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Measuring the Impacts of Nuclear Accidents on Energy Policy[a]

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Abstract

This paper examines the history of nuclear energy, safety developments of reactors and nuclear energy policy from the 1950s on. I investigate the effects of nuclear accidents on energy policy with the help of a panel dataset of 31 countries from 1965-2009, using annual data about the capacity of reactors under construction, primary energy consumption, as well as three nuclear accidents scaled INES five or higher by the International Atomic Energy Agency. After determining the extent of the accident impact in the different countries, I find that neither Three Mile Island nor Lucens had a worldwide negative effect on construction starts, while Chernobyl did. The effect of Chernobyl is however shown to wear-off in certain geographical clusters, after ten to thirty years. I find that nuclear capacity enlargement shows a significant persistence, but it was also driven by primary energy consumption in the past five decades. The effects of real interest rates, inflation, or gross domestic product on reactor construction were not found significant. Thus, an accident is likely to have a negative and long lasting impact in the country where it happened, and possibly in countries affected by the direct consequences, or where governments are subject to severe public pressure. It is difficult to estimate the consequences Fukushima is going to have on worldwide power plant constructions, but areas closer to the accident might be affected more negatively and for a longer time. Growing concerns of energy supply security and greenhouse gas emissions may counteract this impact at the legislative level.

JEL Classification: C33, C52, Q41, Q43.

Keywords: Nuclear Energy, Nuclear Accidents, Energy Policy, Panel Regression

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1 Introduction

Energy policy, including the decision on the energy mix is formed and shaped by many factors, encompassing energy security, the availability of resources, the growth of energy demand, public pressure, and environmental concerns. In the recent years until Fukushima, the notion of a nuclear renaissance emerged and many, mostly Asian countries started aggressive nuclear energy programs. The United States has also passed laws to boost its nuclear industry. Nuclear energy is a clean option, with minimal greenhouse gas emissions, and a secure long term resource supply. Uranium has little share in the price of nuclear generated electricity, which is therefore resistant to commodity price fluctuations. The nuclear industry is however facing the challenge of high up-front financing requirements, energy policy changes over the lifespan of reactor (40-60 years), besides the questions of waste management, security, safety and proliferation.

New nuclear technologies have become in the course of the years more homogeneous, safer and more efficient. Built-in safety measures have had a large share in mitigating the damage resulting from the Fukushima accident, which had also a significantly lower fallout than Chernobyl. Despite these apparent technical facts, there have been immediate policy reactions against nuclear energy in a number of countries. Other states seem at the moment to go ahead with their nuclear programs. Already, in a 2009 study, Joskow and Parsons (2009) noted that “another significant accident at an existing nuclear power plant anywhere in the world could have very negative consequences for any hope of a nuclear renaissance.” (Joskow and Parsons (2009), page 25, electronic version) In this paper I will study the effect of a nuclear accident on the capacity of reactors under construction, along with the regional differences observable, while also investigating the impact of energy consumption and of the major economic variables affecting the profitability of a nuclear power plant.

The effects of nuclear accidents on energy policy have been discussed in a number of studies, among others in Ebinger (2011), Nohrstedt (2005), Nohrstedt (2008), and in Goodfellow, Williams, and Azapagic (2011). Most of these articles deal with the psychology or the politics of after accident policy making. There are only a handful of econometric studies, such as from Fuhrmann (2012) and from Gourley and Stulberg (2010) examining the driving forces of reactor construction. This study contributes to closing this gap by examining the statistical impact of energy consumption, of the main accidents and of a number of economic variables on reactor constructions worldwide. I find that next to energy consumption, and energy security, the lock-in effect is a very strong driving factor in the nuclear industry, and of the three major accidents examined, only Chernobyl had a significant negative worldwide impact on constructions. The effect of nuclear accidents can, but need not wear-off in a time span of ten to thirty years. An accident is likely to have a long lasting negative impact in the country where it happened, and possibly in regions most affected by the nuclear fallout, or where governments are subject to severe public pressure.

This paper is organised as follows: Section 2 gives a short overview of the connected literature. Section 3 examines the economic and policy environment of nuclear energy during the past five decades, elaborates on the safety features of nuclear reactors, as well as on the causes of the major nuclear accidents. Section 4 presents and explains our empirical results, and in Section 5 policy implications are derived.

2 Literature

At the moment only a handful of econometric studies examining the consequences of accidents on nuclear policy and on capacity development exist. Fuhrmann (2012) investigates the motives of nuclear power plant construction using a logit model to test the significance of nuclear accidents, economic development, nuclear proliferation, energy security, the supply of nuclear technology and of norms as the determinants of nuclear power plant construction. He comes to the conclusion that economic development is positively and significantly influencing reactor construction, while energy security is negatively related to it, meaning that the lower the ratio of own energy supply to consumption, the more likely that a country will indulge in power plant construction. Fuhrmann (2012) did not find the nuclear weapons, or nuclear non-proliferation treaty variables significant, implying that enrolling in a civilian nuclear program does not mean sinister intentions from the beginning, although there is no evidence that these intentions might not change. The supply side variable is also insignificant, while the tests on both the Three Mile Island (TMI) and Chernoby dummies show a serious and significant impact on nuclear power plant constructions. Fuhrmann (2012) concludes that nuclear power plant construction is likely to continue in countries which had invested in nuclear technology and infrastructure before the Fukushima accident, but the probability that new countries will enrol in civilian nuclear programs is drastically lowered. He finds it doubtful that nuclear energy will play a meaningful role in global climate change mitigation.

Gourley and Stulberg (2010) investigate the correlates of nuclear energy using a binary logistic regression on the occurrence of construction starts. They look at the characteristics systematically shared by existing nuclear power states that distinguish them from non-nuclear states. They find that energy insecurity is positively correlated with nuclear energy capacity as are GDP per capita levels, however they do not find evidence for common traits in economic growth, political governance, regime duration, or strategic considerations such as enduring rivalries (hostilities). They note that aspirant nuclear states tend to be either large emerging market economies or smaller, but fast growing nations. Nelson (2010) conducted a stepwise regression on nuclear reliance (defined as the fraction of national electricity generated from nuclear energy). He found that coal reserves and the state of the fuel cycle are negatively correlated while international commerce & polity, and energy insecurity are positively correlated with nuclear reliance. Gross domestic product, gas reserves or electricity generation were not found significant. The results of this study were questioned however by Gourley and Stulberg (2010) due to the methodological problems associated with it.

To understand the implications of carrying out a statistical analysis on nuclear energy, we must also cover two important aspects outside the scope of econometrics. Both the political and psychological environment surrounding the nuclear industry might play a vital role in influencing future investment decisions. In this section we shall review the prevailing studies on risk perception regarding nuclear power. It is important to bring in the psychological aspect into the analysis of nuclear power, as in no other case is the perceived risk of an energy form so exorbitantly different from the expected risk (Slovic (1987)). The resulting public pressure may, but need not have an impact on policy. How much public pressure influences policy making varies country by country, depending on cultural aspects, political systems, wealth levels, but also on closeness to elections.

