Energy market Impacts of Nuclear Power Phase-Out Policies

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Abstract

Since the Fukushima disaster in Japan 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 upward pressure on regional electricity prices from nuclear power phase-out in four scenarios with various levels of ambition to scale down the nuclear power industry. We use a global general equilibrium model to calculate regional electricity prices that are matching demand with the constrained power supply after the nuclear power phases out. Nuclear power exit in Germany and Switzerland might increase electricity prices in Europe moderately by 2–3 per cent early on to 4–5 per cent by 2035 if transmission capacity within the region is sufficient. In a gradual and comprehensive phase-out of plants built before 2011, North America, Europe and Japan face an upward pressure on electricity prices in the range of 23-28 per cent towards 2035, representing the incentives for further investments in any kind of electricity.

Keywords: Nuclear power; Fukushima disaster; Energy market; General equilibrium; Carbon emissions

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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 emission reductions, and estimates indicate that a tenfold expansion of nuclear power capacity might avoid 15 per cent of 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 the United States (U.S.) in 1979, at Chernobyl in the former Union of Soviet Socialist Republics (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 illustrated by the current positions of Germany, Russia and Japan.

The public in many countries with nuclear power are skeptical towards the technology (MIT, 2003), but the political and professional consensus has been in favor of nuclear power even though it is surrounded by extremely complicated safety and global security issues of waste disposal, safety, and proliferation. The challenge of climate change poses a strong pressure on demand for carbon free electricity and several studies report that a significant proportion of the population in Europe may reluctantly accept nuclear power for the sake of climate mitigation (Bickerstaff, Lorenzoni, Pidgeon, Poortinga, & Simmons, 2008; Corner et al., 2011; Pidgeon, Lorenzoni, & Poortinga, 2008; Teräväinen, Lehtonen, & Martiskainen, 2011). Except in a few countries, the general trend 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 accident 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.

A natural disaster triggered the Fukushima accident. However, nuclear energy safety and efficiency are also exposed to impacts of climate change. 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 (Kopytko, 2011; Kopytko & Perkins, 2011). Nuclear plants are also exposed to close-downs and production loss during heat waves (Kopytko, 2011; Linnerud, Mideksa, & Eskeland, 2011). Upgrading to gas-cooled reactors would mitigate this risk, however, at a considerable cost.

The situation after Fukushima has provided opportunity for reconsidering the economy of nuclear energy. The cost of construction has escalated for the U.S. and France over the last years (Grubler, 2010; Koomey & Hultman, 2007). In the New Policies Scenario of The International Energy Agency (IEA) the overnight cost of new capacity within the Organisation for Economic Co-operation and Development (OECD) ranges from 3500 to 4600 U.S. dollars (USD) per kilowatts and at the lower end, the cost is almost 5 times that of natural gas plants (IEA, 2011). In addition, there are financial costs up to 50 per cent of total costs. The cost of nuclear power turns out to be considerably higher than that of electricity from natural gas, even in the case of a 25 USD carbon tax (Davis, 2012). Hence, the high cost level might even deter new and improved technologies from being phased in.

It is likely that nuclear power will see investors demanding higher risk premium. Besides risk of accidents, the industry is exposed to political risk of phase-out or long interruptions in production. The costs of decommissioning and safe disposal of used fuel will also be highlighted during the upcoming controlled closedowns in Germany and Switzerland. In Japan, the cost of decontaminating the Fukushima plant will cost 126 billion USD according to the Tokyo Electric Power Company, twice the clean-up fund established by the government (Nature, 2012).

It remains to be seen if and how much governments will contribute financially to nuclear power in a situation where many countries face high unemployment and shrinking budgets. In the United Kingdom (U.K.) an energy market reform already in place was converted to energy law in December 2013 (United Kingdom Government, 2013), reducing the uncertainty of low carbon technologies through a minimum price guarantee. By late October 2013 the U.K. Government agreed with the French utility (EDF; Electricity of France) to build the first new nuclear plant in the U.K. for a generation, with a government price guarantee of 92.50 U.K. pounds per megawatt produced, double the current electricity price and fully indexed to consumer price inflation (The Financial Times, 2013).

