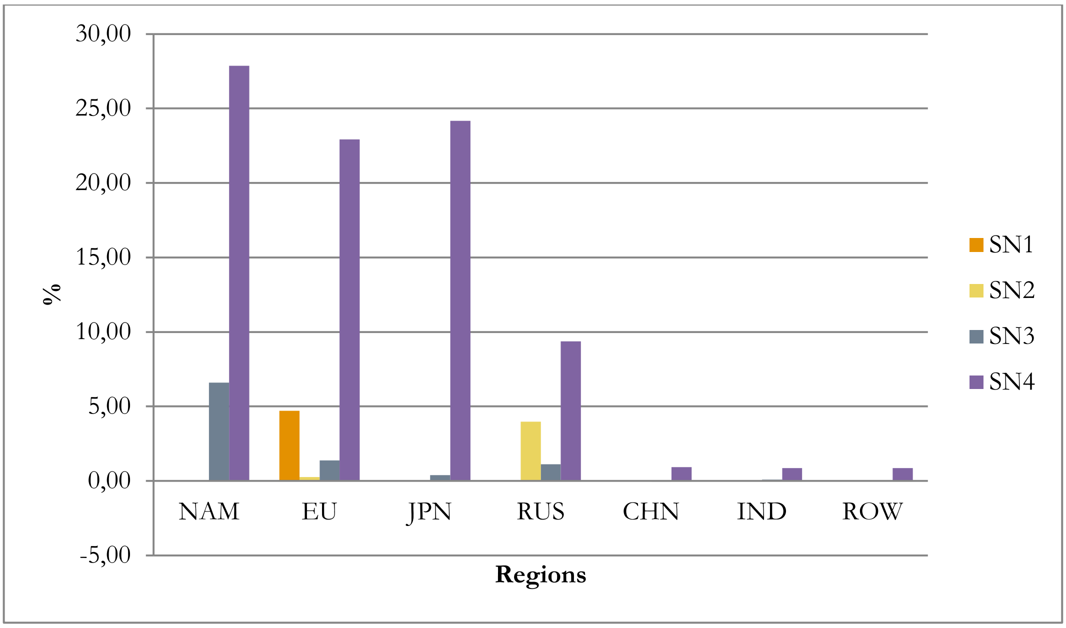

Figure 4 Producer prices of electricity 2035. Deviation from BAU. Per cent

Figure 4 shows the price impacts by region in 2035 of all 4 phase-out scenarios. In the longer term the capacity constraints become tougher, and in SN1 a marked price effect can be expected. However, SN1 depicting nuclear exit in Germany and Switzerland only moderately affects the electricity price in OECD-Europe (5 per cent). In contrast the comprehensive phase-out of all old reactors in SN4 leads to a large increase in the price of electricity in North-America (NAM), OECD-Europe (EUR) and Japan (JPN), and to some extent Russia (RUS).

SN2: "Phase out of very old technologies" mainly affects Russia, which is still relying heavily on Light Water Graphite moderated and Gas Cooled reactors. In this scenario Russia is facing a price increase of 4 per cent. Besides Russia, only UK operates such reactors today. UK already closed one of their plants and a further close down of very old reactors involves a minor share of the EUR capacity. Hence, the price increase in OECD-Europe is limited to 0.25 per cent.

SN3: "Phase out of old technologies" built before 1975 mainly leaves its footprint in North America by raising the electricity price by 6.6 per cent. In particular US, the major nuclear power producer in North America, had a rapid build-up of nuclear power capacity several decades ago. As a consequence there is a substantial number of old reactors built before 1975 to phase out. It adds to the special vulnerability in NAM that no nuclear plant was built in the US after the partial meltdown of the reactor core at Three Mile Island in 1979. Stricter security was introduced, thereby increasing construction costs considerably. Plans for further investments were cancelled. Hence, the existing capacity is largely of first generation reactors. The interest in nuclear power reemerged over the decades, however. In February 2012 the Nuclear Regulatory Commission of the US approved plans for the first new nuclear plant in

30 years, although under objections of the panel chairman who referred to safety concerns after the Fukushima disaster (Reuters, 2012).