Risk perception studies (Slovic (1987), Corner et al. (2001), Goodfellow, Williams, and Azapagic (2011)), examine the "judgements of people about hazardous technologies and activities" (Slovic (1987), page 280). In his cornerstone study, Slovic (1987) noted "that laboratory research on basic perceptions and cognition has shown that difficulties in understanding probabilistic processes, biased media coverage, misleading personal experiences, and the anxieties generated by life's gambles cause uncertainty to be denied and risks to be misjudged." (Slovic (1987), page 281). Using psychometric factor scales, Slovic (1987) finds that people rate nuclear power risks both as dreaded and unknown, reflecting views that the risk is uncontrollable, catastrophic and is likely to affect future generations. These evaluations are in harsh contrast with the evaluation of experts. Slovic (1987) notes that risk perception research demonstrates that peoples' deep anxieties are linked to the reality of extensive unfavourable media coverage and to a strong association between nuclear power and the proliferation and use of nuclear weapons. He comes to the conclusion that a risk communication processes should be a two-way between experts and the public. Goodfellow, Williams, and Azapagic (2011) also come to the conclusion that the public perceives nuclear power as a high risk activity, although further research has shown that people who live in countries with existing nuclear power generation capacity tend to be more positive about nuclear power than those from countries without existing capacity (Goodfellow, Williams, and Azapagic (2011)). Their study argues that policies are needed, including an increased integration of lay public risk perceptions into the design process for nuclear power plants (NPP). In a different study, Corner et al. (2001) have investigated the acceptance of nuclear power among the British public and found that the opinions are still very much divided. However, at the same time concerns about climate change and energy security are widespread, which carry the potential to increase conditional public acceptance of nuclear power, given that other preferred options (renewables) have been exhausted.

Another important social topic that has to be addressed is the external cost of an energy source. The calculated or expected risk of a nuclear accident, depending on reactor type ranges from 10^{-5} to 10^{-7} pro reactor year. Thus, the probabilistic risk of an accident associated with nuclear energy compared to any other energy form is among the lowest. Laes, Meskens, and Sluijs (2011) examine the external cost calculations of the ExternE project. The ExternE estimated the external costs for different energy types and came to the conclusion that both renewable and nuclear power show very limited external costs, generally lower than 1 Euro/MWh, gas technologies have intermediate external costs between 10-30 Euro/MWh, and traditional oil and coal technologies fall generally within the high range of external cost of 30-150 Euro/MWh. Laes, Meskens, and Sluijs (2011) note that this expected value has been criticized in particular for ignoring risk aversion. The authors come to the conclusion that unless full indemnity insurance is required from the nuclear sector, it is impossible to calculate the true cost of nuclear power. The question of indemnity insurance has been regulated differently in countries with nuclear energy, the most notable regulation is the Price-Anderson Act in the United States. As the empirical studies about risk perception and public opinion above also demonstrate, the public perceives nuclear energy at best as a high risk activity, a dreaded and uncontrollable menace at worst, irrespective of the true risk of associated with the commercial use of nuclear power. Policy decisions by governments are thus shaped not only by strategic questions of energy security, safety and energy demand, but also by the prevailing public opinion.

A policy change may take the form of an incremental process, or may come instantly, as a reaction to a major crisis. What moves governments to immediate policy changes in the face of a crisis may be triggered by different causes. A crisis is defined according to Rosenthal and Kouzmin (1997) as “a serious threat to the basic structures or the fundamental values and norms of a social system, which—under time pressure and highly uncertain circumstances—necessitates making critical decisions” (Rosenthal and Kouzmin (1997), page 280). Presently, there is no fully developed theory explaining the crisis - policy change interactions. One of the most frequently used thesis is the advocacy coalition framework (ACF) of policy change. The basic premises of the framework require external perturbations to a subsystem, either in the form of major socioeconomic changes, public opinion shifts, changes in the system of governing coalition and policy decisions or impacts from another subsystem (Sabatier and Jenkins-Smith (1993)). These external events may redistribute resources, and may also offer opportunities for minor coalitions, without sufficient power. Whether an external event will cause a policy change or not, is not easily determined. Sabatier and Jenkins-Smith (1993) claim, that core beliefs change rarely, but could as a result to a major external shock. Nohrstedt (2005) has examined the applicability and the shortcomings of the advocacy coalition framework from Sabatier and Jenkins-Smith (1999), on the example of the Swedish referendum after the Three Mile Island Accident. After TMI the Swedish liberal government called a referendum, backed by the social democrats (SAP) that resulted in the decision to phase out nuclear energy by 2010. Nohrstedt (2005) claims that contrary to the predictions of the ACF, short-term interests can be important in explaining major policy change. Nohrstedt (2005) points out that the notion of revised policy believes is problematic. His major critique of the framework is that “it does not assume actors to be driven by economical/political self-interest goals” (Nohrstedt (2005), page 1045). Self-interests, such as power maximisation are extensively viewed as a powerful explanation of political decision making. Nohrstedt (2005) suggests thus, that “a major policy change is more likely as a result to an external shock, if the incumbent coalition member perceives threats to basic interests, or an opportunity to advance basic interests” (Nohrstedt (2005), page 1045). Nohrstedt (2005) further argues that political interests should be regarded to include next to vote maximisation, office seeking, policy seeking, and party cohesion. Since socio-economic changes occur constantly, it is also a matter of degree, or the depth and importance of that change that determines whether and when such a development triggers a policy move. There is no uniform rule explaining the dynamics how an event may stimulate policy change. Examining the TMI case and the referendum initiated afterwards, he finds that image and short-term political interests were in fact the major drivers. Nohrstedt (2005) comes to the conclusion that without TMI, no referendum about nuclear energy would have taken place. Nohrstedt (2008) also examines the policy impact of Chernobyl, when–albeit the immense public pressure–no decision was taken by the ruling coalition to speed up the nuclear phase out. As a matter of fact, the government actions after TMI, which allowed the loading of fuel rods into new plants, and the construction of further nuclear facilities also highly questioned the seriousness of the phase out. These developments are difficult to explain by any prevailing theory.

Notable policy changes next to the Swedish referendum included the referendum in Italy (1987) that resulted in the shut-down of all four nuclear plants after Chernobyl, the decision of Finland to halt construction, that was revised by 2005, when Finland as the first European country began the construction of a European Pressure Water Reactor (EPR). Belgium, whose energy is supplied approximately 50% by the existing nuclear plants, decided in 2003 to phase out nuclear energy, while a similar German decision from 2000 was reversed before Fukushima, allowing for the extension of the lifetime of existing reactors. After Fukushima the German government has passed a constitutional law, requiring the shut-down of German nuclear power plants, which generated approximately 18% of the country's electricity, or approximately 20 GWe capacity. Other countries, such as the United States, passed no explicit laws against nuclear energy; it is notable however that after TMI no new construction started for approximately 30 years. The new Vogtle plants in the United States are presently the first reactors in construction after the Harrisburg accident. A policy change must not be exorbitantly spectacular, or visible, such as the German, Swedish or Italian. It can take the form of a "latent" decision, in which case the general economic and legal conditions surrounding nuclear power are worsened, and authorization process becomes more difficult.

3 Five decades of commercial nuclear energy

3.1 Nuclear energy economics and policy

This section looks closely at the historical and economic factors that have shaped the nuclear industry as well as the surrounding energy policy during the last fifty years. In the wake of the Second World War, civilian reactor technology was initially developed from the military applications of nuclear power. The International Atomic Energy Agency (IAEA) was established in 1957 to promote the safe, secure and peaceful uses of nuclear technologies. The first commercial reactors were built in the first half of the 1950s in the US, in the USSR, and in West Europe. Arising from the novelty of the technology, many different reactor designs were experimented with in this era (Lester and Rosner (2009)), a number of which either did not prove economically viable, or other technically better designs were favoured instead. This was also the era of the Cold War, when nuclear armament was a strategic priority for both the United States and the Eastern Block.