Three years after the Fukushima accident, Japan experiences its first winter without nuclear power (Japan Times, 2014) and it is highly uncertain if or when plants will be reopened as the Japanese society seems to have lost much of its confidence in nuclear power and turned to programs for renewable energy. Encouraged by a generous feed in tariff solar energy investments in Japan are more than tripled from 2012 to 2013 (The Energy Collective, 2013). Japan's nuclear program with 14 new reactors to achieve a 50 per cent coverage of Japan's electricity demand has been scrapped (Science, 2011). However, the Nuclear Regulation Authority has under consideration seven utilities' plans to restart a total of 16 reactors at nine plants (Japan Times, 2014) even though the process of regulatory clearance for restarting is slow and expected to take some years (World Nuclear Association, 2014b).

Germany and Switzerland have set concrete deadlines for phasing out nuclear reactors aiming at ultimately removing nuclear power from their energy portfolio by 2022 and 2034 respectively. This will remove about 30 per cent of German and 40 per cent of Switzerland power capacity. However, trade in electricity might transfer the supply shortage to a wider European electricity market.

The huge uncertainty and difference in policies between countries can be illustrated by the fact that the U.S. Nuclear Regulation Commission approved a new nuclear plant in 2012 for the first time after the Three Mile Island accident in 1979 (Reuters, 2012), whereas Japanese experts question both the safety and need for nuclear power after the Fukushima disaster (Normile, 2012a, 2012b). To sum up, there is considerable uncertainty about future regional supply of nuclear power, about the prices of alternative feedstock for electricity production and about the climate effect if fossil fuels are filling the gap in electricity supply.

The prospects for nuclear power under various assumptions on climate mitigation policies have been studied by several authors (see Duscha, Schumacher, Schleich, & Buisson, 2013 for an overview). Most studies are bottom up and conclude that additional costs of phasing out nuclear power will be less than one per cent of global gross domestic product (GDP). However, Bauer, Brecha, and Luderer (2012) use a multiregional global energy economy model to simulate phase-out of nuclear power, carrying out an economic assessment of the trade-offs between nuclear phase-out and climate policies towards 2100 under intertemporal optimization with perfect foresight.

This paper explores the impacts of phasing out nuclear power from a different angle. We question how much the loss of nuclear power capacity will raise the electricity price if no new power capacity is filling in the gap between demand and supply[i]. The increase in the price of electricity represents the willingness to pay for new power supply to compensate for the nuclear power phase-out. It informs new investors about their potential return on involvements in fossil, renewable or even nuclear power if new nuclear technologies are accepted. It will also inform governments about the need for subsidies if they want to support one or the other electricity power technologies to fill the deficit in future electricity supply.

2 Model and phase-out scenarios

The GRACE[ii] model (Aaheim & Rive, 2005) is a multi-sector, multi-region, recursively dynamic global computable general equilibrium model. It has seven regions (North America, OECD Europe[iii], Japan, Russia, China, India and Rest of the World). The depiction of each region's economy includes activities of 15 aggregated production sectors (Table 3, Glomsrød, Wei, & Alfsen, 2013). All sectors except the electricity sector produce one composite good (or service) by one single technology. The GRACE model depicts electricity production as a nested constant elasticity substitution (CES) function where the electricity is generated by five technologies: coal-fuelled, oil-fuelled, gas-fuelled, nuclear, and other non-fossil technologies combined (hydropower, solar power, wind power, and bioenergy power).

GRACE's parametric values of the elasticity of substitution are from the Emissions Prediction and Policy Analysis (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 model version GRACE developed and used for this study is calibrated around the Global Trade Analysis Project (GTAP) v7 database with 2004 as base year (Badri & 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[iv]. In this study, we consider carbon dioxide (CO_2) emissions from fossil-fuel combustion from an auxiliary database provided by GTAP (Lee, 2008). 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 electricity as described in the Appendix.