SN4: Comprehensive phase-out of old plants takes all nuclear power capacity in operation before 2011 gradually out of production in all regions, only newly built reactors after 2010 are producing. NAM experiences the highest price increase (28 per cent), Japan 24 per cent and EUR 23 per cent.

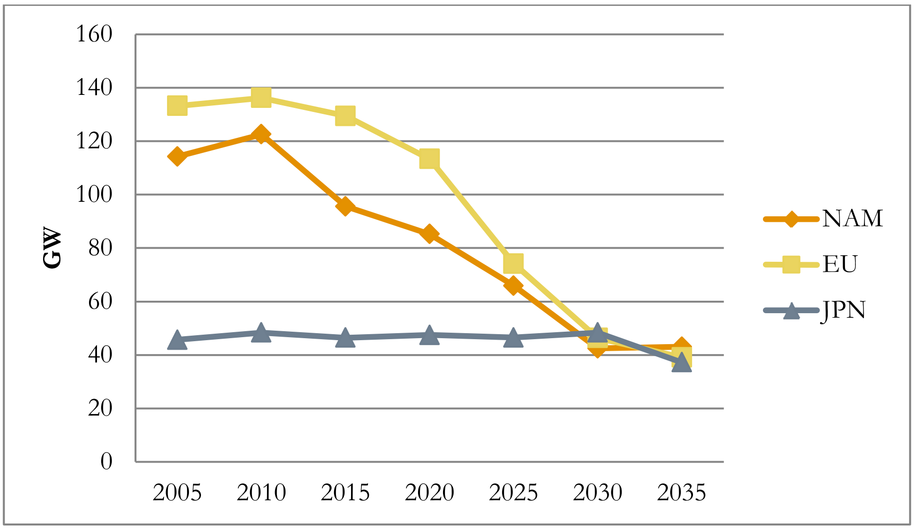

Figure 5. Remaining nuclear capacity in major OECD - regions. SN4.

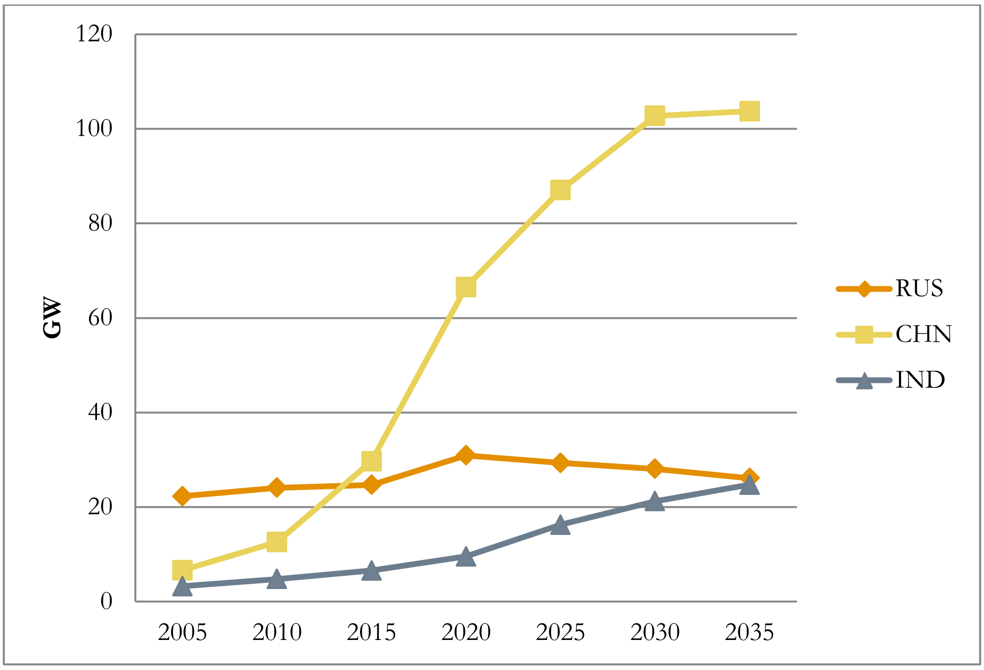

Figure 6. Remaining nuclear power capacity. Major Non-OECD- countries. SN4.