A rapid worldwide commercial expansion of nuclear reactors followed towards the end of the

1960s, irrespective of the ownership structure of the plants (state vs. privately owned plants). However, the 1970s brought a significant change to the international energy landscape. The oil crisis of 1973-74 sent the global inflation and interest rates sky-rocketing in the Western World. In addition, in the United States–partially due to the high costs of the Vietnam War–the USD was decoupled from the gold backing in 1971, and started a downhill race contributing additionally to high inflationary pressures. As a result of high energy prices, the demand for end user energy and energy services broke in considerably, while energy efficiencies began to kick-in, in various technologies. Interestingly, this phenomenon at the time was not observable in the USSR and in the countries of the Warsaw Pact, as the USSR not only had large own oil and gas reserves, but also regulated resource and energy prices. It is argued that in an environment of high interest rates and high inflation, large base load power plants (such as nuclear plants) with high initial investment costs became especially uncompetitive. As Ebinger (2011) notes, the demand for large base load was growing annually 6-7 % in the 1960s, and started falling 1-2% after the first oil crisis. Apart from this, as Ebinger (2011) mentions, a very complicated authorization process evolved in the United States, with the federal regulators and state regulators all doing their independent reviews on construction and operational licenses, that also increased the time needed to build a nuclear plant. Occasionally, costs increased ten fold compared to the budgets in the high inflation area.

By 1979 the nuclear industry was already fighting with overcapacity, high investment costs and inflation, growing public, environmental, and proliferation concerns. It was in this year, when the Three Mile Island accident happened. As described in a later section, the release of radioactivity–mostly thank to the very robust building of the plant–was well under the health safety limits, and there are even after thirty years no deaths or illnesses attributable to TMI (Van Roey (2009)). The accident however received tremendous media attention, and a local public panic ensued. Contributing factors could have been the release of the film “China Syndrome” two weeks before the event, or an evacuation order given by the nuclear regulatory body–based on false information regarding the measurement of released radioactivity–that was later withdrawn. According to Ebinger (2011), after TMI nearly 100 orders for nuclear reactors were cancelled in the United States, and only one reactor (where construction started in 1976) was finished. Many investments were scrapped, among others nearly-ready plants (Joskow and Parsons (2009)). It is argued that TMI, although it had a large echo, had just finished off what the stagflation and high interest rates of the decade have started (Cohen (1990)). The worldwide number of nuclear power plant construction starts had significantly fallen already starting with 1977. Apart from the United States, TMI could have triggered the Swedish referendum on nuclear energy, that resulted in the long-term phase out of nuclear plants in Sweden (as of the end of 2010 still about 2/3 of plants were in operation).

The beginning of the 1980s was marked once again by a severe oil crisis boosting the price of oil, and resulting in significant reductions in end-energy use, but also in primary energy consumption. Interestingly again, the effects were not visible in the USSR and Warsaw Pact Block, for the reasons mentioned above. Natural gas, but also coal drills marked the first part of the decade, along with the deregulation of gas and oil prices in the United States. In 1985, Saudi Arabia for reasons that are up to today disputed, (according to Reynolds and Kolodziej (2008) either to punish the rest of the OPEC members who were unable of agreeing on production cuts, or to boost its own revenues, or to do a favour to the United States) increased its output from 2 million barrels to 6 million barrels per day. Oil prices broke in as a result, which not only helped to boost most Western economies, but also cut the main revenue source of the USSR. It was in these circumstances that the biggest nuclear accident of all times happened in Ukraine. The disaster at Chernobyl was not only due to a bad reactor design, but also to enormous human errors, and the complete disregard of safety procedures (Villa (2008)). The accident contaminated significant areas of Europe, and caused a large public outcry against nuclear energy. It is worth mentioning however, that the radiation doses released from Chernobyl for West Europe were less than the doses that resulted from the atmospheric nuclear bomb tests during the 1950s (Böck and Villa (2011)). Apart from a few countries that kept their nuclear programs, in most parts of the world, new construction starts fell dramatically.

The last twenty years were characterized worldwide by the widespreading of small and medium capacity gas and coal plants (Joskow and Parsons (2009)), but also by the remarkable increase in commodity prices starting in the early 2000s until the great financial depression of 2008. Liberalisation and quasi-liberalisation of electric markets sped up in West Europe but also in Eastern Europe and in the former USSR. Especially in the East Block, the adjustment to market prices has caused drastic increases in energy prices, along with a very strong downward pressure on energy consumption. Primary energy consumption of the former East Block decreased by 2010 to the level of the 1970s, after a peak around 1990. In the US, deregulation marked the 1990s, but these efforts suffered considerably as a result of the California Electricity Crisis in 2000-2001.

During the past decade, due to the high and fluctuating oil and gas prices, as well as to the increasing concerns related to climate change attributable to greenhouse gas emissions from carbon dioxide and methane and to the looming problem of energy security, many states have again realistically considered utilising nuclear power (Joskow and Parsons (2009), Lester and Rosner (2009)). It is as a clean, concentrated and secure energy source that had – apart from the disaster at Chernobyl – a very good safety record. Among others, President Obama initiated a stimulus package to boost the building of new nuclear power plants. China, India, and a number of Asian states also turned to nuclear energy to satisfy their strongly growing energy needs. China passed a “Medium and Long-term Nuclear Power Development Plan” (Zhou, Renfigo, Chen, and Hinze (2011)), running until 2020, to build new nuclear capacity of around 40 GW(e). Later these plans were reassessed and are currently around 70-80 GW(e), almost 7-8 fold of the existing nuclear capacity in 2010 (Zhou, Renfigo, Chen, and Hinze (2011)). The conditions faced by the nuclear industry in China compared to those in the Western economies are distinctly different. While in China the industry is characterized by competing state owned corporations, backed by a firm government decision towards capacity enlargement, in the United States and Europe the privately owned nuclear industry is competing with natural gas and shale gas plants, with much lower initial investment, faster construction times, and less regulatory hazard.

On March 11^{th} 2011, a 9.0 earthquake hit Japan, and the resulting tsunami devastated large coastal areas. Due to the loss of the emergency cooling system caused by the tsunami, the operating company TEPCO reported a (partial) meltdown in three of the damaged reactors of the Fukushima Dai-ichi nuclear power plant. The exact status of the fuel will however not be certain until much longer, when the reactor core can be properly inspected. The question concerning the impact Fukushima will have on the energy policy of different countries, is one that this study is investigating.

3.2 Safety features and technical development of reactors

In this section I present a short overview on the development of basic reactor safety and efficiency during the past fifty years. Not only did present reactor designs become much safer with built-in passive safety measures, but their efficiency has also increased greatly. As noted earlier, commercial nuclear power technology originally developed from military use, and many plants were built during the Cold War era. Undeniably, the historical and political setting played an important role in reactor technology. For instance, in the former USSR, RBMK reactors were designed to breed weapon grade plutonium besides their commercial operations, necessitating a reactor design where safety suffered for this reason.

Also, perhaps one of the most significant strategic setbacks for the nuclear power prospects in the United States were the many different reactor designs of the 1970s. All built by private utilities, the plants had to go through separate licensing processes, lacking thus homogeneity that would have not only facilitated safety, but also efficiency. When China embarked on its nuclear program in the early 2000s, the explicit drive for homogeneity was a prerequisite, and consequently only a few reactor designs are officially supported and pursued. At the moment, the majority of operating reactors around the world are pressurized water reactors, followed by boiling water reactors, and Canadian pressurized heavy water reactors (CANDUs). A small amount of gas cooled reactors, including MAGNOX reactors and advanced gas cooled reactors (AGRs) are currently producing electricity, as well as Chernobyl type RBMKs, and two fast breeder reactors. The total number of reactors worldwide as of December 2010 was 441, with a total installed capacity of 375 GW(e).