Scenarios

Scenario 1 (SN1): Concrete plan

We consider four phase-out scenarios: Concrete plan; Closing very old reactors; Closing reactors built before 1975; and Comprehensive phase-out. In SN1, concrete plan adjusts 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. World Nuclear Association (2014a) presents the technologies and time line for Germany's nuclear reactors and the associated loss of capacity from the electricity grid.

Germany has two different types of reactors, i.e. boiling water reactor and pressurized water reactor. Of total capacity, about 40 per cent were withdrawn from the power grid already in March 2011 immediately after the Fukushima accident. Further closure will resume in 2015 and by 2022, all of the nine 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. Close-down of these reactors will begin in 2019 and the last one will end operation in 2034 (World Nuclear Association, 2014c).

Scenario 2 (SN2): Closing very old reactors

The scenario of closing very old reactors focuses on the very old reactor technologies light water graphite moderated reactors and gas cooled reactors. These technologies are still in operation in the United Kingdom and Russia. In SN2, these very old reactors are phased out by 2015 from both the U.K. and Russia. Security arguments are relevant for these shutdowns. Gas cooled 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 (further considered in scenario SN4), but the early gas cooled reactors have now reached the end of their operational life cycles. Light water graphite moderated reactors notably used in Russia 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 rather than reduce power output 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 U.K. 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): Closing reactors built before 1975

These rectors are now at least 40 years and might still have permission to extend operations. However, in 2035, the youngest reactor will be 60 years and a closedown might be expected. The scenario involves phasing out of all plants built before 1975 in a uniform manner by 2035 (the same absolute reduction annually within each region). This group of reactors are mainly early adoptions of the boiling water reactor and pressurized light water reactor 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 boiling water and pressurized light water 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. SN3 represents a path where the political will to extend their operational lifetime is limited and reactor age and security systems trigger a phase-out.

Scenario 4 (SN4): Comprehensive phase-out

Comprehensive phase-out is illustrating a strict control regime towards all old technologies by not extending their operational lifetime as is currently the practice. It is less drastic than the policies of Germany and Switzerland as SN4 allows new and safer technologies to be built. SN4 is shutting down all reactors built before the Fukushima accident in 2011. 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 and Canadian deuterium-uranium reactor. Such later types have distinct advantages over the early light water and boiling water reactor 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, therefore, are 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 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 BAU 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 fossil-based capacity is constrained to hold back CO_2 emissions, thus withstanding a pressure for more fossil electricity after nuclear plant closures. Our time horizon is towards 2035, a period over which carbon capture and storage technology is not expected to mature and achieve widespread implementation, thus unable to give relief to the climate burden of fossil combustion.

The New Policies Scenario was established before the Fukushima disaster and still reflecting the emerging trust in nuclear power as a source of electricity as well as a climate mitigation option. On the other hand, new and ambitious programs for investments in renewables in the wake of Fukushima were not taken into account.

Post-Fukushima-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 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 gigawatts (de Saint Jacob, 2011) and a new and ambitious law to make the power sector greener is implemented by the U.K. government. For Russia, we assume that five gigawatts (GW) of very old reactor capacity and additional five GW of more recent plants built before 2011 are already phased out in the BAU scenario.

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. Consequently, the upward pressure on the electricity price is somewhat relieved.

There is practically no trade in electricity between regions as defined in our model. Hence, the regional price effects strongly relate to the history of investments in nuclear power and to what extent the existing capacity in nuclear power plants in the region is vulnerable in our phase-out scenarios, which target generations of technologies built during different 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 scenario, there might be new investments after 2010 along with the on-going process of shutting down all older plants.