Figures 5-6 shows the remaining nuclear power capacity in the comprehensive phase out scenario (SN4). Japan is roughly maintaining capacity with a moderate price increase of 8 per cent by 2030. Then a marked price rise to 24 percent above BAU occurs as a 23 per cent decline in nuclear power capacity and production takes place.

Our comprehensive phase-out scenario reduces the capacity of nuclear power in North America, OECD-Europe and Japan by 72, 70 and 48 per cent respectively. Although nuclear capacity is declining markedly, the loss in total supply is moderate to negligible on the regions. Most affected is Japan (10%), whereas North-America and OECD-Europe face reduction of 7 percent each. These capacity reductions are followed by price increases of 28, 23 and 24 per cent, respectively (Figure 7).

IEA (2011) presents a Low Nuclear case where global capacity in nuclear power plants is reduced to about half the level in New Policies scenario in 2035. The Low Nuclear case assumes that OECD - countries will build no new reactors beyond those already under construction, and in Non-OECD all plants under construction are completed, but only 50 % of additional projected plants in New Policies scenario proceed as planned. Reactors built before 1980 are supposed to retire after 45 years (50 years in the New Policy scenario, whereas reactors built 1980 onwards retire after 50 years (55 in New Policy scenario).

This represents a reduction in global nuclear power capacity from 633 GW in the New Policies scenario to 335 GW in 2035. For OECD there is a decline from 380 GW in the New Policies scenario to 171 in the Low Nuclear case, i.e. a 55 per cent reduction. Although we cannot compare directly it is interesting to see our results concerning price impacts in relation to the nuclear power scale down in the Low Nuclear case. For our OECD-members NAM, EIR and Japan the capacity reduction in our SN4 is 72, 70 and 48 per cent respectively. The Low Nuclear case assumes a higher supply of electricity from fossil fuels and renewables than in the New Policies scenario, assuming that globally coal and gas use will increase by 290 million tons coal equivalents (Mtce) and 130 billion cubic meters (bcm) respectively. Renewables are supposed to increase by 550 TWh compared with New Policies, an increase which is equivalent to 5 times current consumption of renewables in Germany.