Without embarking on the specifics of each reactor type, which may significantly differ in design, I summarise the most important inherent technological reactor safety features in the next sections, most of which are supported by simple physical principles. One important built-in safety feature is the so called ”negative void coefficient”. In water moderated reactors water slows down neutrons (moderates), and also acts as a neutron absorber. When the water in the reactor core starts to boil due to higher temperatures and thus steam forms, neutrons are not slowed down any more. Fast neutrons can fission only a small percentage of nuclei of what thermal neutrons do. Consequently, fission will slow, and eventually break down. Both pressurized water reactors and boiling water reactors possess this feature. Markedly, graphite moderated reactors including the Russian built RBMK reactors lack this effect and have positive void coefficients. In this case, when water evaporates, it fails to absorb neutrons, to cool and transport the cumulating heat. However, graphite continues moderating and thus does not allow for an automatic stop of the chain reaction, eventually reactivity increases. Apart from these, CANDU reactors have also a small positive void coefficient that they have to compensate for with different measures. MAGNOX reactors are gas cooled and thus the void coefficient is not relevant for this type of reactor.

The most important feature, the Doppler-effect describes the phenomenon that occurs with the rise of the temperature. The atoms and molecules start vibrating faster, and consequently increase their neutron uptake, which also leads to higher absorption and reduction to the number of fissions. A built-in SCRAM system and independent shut down systems are a basic requirement for each design. SCRAM is a fast shut down system that requires the automatic insertion of control rods–usually material with very large neutron capture cross section–within 3,5 seconds after recognition of non-normal operations (Böck and Villa (2011)). Besides these, reactor safety regulations require today the strict separation of redundant systems, a sound containment building above the reactor pressure vessel, and a full capacity emergency core cooling system. Another safety measure is that the heavy mass component should be placed in the lowest position. A serious critique of the Russian built water moderated VVER 1000 reactors today is that the core is not at the lowest point.

Specific developments in the past decades were the introduction of passive safety features for emergency cooling, operating also in the presence of power loss. For BWRs, such as the newer type SWR 1000 or ABWR, water from a core flooding pool will flow, in case the water level drops in the pressure vessel (Böck and Villa (2011)). Certain boiling water reactors also have passive pressure pulse transmitters. A drop of the water level increases pressure on the secondary side, which delivers safety related pulses, and scrams the reactor without external power. This gives a grace period of three days without intervention. A built-in safety feature of newer EPRs is a core catcher designed in case the corium escapes the reactor pressure vessel (Böck and Villa (2011)). The EPR structure is designed to avoid steam explosions between the molten corium and water. It is most important that a dry reactor area has to be maintained before corium flooding. The newer pressurized water reactors, especially the AP1000, are greatly simplified with significantly lower number of tubes, pipes, valves, but larger safety margins (Böck and Villa (2011)).

Important challenges faced by nuclear power include the question of plutonium creation and nuclear waste. From the array of presently operating plants, MAGNOX and CANDU reactors create more plutonium than conventional pressurized water and boiling water reactors. RBMK reactors on the other hand were designed for easy weapon grade plutonium access. Answers to the problem of plutonium included its extraction from the waste, and re-usage as a MOX fuel. Another, presently not commercially practised procedure is the application of fast burners. Plutonium and other transuranic elements can be fissioned in fast reactors. If the breeding ratio is set below one, these fast reactors can operate effectively to fission “away” accumulated transuranic elements, and reduce the amount of high level nuclear waste.

Apart from the inherent technical features, there are a number of regulatory and procedural rules documented by the IAEA to ensure reactor safety. The IAEA “Basic Safety Principles for Nuclear Power Plants” (1999) guideline mentions among its specific principles, next to siting, the importance of design. Under design, it elaborates on the specific requirements relating to emergency plans, plant process control systems, automatic safety systems, radiation protection, protection against power transient accidents, reactor core integrity, normal heat removal, startup, shutdown and low power operation safety, emergency heat removal, reactor coolant system integrity, the confinement of radioactive material, preservation of control capability, monitoring of plant safety status, station blackout (simultaneous loss of on and off site power), plant physical protection, and spent fuel storage. Apart from these, very high quality standards and continuous inspection is required in the manufacturing and construction phase. The IAEA gives detailed instructions on the commissioning and operating phase, including the necessity of safety reviews, trainings, maintenance, testing, inspection, and feedback of operating experience. Other parts of the specific principles deal with accident management, decommissioning and emergency preparedness.

The efficiency of nuclear power plants is determined by many factors. The burnup of a reactor gives the electricity generated by one ton of heavy metal fuel. One ton of 4-5 % enriched uranium fuel contains about 40-50 kg U235, and about 10,25 tons of natural uranium are used in assembling the fuel. If the thermal efficiency factor of 33% is met, the electricity generated will be around 370-400 million kWh from a 4-5 % enriched fuel. This gives the burnup of about 45-50 gigawatt-days/metric ton of heavy metal (GWd/MTHM), a general burnup of a light water reactor. Boiling water reactors have higher burnups up to 50-60 GWd/MTHM, for fast breeders a burnup of 100 GWd/MTHM has been assumed by the Massachusetts Institute of Technology (2011). The burnup could be increased by increasing the thermal to electrical power conversion. While a regular PWR works at around 34 % conversion efficiency, an advanced boiling water reactor (ABWR) can reach 37,2 %, while advanced high temperature reactors (AHTR) and supercritical water moderated reactors can achieve 47%. The notion of base load is also important in determining the efficiency and profitability of a plant. Nuclear power plants are often not running at full capacity, although it would be sensible to run them as base load plants.

3.3 Description of notable nuclear accidents

In this section I describe three notable accidents in detail, which are widely regarded to have had the biggest policy impact and public reaction, for various reasons. These are the Three Mile Island accident (1979), the Chernobyl disaster (1986) and the Fukushima nuclear accident (2011). As we will see, the actual severity of an accident is often not the main factor in causing grave policy impacts. Other non-technical issues, such as public perception and fear resulting from a not-well understood technology and negative media coverage will in a certain environment lead to significant pressure on policy makers. Policy impacts are not only reflected in illustrious decisions like that of the German government in 2011 to phase out nuclear energy, but also in the strengthening of licensing and the withdrawal of government guarantees.

The IAEA adopted the International Nuclear Event and Radiological Scale (INES) in 1990, to "communicate to the public in a consistent way the safety significance of nuclear and radiological events" (International Atomic Energy Agency (1990), page 1). The scale encompasses seven levels, of which levels four (4) to seven (7) are classified as accidents, and levels two (2) to three (3) as incidents. In practice, the classification of an accident or incident is carried out by national authorities or by the operators of nuclear power plants. One potential bias from using the INES scale arises from the fact, that the INES database was only developed in the early 1990s and does not contain information on events prior to that (International Atomic Energy Agency (1996)), save for a few spectacular cases. There were a number of accidents or incidents during the 1950s to 1980s where classification is currently not available, although experts might rate them up to level five (5). The Los Alamos National Laboratory however compiled a database of criticality accidents (Los Alamos National Laboratory (2000)), and the IAEA also published a list of serious incidents (International Atomic Energy Agency (1996)).