3. Results and analysis

Our results differ considerably across scenarios and regions. Figure 1 gives an overview of capacity reduction by region in 2035 as deviation from BAU in absolute terms. SN1 is implementing the nuclear power exit by of Germany and Switzerland, which removes 22 GW of the OECD Europe's nuclear power capacity in 2035 but affects no other region directly, by assumption. Closing very old plants (SN2) has a minor impact on capacity in the OECD Europe, but a somewhat more pronounced impact in Russia, as Russia and U.K. are hosting the oldest technologies. SN3 involves phase-out of reactors built before 1975 and shifts nuclear power capacity markedly downwards by 32 GW in North America, reflecting that this region had an early expansion of nuclear power.

(Insert Figure 1 about here)

SN4 is the major game changer, imposing a comprehensive phase-out of all plants built before 2011, i.e. closing plants after about 40 years of operation, which is the operation period plants generally are certified for. The SN4 depicts a lack of political will to prolong their operational lives, but accept the industry's right to run according to contracts. This policy removes 110 GW of the capacity in North America in 2035, compared with the expected capacity level of the New Policies Scenario. The large capacity reduction in North America, OECD Europe and to some extent Japan reflects that IEA expects prolonged operational periods to be broadly practiced in their New Policies Scenario.

Effects on available nuclear capacity

Figure 2 shows the remaining capacity of nuclear power in 2035. Non-OECD countries are not heavily affected except Russia, which loses about 13 per cent of nuclear capacity in SN2 and more than 30 per cent in SN4. China and Rest of the World including Non-OECD Europe are expected to reach about the same level of nuclear power capacity as the OECD Europe by 2035.

(Insert Figure 2 about here)

Figure 3 shows the phased out capacity as share of total expected capacity available for electricity production by scenario and region in BAU (New Policies Scenario) in 2035. The OECD Europe and Russia lose 1.8 and 1.7 per cent of their total electricity capacity in SN1 and SN2 respectively. Only SN4 results in 4 per cent or larger reductions. Japan loses close to 10 per cent, North America and OECD Europe 7 per cent. This gap between baseline and scenario supply is the driver behind the price increases necessary to bridge the gap between demand and supply of electricity in the nuclear phase-out scenarios.

(Insert Figure 3 about here)

Effect on electricity producer prices

Figure 4 shows the effect on producer prices of electricity estimated to balance the supply and demand in the various nuclear power constrained scenarios as calculated by the GRACE model. These price movements indicate the economic incentives for all kinds of electricity production, both renewable and new nuclear investments. Nuclear exit in Germany and Switzerland (SN1) increases the electricity price in the OECD Europe only moderately (5 per cent). In contrast, the comprehensive phase-out of all old reactors in SN4 leads to larger increases in the price of electricity in North America (28 per cent), OECD Europe (23 per cent) and Japan (24 per cent).

(Insert Figure 4 about here)

Further comments on scenarios SN1 and SN4

Figure 5 shows the development of nuclear power capacity in the OECD Europe after Germany and Switzerland have implemented their exit policy. The capacity falls markedly from 2020 and creates a difference between BAU and SN1 nuclear power capacities around 16–17 per cent during 2025–2030 as illustrated in Figure 6. However, the decline in total electricity production capacity is limited to 1.8 per cent in 2035.

(Insert Figure 5 about here)

(Insert Figure 6 about here)

(Insert Figure 7 about here)

Figure 7 shows the corresponding effect on the electricity price path of the OECD Europe over time in the case of nuclear phase-out in Germany and Switzerland. The price level increases by modest 2–3 per cent during 2015–2020 before reaching a level around 4.5 per cent above the BAU price level during 2025–2035. Although the economy in the OECD Europe keeps growing, the growth rate falls below 2 per cent per year towards the end of the time horizon. For the OECD Europe as a whole, the electricity demand in the New Policies Scenario stagnates during the whole period 2010–2035 (IEA, 2011). The upward pressure on the electricity price levels off, as the moderate growth in demand to a large extent is offset by energy efficiency improvement at 1.5 per cent annually in households and industries. The higher energy costs are expected to generate shifts in production and trade, like shrinking energy intensive industries and encouraging import of energy intensive goods. However, in SN1 the effect on the steel market is marginal. The production of steel in the OECD Europe is reduced by less than one per cent in 2035 compared with in BAU. A third of this fall in steel production is compensated by import growth, whereas the export is reduced by 0.8 per cent. Hence, the German and Switzerland nuclear power phase-out policies are not having a large effect on the cost of using electricity or on energy intensive industries as long as there is transmission capacity and trade options within Europe. These policy measures are not improving the incentives for new investments in electricity substantially. Notice however, that in our scenarios price is the only factor that closes the gap in supply and demand notably by forcing demand downwards. In practice, power based on fossil or renewable energy will respond to fill the gap. The study of Kemfert and Traber (2011) based on a model for the