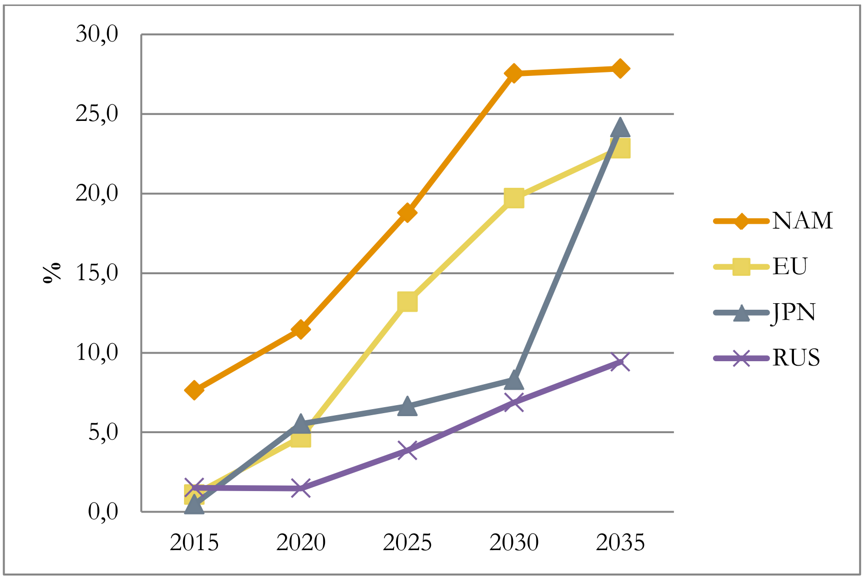

Figure 7 Purchasing price of electricity in SN4 Deviation from BAU. Per cent

3.1 GDP changes

In our scenarios with nuclear power phase-out, GDP is generally lower than in BAU (Figure 8). The only exception is Russia in SN2, the case with phase-out of the very old technologies, which are mainly found in Russia. It seems peculiar that an electricity shortage enhances Russian GDP, and it actually is an index issue. To estimate the future GDP by region in real terms, the world consumer price index (W-CPI) is used to deflate the nominal values. It turns out that Russia gains in purchasing power in the global market from the reduction of the nuclear power phase-out in SN2. When Russia's GDP is calculated with domestic CPI, it shows a decline.

Generally the impacts on GDP in SN1, SN2 and SN3 are negative but negligible in all regions. In the most drastic phase-out scenario SN4 with comprehensive phase out of all plants built and in operation before 2011, the GDP reductions in 2035 are around 0.3-0.4 per cent for all regions. It is somewhat surprising that the largest GDP reduction in SN4 appears in China. China has the world's most ambitious program for increase in nuclear capacity (IEA, 2011). China has rapid economic growth and even a minor constraint on the electricity supply might be expected to affect the GDP growth markedly. However, the price of electricity in the Chinese market is increasing less than 1 per cent and does not signal a serious constraint. The reduction in China's GDP might rather reflect that China depends strongly on global economic growth. Reduced GDP in countries that are more exposed to the nuclear phase-out might compound into reduced export and GDP for China. The fact that the producer price on electricity in China increases only marginally indicates that the general effect via reduced export of manufactured (consumer) goods is dominating, Electricity is a substantial input factor in the consumer goods industry, thus facing the combined effect of less demand globally and a domestic cost increase.

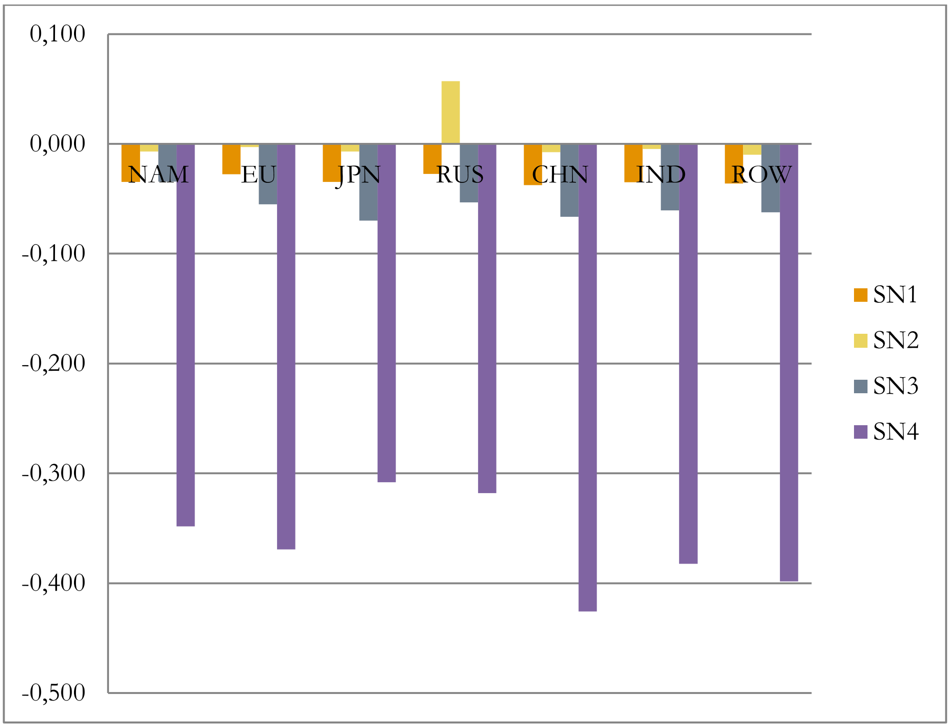

Figure 8. Effects of nuclear power phase-out on GDP. 2035. Per cent.