Currently, two accidents are rated level seven (7), or a major accident, which is defined by the (IAEA(1990), page 4) as a "major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures." These events are the nuclear accidents at Chernobyl (1986) and in Fukushima (2011). Although both cases fall into the highest category, by comparing the technical facts it becomes apparent that both the amount and the type of radionuclide released into the environment, as well as the extent of the contaminated areas are significantly lower in case of Fukushima. Only one event is rated at level six (6), "a serious accident, with significant release of radioactive material, likely to require the implementation of planned countermeasures" (International Atomic Energy Agency (1990), page 4). The Kyshtym accident occurred in the former USSR in 1957, where the cooling system of a high level radioactive waste storage failed, and a steam explosion caused by decay heat has led to the release of significant amount of radioactive material in the environment, mostly Cs137 and Sr90, both of which are highly volatile materials. This event happened at a military facility, and consequently it received very little media coverage either in the USSR or in the West.

There are a few level five (5) events, including among others the Windscale (UK, 1957), Rocky Flats (US, 1957), the First Chalk River (CAN, 1952), the Lucens (CH, 1969) and the famous Three Mile Island (US, 1979) accidents. This level is defined as "limited release of radioactive material likely to require implementation of some planned countermeasures; several deaths from radiation. Severe damage to reactor core, and release of large quantities of radioactive material within an installation with a high probability of significant public exposure. This could arise from a major criticality accident or fire" (International Atomic Energy Agency (1990), page 4). Level four (4) events, or accidents with local consequences are defined as "the minor release of radioactive material unlikely to result in implementation of planned countermeasures, other than local food controls. At least one death from radiation. Fuel melt down or damage to fuel resulting in more than 0,1% release of core inventory. Release of significant quantities of radioactive material within an installation with a high probability of significant public exposure" (International Atomic Energy Agency (1990), page 4). There have been a number of level four cases throughout the years, such as the SL-1 with a prompt criticality due to removal of central control rod, (US, 1961), several incidents at Sellafield (UK), or the Tokai Mura accident (Japan, 1999). We now turn to the description of first the Three Mile Island accident, then to Chernobyl and Fukushima, to examine the extent of these events and the actual damage caused.

3.3.1 Three Mile Island (level 5)

The Three Mile Island nuclear accident on March 28^{th} 1979 was initiated by a series of small technical failures that turned into a serious mishap, partially due to the lack of nuclear engineering knowledge of the operating staff, but also due to the very confusing and complex design of the control systems, that made it practically impossible for the staff dealing with the emergency to filter out important information. The Three Mile Island Unit 2 was a pressurized water reactor design, connected to the gird exactly one year earlier. A pressurized water reactor has three separate cooling circuits. The primary circuit cools the reactor itself, and transports the heat from the fission. This circuit is under 150-155 bar pressure to ensure water stays liquid under very high temperatures. The secondary circuit cools the first circuit and works as a steam generator. When the water of the secondary circuit takes up the heat from the primary circuit, it boils and the resulting steam drives the turbines to produce electricity. The condenser circuit is cooling the steam in the secondary circuit, and thus transforming it back to water.

According to a study by Van Roey (2009), accident started out when at the second unit of the TMI plant the main water pump stopped at the secondary circuit, eliminating the cooling water supply to the steam generator, therefore temperature and pressure in the primary circuit started to rise. After nine seconds, the control rods as designed dropped into the reactor, shutting it down. Although the fission stopped, the decay heat would have had to be removed from the core. The emergency water pumps started at the secondary side as designed, but a valve was closed due to earlier maintenance, so the water could not reach the secondary side of the steam generator (Böck and Villa (2011)). This mistake was only noticed and eliminated eight minutes later. As the temperature rose in the reactor, the water in the primary circuit started to evaporate, and the pressure relief valve at the top of the pressuriser opened. However, when the pressure has sufficiently decreased in the system, the valve did not close as foreseen. The operators in the control room could not see this because the status of the open valve was not displayed on the control panel (Böck and Villa (2011)). From this moment on, a large amount of primary water began to escape through the open valve into a drain tank. Due to the insufficient cooling, the reactor core began to overheat and steam bubbles formed. Two pumps pushed extra water into the primary circuit, but one was manually closed by the operators, who, at the time still did not realise that the water was escaping. Due to the mixture of water and steam that the primary pumps had to deal with, they started vibrating. To prevent consequent damage to the pumps, they were completely turned off, cutting all water supply to the fuel (Van Roey (2009)). The temperature in the core kept rising. No one at this point noticed that they were losing coolant. The core became partly uncovered and the zirconium cladding of the uranium fuel rods broke off, and started melting. It is estimated that the temperature could have risen to 5000 degrees (Van Roey (2009)). About half of the core melted down by the time the engineers of the operating company arrived at the site and discovered that the valve was open, which they closed immediately. At this point radioactive particles already escaped the reactor through the open valve with the contaminated cooling water. Despite of the core melting, it speaks for the robustness of the reactor design that the corium did not penetrate its way through the reactor pressure vessel (Van Roey (2009)). This could also be due to a thin layer of water in-between the pressure vessel steel and the corium (Böck and Villa (2011)), and thus the biggest disaster was avoided. The cooling of the core was resumed soon after with high pressure emergency water, that compressed the bubbles. During the evening the primary pumps could be turned on without significant vibration.

About a day later due to the high temperature, water vapour reacted with the zirconium cladding, and formed hydrogen. There was a high probability of a hydrogen explosion that experts worked on to hinder with all possible measures, among others by opening the valve above the pressurizer. The accident above is a known as a loss of coolant accident (LOCA). Some radioactivity did escape through the open valve into the drain tank, and through the controlled opening of the valve to reduce pressure later on. Radioactive gas also found its way to the auxiliary building through the pipe systems, and escaped to the environment (Van Roey (2009)). It took about a month to reach a cold shut down condition, where water could be circulated in the reactor below the boiling point. The cleanup and decontamination operations are estimated to have cost about 1 billion dollars (Van Roey (2009)). The reactor core was first inspected with a camera in 1984, and dismantling of the reactor started in 1985 and finished in 1990. The exposure to the public was well below health levels during the entire time. Exposure to ionizing radiation is measured as absorbed dose in Gray (Gy) The “effective dose” measured in Sievert (Sv) takes account of the amount of ionizing radiation in energy absorbed, the type of radiation and the susceptibility of various organs and tissues to radiation damage (Hajek (2012)). It is estimated that people within a radius of 16 km have received about 0,08 mSv radiation (Van Roey (2009)). The average dose in Europe coming from the cosmic radiation and the background radiation is around 2 mSv a year. Medical applications such as CTs and x-rays, as well as intercontinental flights can increase this dose significantly, up to 10 mSv per year. Up to now no study has found any health effect of Three Mile Island, on infant mortality, or on cancer (Böck and Villa (2011)). An interesting fact, and highlighting the over-complicated organization of nuclear power utilities in the United States was that the same valve dysfunction happened 18 months earlier at Davis Besse, and although the engineers requested that all similar plants should be notified about the deficiency of the pressure valve, this information was lost in the administrative process.

3.3.2 Chernobyl (level 7)

The largest nuclear disaster of our times happened in Chernobyl (Ukraine) on April 26^{th} 1986. The accident was caused by a mixture of bad reactor design, a faultily designed experiment, and the breaching of a number of safety regulations by the operators carrying out the experiment. The reactor in question was a light water cooled, graphite moderated pressure tube reactor. Originally these reactors were constructed to fulfil also military purposes, and thus allowed for on-load refuelling. The main purpose of this feature was to divert sufficient amounts of weapon grade plutonium (Pu239) from the core.