German electricity market[v] concluded that the surplus capacity in coal and gas-fired plants compensate for the immediate moratorium on the 7 nuclear plants. In the short term, the electricity price in Germany will only increase slightly by about 1.5 per cent for households, relatively close to our estimate of 2.2 per cent price increase by 2015. According to Kemfert and Traber (2011), Germany generates more electricity than the country consumes. A consequence might be that the export surplus might dwindle and impose price increases in other parts of the Europe. However, if trade options within the region are unconstrained, our study shows that the short to medium term effect on the electricity price in the OECD Europe as a whole will also be moderate even over the next two decades. It is reasonable to assume that in the future the transmission capacity will facilitate electricity trade even better than today. Incentives for investments in electricity transmission will increasingly come from the potential benefits of trade, but also from an increase in electricity exchange as rising shares of renewable electricity requires exchange or storage capacity to serve the market timely.

The time horizons of Kemfert and Traber (2011) is short and differs from our study. In addition, 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.

Figures 8-9 shows the remaining nuclear power capacity of major OECD and Non-OECD countries in the comprehensive phase-out scenario (SN4). Japan is roughly maintaining capacity with a moderate price increase of 8 per cent towards 2030 and then follows a marked price rise of 24 per cent above BAU in 2035 when a 23 per cent decline in nuclear power 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 of the BAU level respectively. Although nuclear capacity is declining markedly, the loss in total supply is moderate to negligible in the regions. Most affected is Japan (10 per cent), whereas North America and OECD Europe face reductions of 7 per cent each.

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 the 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 per cent 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).

The low nuclear case reduces global nuclear power capacity from 633 GW in the New Policies Scenario to 335 GW in 2035. In SN4, the global capacity in 2035 amounts to 376 GW. For the OECD, there is a decline from 380 GW in the New Policies Scenario to 171 GW in the low nuclear case whereas SN4 comes out as low as 119 GW for North America, OECD Europe and Japan. Hence, the underlying upward price pressure in the low nuclear case might be somewhat weaker than in SN4.

(Insert Figure 8 about here)

(Insert Figure 9 about here)

GDP changes

According to Duscha et al. (2013) most studies exploring the interaction between climate mitigation and nuclear power find that the additional cost of climate mitigation amounts to less than a percentage of global GDP. Our approach does not include a climate policy, but imposing various scenarios with nuclear power constraints tends to reduce regional GDP compared with the BAU as shown in Figure 10. 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 (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.

(Insert Figure 10 about here)

In all other regions, the impacts on GDP in SN1, SN2 and SN3 are negative but negligible. In SN4 with comprehensive phase-out of all plants built before 2011 the GDP reductions in 2035 are 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 the 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 of electricity in China increases only marginally indicates that the general effect via reduced export of manufactured (consumer) goods is dominating over a reduction in export of energy intensive goods. 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.

Emissions from fossil fuels

In our study, the use of fossil fuel for electricity production is fixed. However, use of fossil fuels for other purposes is flexible and affected by price changes. 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 leads to higher energy prices and discourage energy consumption including fossil fuels. When considered separately, this first order price effect implies fewer emissions from fossil fuels. However, substitution effects will also show up because 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 CO_2 emissions, but generally the price elasticity of electricity is low and the switch to fossil fuels is rather limited.