3.2 Emissions from fossil fuels

Nuclear power phase-out in one or more regions always implies less energy supply as a whole in both the regional and the global economy. This must result in higher energy prices and discourage energy consumption including fossil fuels in the region. When considered separately, this first order price effect implies fewer emissions from fossil fuels. However, substitution effects will also show up as a result of changes in relative prices among electricity and other energy goods. The electricity price increases faster than other energy prices when nuclear power plants are shut down. Whereas supply of fossil based electricity is constrained in our scenarios, supply of fossil energy to other end use is flexible, including supply to production of energy intensive goods largely based on fossil fuels. A relative price increase for electricity can encourage consumers to use more fossil fuels for heating and cooking to replace increasingly expensive electricity, thus increasing the share of fossil fuels in total energy use in the region.

In our study the non-nuclear electricity production by intention follows exogenous trajectories, the purpose being to assess the pressure on the electricity price in the wake of a nuclear power phase-out. Thus, a potential switch to fossil and other feedstock for electricity production beyond what is covered by the New Policies scenario is not visible to us. However, users are free to switch from electricity towards other energy sources in our study. More use of fossil fuels will lead to higher CO2 emissions, but generally the price elasticity of electricity is low and we see that the switch to fossil fuels is rather limited.

It turns out that the change in global CO2 emissions are negligible and tends to be negative (Figure 9). Fossil fuel combustion is generally reduced as the GDPs of the regional economies are somewhat reduced, and this effect dominates over the increase of fossil fuel combustion as a substitute for more expensive electricity.

Russia in SN2 and SN4 are the only cases with marked reductions in CO2 emissions. Higher electricity prices lead to as much as 5.4 per cent reduction in steel production by in 2035, Steel production is a large CO2-emitter and electricity represents a major cost element in that industry. Reduced steel production also means lower demand for gas, with the domestic gas price slightly falling.

In SN4 Russia experience the smallest reduction in GDP, and one might expect Russia's emissions to be less affected than emissions in other regions. However, the effect of lower steel production is dominating and Russia is reducing emissions by as much as 0.8 per cent in SN4, more than the reduction in GDP in relative terms (3 %).

For Russia the scenario of comprehensive phase-out of old technologies in SN4 is quite similar to SN2 as the very old plants phased out in SN2 dominates the sector and SN4 and SN2 therefore to a large extent overlap. As a result the comprehensive nuclear power phase-out by 2035 generates only slightly higher price increase of electricity (9 per cent) than scenario 2 (8 per cent). However, Russia's GDP decreases in SN4 whereas it increases in SN2. The decrease in GDP in SN4 is the impact of a worldwide reduction in economic activity as electricity and other sources of energy are increasingly scarce and constrain production somewhat. In SN2 this effect was negligible. Russia in SN2 was more or less alone in the phasing out nuclear power, i.e. the very old technologies, without the reactions in the world economy.

In SN4 Russia experiences a much smaller electricity price increase than North America, EU and Japan, but still emissions are reduced more. Declining steel production in Russia creates a domestic slack in demand for gas. Rather than using more gas at home, it has become more attractive to export gas to regions with increasing prices of fossil energy.

North America and OECD - Europe increase their emissions somewhat, but not enough to raise the global emission level in SN4.