Very simply put, the neutrons resulting from the fission of the U235 or any other nuclide might follow two paths. In the first path they cause fission as fast neutrons. Fast neutrons, possessing a kinetic energy of over 1,1 MeV are capable of fissioning also fertile nuclide such as U238. Fast fission is however a negligible part of the total fission process. In the second path neutrons are slowed down by moderators such as water or graphite and are either causing fission, or are parasitically absorbed by U238 or any other nuclide that accumulated during the operations of the reactor. By the absorption of a neutron and a successive beta decay U238 will form Pu239 which is again a fissile material. The reason that the entire fuel in a reactor cannot be consumed, is the gradual increase in the amount of parasitic absorbers with time. The major absorbers are Xe135, Sm149 and Sm151. Parasitic absorbers, especially Xenon135, played a significant part in the Chernobyl accident (Villa (2008)). These short half-life fission products are sometimes also referred to as reactor poisons, or nuclear poisons. During normal operations, absorbers are formed, but with neutron capture they are also destroyed. Xe135, which is formed from I135 reaches its maximum after the shut-down of the reactor, therefore a restart of a reactor is only possible after the sufficient decrease in the amount of neutron poisons. For Xenon, this would first be possible after 40 hours. During the shut-down phase Xenon contributes to large amounts of negative reactivity. With a new start-up of the reactor, it should be regarded however that due to burning of the reactor poisons, positive reactivity sets in (Villa (2008)).

The Chernobyl accident started out as a simple test. In case of a power cut, it was known that the diesel generators supplying the water pumps of the cooling system with electricity need approximately 30-50 seconds to start. To overcome this approximately one minute gap in power supply, a test was designed for the Chernobyl block that should have utilized the rotating energy of the turbines (that were still rotating after shut-down due to their mass and energy). The test should have been carried out before the reactor was shut down for annual outage. On the morning of April 25^{th}, the power output was reduced according to plan from 3200 MW(thermal), to 1600 MW(thermal), but due to the request of the electricity utility in Kiev, the power had to be kept at this level, to fulfil electricity demand. This output level was kept until about the end of the day, which caused significant Xenon build-up in the reactor, introducing large negative reactivity. Next, the emergency cooling system was shut off. It turned out later that this step was in fact authorized earlier by the chief engineer. The INSAG review of the International Atomic Energy Agency (1992) states however that this step probably did not affect the development of the accident. At 23.00 hours, the test started, and the power was further reduced to 500 MW(th), despite that RBMK reactors are known to be very unstable below 700 MW(th). Unlike water moderated reactors, RBMK reactors have positive void coefficients, meaning that a temperature increase evaporates water, which is the primary coolant, but also a neutron absorber. But since graphite is the moderator, the chain reaction continues, and with water converted to steam, reactivity also increases.

Due to the above facts, the power output of the reactor dropped to 30 MW(th). At this point the reactor should have been shut down, and the test terminated. To increase power again, the operators withdrew almost all control rods, in total over 200. But even with the withdrawal of control rods, the power could only be increased to 200MW(th) due to the serious Xenon poisoning of the reactor. According to the prevailing regulations, the permission of the chief engineer would have been needed to run the reactor with less than the effective equivalent of 26 control rods. As planned, additional water pumps were switched on to cool the reactor that resulted in lower water levels in the steam separator (Böck and Villa (2011)). To normalize the levels and the pressure, all but 6 manual control rods were pulled out, and the reactor shut down signals were bridged. The cooling water flow was reduced to normalize pressure, and thus the heat removal from the core was slowed. At this point, the operators did not realize there was any problem with the reactor operation. The experiment started, in the course of which the turbine generator and the pumps were run down. Half a minute later, the water started to evaporate, the temperature rose quickly, the reactor became prompt-critical, due to the positive void coefficient. Steam formation became uncontrollable and the staff pressed the emergency shut-down button, but the control rods were dropping into the core too slowly. It is estimated, that the power reached 100 times of the planned capacity, the temperature rose over 3000 degrees Celsius, the pellets of the fuel were breaking and reacting with the water. Two explosions followed, one of them was either a hydrogen or a steam explosion, and the second one was a prompt nuclear transient explosion of the fuel cloud (Böck and Villa (2011)). The reactor cover lifted and about 8 tons of highly radioactive nuclear fuel and parts of the graphite moderator were blown out of the reactor core. The incoming air reacted with the graphite, building carbon monoxide that caught fire, and set the entire building on fire. Besides this, radioactive iodine 131 and cesium 137 gases have escaped. About 250 tons of graphite burned completely in the following 10 days, setting radioactive particles afloat (Villa (2008)).

The causes of the accident were partly a bad reactor design, including the positive void coefficient, and the absence of proper containment structures, mostly due to financial reasons. As the reactor was very tall, a concrete containment building would have doubled the costs. The IAEA safety report on Chernobyl estimates the effect on reactivity of a total loss of coolant around 4-5 β for the steady state refuelling scheme, where β is the delayed neutron fraction (International Atomic Energy Agency (1992)). Furthermore, the reactor core was massive, being seven meters tall, and twelve meters in diameter, and thus chain reaction in one part of the core was only vaguely connected to what happened in other parts of the core. This could have resulted in significant spatial power redistributions. The control rods had a graphite displacer at the end, which caused initially after the insertion of the rods a positive reactivity at the lower part of the reactor. According to the INSAG-7 report, this positive scram effect of safety rod insertion could have been a significant contributor to the reactivity driven transient (International Atomic Energy Agency (1992)). Other pitfalls included according to the IAEA that could have caused the augmentation of power were pump failures and the failure of the zirconium alloy fuel channels near the core inlet at the bottom of the reactor. Another important fact is that the minimum operating reactivity margin (ORM) was violated several times. All but six of the control rods were removed from the core which was clearly against the operating regulations. The

International Atomic Energy Agency (1992) notes that a “particular configuration of control and safety rods was necessary for the positive scram to occur, and the double humped distribution points to the fact that decoupling had occurred between the upper and lower halves of the reactor. All of these conditions prevailed at the same time” (International Atomic Energy Agency (1992), page 16). This deficiency was known to the Soviet engineers since 1983, but had never been eliminated. Allegedly, the Leningrad Unit 1 accident in 1975 had been similar but was never communicated.

Apart from the technical issues, the important causes of the accident also included deficiencies in the operator training and the lack of in-depth understanding of the reactor operations, the repeated violation of safety rules, and the poor quality and documentation of safety procedures for this type of reactor. Presently there are eleven RBMK reactors in operation, in all of which some upgrading of safety took place, such as the installation of additional absorbers and manual control rods. The speed of the shut-down system was also increased. Furthermore the lower limit of 700 MW(th) was set for continuous operations, and new computational codes for ORM have been prepared. The fuel was enriched to 2,4% to compensate for additional absorbers. It is noted by the IAEA that this will only lead to the desired effect if it is not used to extend fuel life, in which case Pu239 would accumulate and contribute to the increased positive void fraction (International Atomic Energy Agency (1992)). However, the safety is still largely dependent on the timely and correct actions of the staff operating these reactors (Villa (2008)).