It turns out that the change in global CO_2 emissions are negligible and tends to be negative (Figure 11). 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.

(Insert Figure 11 about here)

Russia in SN2 and SN4 are the only cases with marked reductions in CO_2 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 CO_2 emitter and electricity represents a major cost element in the industry. Reduced steel production also means lower demand for gas, with the domestic gas price slightly falling. In SN4 Russia experiences 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 (0.3 per cent).

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 industry. SN4 and SN2 therefore largely overlap. As a result, the comprehensive nuclear power phase-out by 2035 generates only slightly higher price increase of electricity (9 per cent) than SN2 (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 is negligible. Russia in SN2 is more or less alone in phasing out nuclear power, i.e. the very old technologies, not exposed to a marked reaction in the world economy.

In SN4 Russia experiences a much smaller electricity price increase than North America, OECD Europe 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.

4 Conclusions

We have used the New Policies Scenario of IEA as baseline and the multiregional global general equilibrium model GRACE to assess the underlying upward pressure on electricity prices in four nuclear phase-out scenarios, assuming that electricity supply from other feedstock than nuclear are fixed in line with the New Policies Scenario. By illustrating the price effects, our study provides useful indications of future incentives for power investments in case of a nuclear phase-out. The model ensures consistency with economic development 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. Our study does not consider how the deficit in electricity demand from nuclear phase-out eventually will be covered.

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

On the other hand, a comprehensive phase-out of plants built before 2011 while allowing new nuclear plants built after 2010 to operate will generate a considerable upward pressure on the electricity price in North America, OECD Europe and Japan. In 2035, Japan might face a price increase of 24 per cent, slightly more than the OECD Europe (23 per cent) but markedly less than North America (28 per cent).

The global CO_2 emissions outside the electricity sector will only be negligibly affected. In the case where Germany and Switzerland exit nuclear power, CO_2 emissions tend to increase. In the most comprehensive phase-out scenario the non-power emissions tend to decrease because global GDP is somewhat reduced by the power constraint.

Appendix Electricity generation in GRACE

In the standard GRACE model, there is only one electricity generation sector. To analyse the implications of nuclear power phase-out, we split the electricity generation sector into the five sub-sectors: electricity fuelled by coal, gas, oil, nuclear, and others.

To determine the activity level of each sub-sector of the electricity generation, we use 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)[vi], we calculate total costs of electricity generation by sub-sectors. Assuming zero profit, total costs of each sub-sector are shifted proportionally 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-fuelled power, all oil inputs by oil-fuelled power, all gas inputs by gas-fuelled power, all refined oil inputs (serving as an indicator of uranium) by nuclear power, and all agricultural inputs (serving as an indicator of bioenergy) by others.

To allocate labour 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 labour and capital within each sub-sector leads to the sum of labour inputs across sub-sectors slightly different from labour 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, labour 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 total intermediate inputs of the sub-sector. The remainder of the fuel inputs is allocated to other sub-sectors in the same proportion as other intermediate inputs, which are allocated to sub-sectors based on 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-fuelled power and gas for gas-fuelled 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.

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 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.

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[i] In real life new power capacity will fill the supply-demand gap. Scenario analyses considering the feedstock mix in future electricity production describes this process. Depending on cost assumptions, the mix of future power supply is calculated based on profit maximization. However, there is substantial uncertainty about future costs of most kinds of power production. There is economic uncertainty associated with the cost for renewable and nuclear power, and political uncertainty related to government subsidies or carbon taxes. While such scenarios are useful, our study complements with an approach quantifying the underlying upward pressure on the electricity price in the wake of nuclear power phase-out, which is not a marginal issue for power supply.

[ii] GRACE stands for the Global Responses to Anthropogenic Change in the Environment.

[iii]OECD Europe include Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey and United Kingdom. Eastern Europe except Russia is part of the Rest of the World.

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

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

[vi] The latest version of Projected Costs of Generating Electricity is the 2010 version (OECD/NEA, 2010). 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.