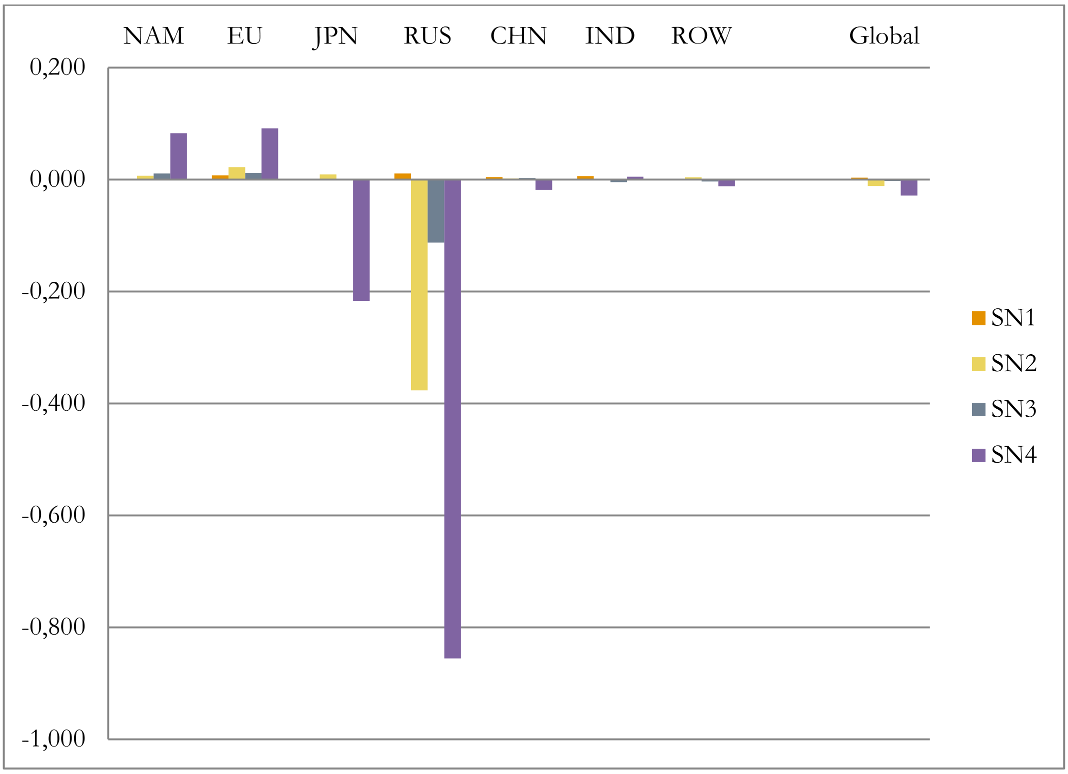

Figure 9. CO2 emissions from fossil fuels. Deviation from BAU. Per cent.

4 Concluding remarks

The future role of nuclear power is highly uncertain and model based analyses might be useful. Our study indicates the upward pressure on the electricity price from specific reductions in nuclear power production in a hypothetical case where supply of non-nuclear power is frozen and follows the IEA 2010 New Policies scenario. By illustrating the price effects our study provides useful indications of the change in incentives for future power production in general, in case of a nuclear phase-out. The model ensures consistency with development in economic growth and trade and our results account for the adaptation through markets, for instance through trade in energy intensive goods and location of their production capacity.

Nuclear power phase-out in line with political decisions in Germany and Switzerland will only cause a minor upward pressure on the electricity price in OECD-Europe if internal regional trade in electricity is flexible. This limited phase-out takes place in a region with a rather moderate expected increase in electricity demand. The foreseen growth in electricity demand in OECD-Europe during 2015-2035 is about 1 per cent per year (IEA, 2010), whereas annual economic growth rate is around 2 per cent. Hence, a phase–out might not impose serious constraints on the economies of OECD-Europe.

On the other hand a comprehensive phase-out only allowing new nuclear plants built after 2010 to operate generates a considerable upward pressure on the electricity-price in North America, OECD-Europe and Japan. By 2035 Japan experiences a price increase of 24 percent, slightly more than OECD-Europe (23 per cent) but markedly less than in North America (28 per cent). Japan was expected to increase nuclear power capacity after 2010 and consistent with our BAU Japan increases its share of nuclear power in electricity production to 44 per cent by 2035. Notice that the BAU scenario depicts a substantial reduction in coal based electricity in Japan, in line with high climate mitigation ambitious. Notice as well that no post-Fukushima changes in policy towards nuclear power are considered in our scenarios.