Up to today, the explosion at Chernobyl was the largest nuclear accident, spreading radioactive material over large parts of Europe. It is at the same time notable that the atmospheric nuclear bomb tests of the 1950s and 1960s have contributed to–depending on the geographical area examined-– similar or higher radiation doses as Chernobyl for most part of Europe (Böck and Villa (2011)). The accident caused two immediate deaths due to the explosion, and 56 deaths due to very high doses of radiation, between 100mSv to 10 Sv (International Atomic Energy Agency (1992)). There is a noted increase in thyroid cancers, and up to 4000 new thyroid cancer cases are attributed to the accident, especially in the younger generation who were under the age of 4 during the time of the accident. The survival rates for thyroid cancer are luckily very high, up to 99% as reported by the World Health Organisation (2005). No study found any convincing evidence of leukaemia. The “liquidators”, about 200 000 men who participated in the cleaning-up after the accident, were the group most exposed to radiation. Although the Soviet authorities have measured the doses for the cleaning staff, the dosimeters used were very heterogeneous. According to the report of UNSCEAR the average dose for the clean-up workers for the years 1986-2005 was about 117mSv (UNSCEAR (2011)). The WHO estimates that about 2200 radiation caused deaths can be expected in this group (World Health Organisation (2005)). In the first weeks following the accident approximately 115 000 people were evacuated from the most contaminated areas from Ukraine and Belarus. According to the SCK-CEN (2011) report on Chernobyl, “about 30% of these people were exposed to doses lower than 10mSv, 56% to doses between 50-100mSv, and about 4% to dose higher than 100 mSv.” Another 200 000 people were resettled in the following years.

The heavy nuclide (Zr95, Ce144 but also different plutonium, uranium, strontium, and barium particles) have settled around the vicinity of the plant. The major long-range contamination came from I131, and Cs137 both of which are gaseous/fine particle materials. Long term contamination in Central Europe is found from Cs137, which has a half life of approximately 30 years. Caesium will remain in organic soils and many plants, especially mushrooms, can take it up. A number of people despite the accident decided to stay in the contaminated areas. In these areas, countermeasures were implemented to reduce radiation doses, such as the usage of artificial fertilizers that limited the uptake of Cs137, or liming acid soils. Based on these countermeasures radiation doses could be reduced to levels comparable to the background radiation levels. After the downfall of the USSR however, due to financial reasons many of these countermeasures were not administered any more, and the level of contamination increased significantly (SCK-CEN (2011)). The WHO remarks that lifestyle disease and poverty cause currently much higher threat to health than radiation exposure in the former USSR (World Health Organisation (2005)). It is noted that myths and misperceptions of radiation have lead to "paralysing fatalism" among many in the affected areas. Although Chernobyl was indisputably a disaster, the number of deaths and expected deaths as well as serious health problems caused by the event are considerably smaller than casualties connected to other forms of energy extraction, such as coal mines or oil extraction in the corresponding period (Nuclear Energy Agency (2010)).

3.3.3 Fukushima (level 7)

The Fukushima accident originated in the earthquake of March 11^{th} 2011 that resulted in 0.56 g ground acceleration in the area of the Fukushima Dai-ichi power plant, which was 20% above the maximum ground acceleration plant design. Nevertheless, the structures of the plants were not damaged at that time. The tsunami countermeasures were set at 5.7 meter, and as an additional safety, the reactor building was set at 10 meter above sea level. The wave that devastated the plant was, however 14 meter high. During the construction of the plant, Japanese engineers worried that the diesel generators were set too low but the operating company, TEPCO, decided to keep strictly to the original construction plants of the planner, General Electric. The Fukushima Dai-ichi plants (1-4) were an early boiling water reactor type, built between 1971-1978 (Böck and Villa (2011)).

Shortly before the seismic activity, the automatic scram system shut down the reactors. After the earthquake, the electricity grid collapsed in Northern Japan. As designed, the emergency diesel generators started, and supplied the power necessary for the reactor cooling. When a reactor is shut down, residual heat continues to be produced from the decay products. The reactor has approximately 6% of the full power output immediately after shut down, and about 1% of the full power after one day, as decay heat is characterized by an exponentially falling function. About one hour after the earthquake, the tsunami arrived and washed away the diesel generators. What happened afterwards or exactly what processes took place and how much damage was done to the core of the plants is still to be examined in the coming years. In the sections below, I will attempt to give the most likely course of events that followed the tsunami, based on Böck and Villa (2011) and on the International Atomic Energy Agency (2011a) reports. The magnitude of the Fukushima accident is well characterized by the fact that while in case of TMI or Chernobyl we were talking about one reactor block, in Fukushima workers and engineers had to cope with emergencies in four reactor blocks simultaneously.

The moment the power was lost, the heat removal from the core came to a halt and the work of the reactor core isolation pumps (isolation condensers) were limited. It is estimated that 75% of the core was cooled by steam only. Steam, as discussed earlier, has a strong negative reactivity effect. When the temperature increases above 1200°C, the zircaloy cladding of the uranium fuel rods crack and begin reacting with water vapour, creating hydrogen and additional heat. The produced hydrogen was pushed into the drywell. Consequently, hydrogen explosions occurred in the reactor units 1, 2 and 3, allowing for radioactive gases and particles to escape, including mostly xenon, iodine131, caesium 134 and caesium 137. The emergency troops - in order to keep the core cooled – flooded the reactor with sea water, later also added soluble boron and boric acid, which is a strong absorber (Böck and Villa (2011)). There have been claims that after the scramming the reactors there could have been local events of spontaneous criticality (sustained chain reaction) in at least two reactors. As the IAEA reports, the cleaning of the contaminated seawater began in the second half of 2011 (International Atomic Energy Agency (2011a)). At the time of the writing of this study it is not yet known in exactly what state the reactor core is in Fukushima. The IAEA is constantly monitoring the situation, and publishes the newest information about Fukushima each month.

Although four reactors at the Fukushima plant were damaged, the release of radioactive particles (approximately 390.000 to 1.600.000 TBq) were approximately one third to less than one eighth of the Chernobyl release (estimated at 5.200.000 TBq), which was a nuclear explosion (Hajek (2012)). The number of evacuated people in Fukushima is estimated around 85.000, in Chernobyl in total to about 315.000 persons. A significant difference is that the evacuation in Japan took place within days of the accident. The estimated doses sustained by workers and population are thus expected to be considerably lower than in the case of Chernobyl. The Fukushima Prefecture estimates that about 292.000 people have received doses between 5-10 mSv, 43.000 between 10-16 mSv, which is approximately the dose received from an abdominal CT, 21.100 between 16-50 mSV, 3.100 between 50-100 mSv, and about 2.200 between 100-500 mSv, which classifies as a very high dose (Institut de Radioprotection et de Sûreté Nucléaire (2011)). The long term health impacts of Fukushima will have to be officially estimated, at the moment no immediate deaths have been reported due to radiation illness (World Health Organisation (2012)). The significantly contaminated land areas (higher than 600kBq/square meter) in case of Fukushima are estimated around 600 km^2 while for Chernobyl around 13,000 km^2 (Hajek (2012)). Due to the above facts, expert discussion began that two accidents should not be classified in the same category, or the categorization should be extended to be more precise (Brumfiel (2011)).

4 Empirical results: policy impacts of nuclear accidents

In the previous sections we looked at the recent history of nuclear energy and energy policy, as well as at the development of reactor safety. Since the scope of this paper is to study the effects of nuclear accidents on policy, I described the three most influential accidents in nuclear history. Although there have been other INES 5 events next to TMI, they have received for various reasons comparatively little media attention. After Fukushima, the German government in an unprecedented reaction to a nuclear accident decided to phase out its nuclear energy program until 2022, with the immediate shut-down of older power plants. At the time of this study about 8 GWe capacity were disconnected from the grid in Germany. How much this decision has been driven by strategic or by near-election political reasons is debatable. The German decision followed the Italian phase-out and the Swedish referendum after TMI in the line of after-accident policy reactions. In other countries such as in the United States and China, at the moment we see little immediate policy effects of Fukushima. In the next sections I will look at the main factors influencing reactor construction starts over the past decades, while controlling for the effect of three accidents from 1965 on. It is often argued that high interest rates, inflation and overcapacities have shuttered the nuclear industry years before TMI (Cohen (1990), Ebinger (2011)). Looking purely at the construction starts, this seems plausible, therefore I test the effects of real interest rates jointly with inflation on the annual construction starts, where possible. Strategic security considerations such as energy security of a country are also claimed to play a significant role in driving constructions, (Nelson (2010), Fuhrmann (2012), Gourley and Stulberg (2010)). Utilizing these results, while taking into consideration the current concerns of energy security and greenhouse gas emissions, I wish to look at the possible impact Fukushima is likely to have on worldwide nuclear power plant construction.