The global CO2 emissions will only be negligibly affected, since electricity based on fossil fuels is exogenous in our scenarios. In the case where Germany and Switzerland (OECD-Europe) reduces capacity CO2 emissions tends to increase. In the most drastic phase-out scenario the emissions tend to decrease.

The future role of nuclear power is challenged from two sides by safety concerns and high costs. The up-front investments and production costs are high, and the costs of decommissioning and fuel storage will emerge as plants are ending their life cycles. The competition from natural gas will become tougher. Huge shale gas reserves in the U.S. are already on stream, and the Middle East, particularly Iran and Qatar have large reserves, able to keep the gas price low years ahead. Gas fuelled power production has far lower investment costs, which is a benefit in the current economic crisis.

Our results illustrate that even a comprehensive phase-out in OECD can be handled without extreme price increases, but still provide incentives to add more renewable capacity than what is already embedded in the New Policies Scenario.

Appendix 1 Tables

Brief	Explanation
agr	Agriculture
ser	Services
frs	Forest
fsh	Fisheries
iron	Iron and steel
nmm	Non-Metallic minerals including cement, plaster, lime, gravel, concrete (cement)
pro	Other manufacturing
air	Air transport
sea	Sea transport
tran	Other transport
cru	Crude oil
col	Coal
ref	Refined oil
elc	Electricity
gas	Gas

Table A1_ 1. Sectors in GRACE

Plant	Type	MWe (net)	Commercial operation	Operator	Provisionally scheduled shut-down 2001	2010 agreed shut-down	March 2011shutdown & May closure plan
Biblis-A	PWR	1167	2/1975	RWE	2008	2016	yes
Neckarwestheim-1	PWR	785	12/1976	EnBW	2009	2017	yes
Brunsbüttel	BWR	771	2/1977	Vattenfall	2009	2018	yes
Biblis-B	PWR	1240	1/1977	RWE	2011	2018	yes
Isar-1	BWR	878	3/1979	E.ON	2011	2019	yes
Unterweser	PWR	1345	9/1979	E.ON	2012	2020	yes
Phillipsburg-1	BWR	890	3/1980	EnBW	2012	2026	yes
Krummel	BWR	1260	3/1984	Vattenfall	2016	2030	yes
Total shut down (8)		**8336**					
Grafenrheinfeld	PWR	1275	6/1982	E.ON	2014	2028	2015
Gundremmingen-B	BWR	1284	4/1984	RWE	2016	2030	2017
Gundremmingen-C	BWR	1288	1/1985	RWE	2016	2030	2021
Gröhnde	PWR	1360	2/1985	E.ON	2017	2031	2021
Phillipsburg-2	PWR	1392	4/1985	EnBW	2018	2032	2019
Brokdorf	PWR	1370	12/1986	E.ON	2019	2033	2021
Isar-2	PWR	1400	4/1988	E.ON	2020	2034	2022
Emsland	PWR	1329	6/1988	RWE	2021	2035	2022
Neckarwestheim-2	PWR	1305	4/1989	EnBW	2022	2036	2022
Total operating (9)		**12,003**					

Source: WNO (http://www.world-nuclear.org/info/inf43.html accessed 1/27/12)

Table A1_2. German Nuclear Power Units

Reactors	Operator	Type	Net MWe	First power	Expected closure (approx)
Beznau 1	NOK	PWR	365	1969	2019
Beznau 2	NOK	PWR	365	1971	2021
Gösgen	KKG/Alpiq	PWR	985	1979	2029
Mühleberg	BKW	BWR	372	1971	2022
Leibstadt	NOK/Alpiq	BWR	1165	1984	2034

Source: WNO (http://www.world-nuclear.org/info/inf86.html accessed 1/27/12)

Table A1_3. Operating Swiss Nuclear Power Reactors

Appendix 2 Electricity generation in GRACE

In the standard GRACE model, there is only one electricity generating sector. To analyze the implications of nuclear power phase-out, we split the electricity generation sector into the 5 sub-sectors: electricity fueled by coal, gas, oil, nuclear, and others such as hydro, solar, wind and bioenergy.

To determine the activity level of each sub-sector of electricity generation, we used the data on electricity generation in physical terms of World Energy Outlook (IEA, 2006). Assuming the sub-sectors have unit costs as summarized from Table 3.13 in OECD/NEA (2005)[4], we calculated total costs of electricity generation by sub-sectors. Assumption zero profit, total costs of each sub-sector were shifted up/down at the same rate to obtain output value of each sub-sector to ensure that the sum of output values of all the five sub-sectors equals the output value of the aggregated electricity sector in the GTAP database.

We then split the energy use by sub-sector from their use of other intermediates. We assume all coal inputs in the aggregate electricity sector of GTAP are used by the sub-sector coal-fueled power, all oil inputs by oil-fueled power, all gas inputs by gas-fueled power, all non-metallic minerals (serving as an indicator of uranium) by nuclear power, and all agricultural inputs (serving as an indicator of bioenergy) by others.

To allocate labor and capital to sub-sectors, we first sum them up and then allocate back to them based on their shares summarized from a study by McKinsey (2009). This allocation of labor and capital within each sub-sector leads to the sum of labor inputs across sub-sectors slightly different from labor inputs to the aggregated electricity sector in the original GRACE model. To solve the problem, we run the model just for 2004 to obtain an equilibrium that is slightly different from the initial data of 2004 in GRACE.

Having allocated fuel, labor and capital to sub-sectors, intermediate input is found as the residual. If fuel input is larger than total intermediate inputs of corresponding sub-sector, we directly set the fuel input equal to the total intermediate inputs of the sub-sector and the

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[4] The latest version of Projected Costs of Generating Electricity is the 2010 version OECD/NEA, 2010. Projected Costs of Generating Electricity 2010. OECD/Nuclear Energy Agency, OECD Publishing.. We did not use the unit costs of the 2010 version since we have 2004 as the base year. The information of the 2005 version is closer to the base year case.

remainder of the fuel inputs is allocated to other sub-sectors in the same proportion as other intermediate inputs.

All the other intermediate inputs are allocated to sub-sectors on the basis of the shares of the remainder of total intermediate inputs among sub-sectors.

We assume each sub-sector has the same production structure as the initial aggregated electricity sector except two adjustments. One is key fuels used by sub-sectors, such as coal for coal-fueled power and gas for gas-fueled power, which are assumed to be on the top level of a Leontief combination. This implies that electricity cannot be generated without inputs of the fuels. The other adjustment is the introduction of capacity constraint for each sub-sector. We assume there are linear relations between capacity and generation of electricity from each sub-sector. The capacity constraints are exogenously given such that the electricity generation levels from sub-sectors are calibrated to the baseline projection made by World Energy Outlook 2011 (IEA, 2011).

All the electricity generated from sub-sectors is supposed to be bought by a virtual electricity distributor who then supplies consumers at a uniform market price and with zero profit. We assume almost perfect substitution between electricity from sub-sectors by letting a CES combination with the substitution elasticity between sub-sectors at 10 aggregate the supply. The generation level of each sub-sector is controlled by capacity constraints such that the sub-sector may earn net profit in the form of shadow value of the capacity constraints.

In this study of nuclear power phase-out the capacity and so the generation from sub-sectors is assumed to be exogenous in all scenarios, i.e., the phase-out of nuclear has no effects on generation from other sub-sectors. Hence, the phase-out of nuclear power then directly implies higher electricity prices in the market compared with baseline scenario since the phase-out introduces a shortage of electricity supply.

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