4.1 Data description and methodology

I employ multiple panel and individual regressions on the net civilian nuclear capacity constructions starts of 31 countries [1] from 1965 to 2009, while controlling for the general primary energy consumption (E), as well as for real income (Y), economic growth, inflation (infl), interest rates (r), the persistence of construction starts, and the three major accidents. The data related to the capacity of nuclear power plants and construction starts comes from the IAEA. Power plants abandoned in-construction after TMI are not included here, as only limited data are available on these plants. One exception is the Shoreham nuclear power plant, which was licensed but never operational. It is well-known that in the 1950s and 1960s many experimental design nuclear plants were constructed, a good portion of which were shut down shortly for different reasons. This turbulent early period of nuclear history is however excluded in this study by choosing to examine the time period starting with 1965. The number of shutdowns after the accidents is a

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[1] Argentina, Belgium, Brazil, Bulgaria, Canada, China, Czech Republic, Finland, France, Germany, Hungary, India, Iran, Italy, Japan, Kazakhstan, Republic of Korea, Lithuania, Mexico, Netherlands, Pakistan, Romania, Russia, Slovak Republic, South Afrika, Spain, Sweden, Switzerland, Ukraine, United Kingdom, United States

variable, which could be potentially investigated, but as it turns out, no country has decided to immediately shut down running plants after TMI or Chernobyl.

I control for the general development of primary energy consumption for countries with nuclear power, by taking the primary energy data from the British Petrol Statistical Review of World Energy database, from 1965 to 2009. Economic variables, such as GDP are sourced from the Penn World Table 7.0. Inflation and real interest rates between 1965-2009 are taken from the *World Bank Database: World Development Indicators.* Both datasets are unfortunately incomplete, often starting in the 1980s and in the mid 1990s for the countries of the former East Block. This results in the loss of very large amount of data when controlling for real interest rates and inflation, therefore I decided to test different sets of models, with and without the real interest rate and inflation variables.

The energy security variable for the period 1965-2009 is constructed as in Fuhrmann (2012), by taking the World Bank's measure of a country's net energy imports (ENSEC[2]) as a percentage of its primary energy use, multiplying it with minus one, rescaling and logging it.

$$ENSEC* = log(\frac{-ENSEC}{100} + 1)$$

Unfortunately the energy security variable database is incomplete and for many Warsaw Pact countries starts only in the 1990s. The descriptive statistics relating to the main variables are found in Table 1.

Table 1: Descriptive Statistics of Main Variables

	$S_{rescaled}$	E	Y	ENSEC*
Mean	317,99	204,60	998.193,80	- 0,54
Median	1,00	70,93	361.448,40	- 0,46
Maximum	23.246,00	2.432,20	13.191.482,00	2,80
Minimum	1,00	6,05	22.846,07	- 2,38
Std. Dev.	1.252,89	388,51	1.713.977,00	0,75
Skewness	8,78	3,83	4,05	0,18
Kurtosis	113,94	18,18	22,62	3,69
Observations	1450	1346	1224	1217

* Source: Own Calculation, Descriptive statistics of the pooled variables, S =construction starts in a given year (MWe), E=primary energy consumption in given year (MTOE), Y=real income in a given year (million USD), ENSEC*=rescaled measure of the World Bank's measure of net energy imports.

4.2 Panel regressions and results

Construction starts–measured in MW(e) capacities–is our main dependent variable, which I regress first in a panel setting, controlling for a lag of the dependent variable, due to the autoregressive

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[2] "Net energy imports are estimated as energy use less production, both measured in oil equivalents. A negative value indicates that the country is a net exporter. Energy use refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport" (World Bank Database: World Development Indicators).

nature of the series, for the lag of primary energy consumption, country and period fixed effects.

$$LogS_{i,t} = \beta_0 + \beta_1 logS_{i,t-1} + \beta_2 logE_{i,t-1} + \mu_i + \lambda_t + \epsilon_{i,t} \tag{1}$$

The construction starts in a given year in a country are denoted as $S_{i,t}$, energy consumption is denoted as $E_{i,t}$, country fixed effects are denoted with μ_i, and time fixed effects with λ_t. Construction starts were rescaled by adding one MW(e) capacity to each year, to allow the log-transformation. The results can be seen in Table 2.

Table 2: Accident Impact on Reactor Construction

	β_0	$logS_{i,t-1}$	$logE_{i,t-1}$	$LUC_{i,t}$	$TMI_{i,t}$	$CHER_{i,t}$	trend	μ_i	λ_t
Accident Model I	-4,99	0,31	1,30					incl	incl
	(0,00)	(0,00)	(0,00)						
Accident Model II	-0,74	0,37	0,37	0,34	-0,02	-0,82		incl	not incl
	(0,32)	(0,00)	(0,03)	(0,06)	(0,92)	(0,00)			
Accident Model III	-3,18	0,31	1,23	-0,04	-0,15	-0,54	-0,05	incl	not incl
	(0,00)	(0,00)	(0,00)	(0,82)	(0,39)	(0,00)	(0,00)		

[*] Source: Own Calculation, S_{t-1} =construction starts in year t-1, E_{t-1}=primary energy consumption in year t-1, $LUC_{i,t}$= Lucens accident impact, $TMI_{i,t}$=Three Mile Island Accident Impact, $CHER_{i,t}$=Chernobyl accident impact, μ_i=country fixed effects, λ_t=period fixed effects. P-values are in parenthesis.

We can see that the series shows strong persistence, and both the first lag of primary energy consumption and the lag of the construction starts is highly significant, with an expected positive sign. The regression estimates that 1% increase in the primary energy consumption of the previous year results in a 0,3%- 1,3% increase in nuclear power plant construction, while controlling for the autoregressive parameter and optionally the effect of accidents. The significant positive persistence parameter of the series supports the lock-in theory that countries, which have already invested in nuclear infrastructure are more likely to build nuclear power plants. This supports the finding of Fuhrmann (2012), and those of Miller and Sagan (2009) and Gourley and Stulberg (2010), who claim the presence of historical inertia, and note that nuclear entrants in the past were likely Warsaw Pact or North Atlantic countries. Apart from the evident historical reasons, the results might be explained by the fact, that operating nuclear plants economically requires large economies of scale, well-trained personnel, and adequate grid infrastructure to accommodate nuclear energy, all of which need heavy initial investment. Of special interest are the period fixed effects in Accident Model I, which we can see in Figure 1, showing a possible decrease of the positive fixed effects already in 1976-77, and the permanent turn in the sign of the period fixed effects in 1986. This means that while controlling for the effects of both energy consumption and the persistence of construction starts, there was a global downward trend in the construction of new power plants since 1986. Whether or not these period fixed effects can be explained by the accidents described before, we have to test.

As a next step, I account for the influence of accidents on nuclear power plant construction. The accidents chosen are Chernobyl and TMI, as well as the Lucens accident, which is the only public INES 5 accident next to TMI in the examined time period. There were two other nuclear

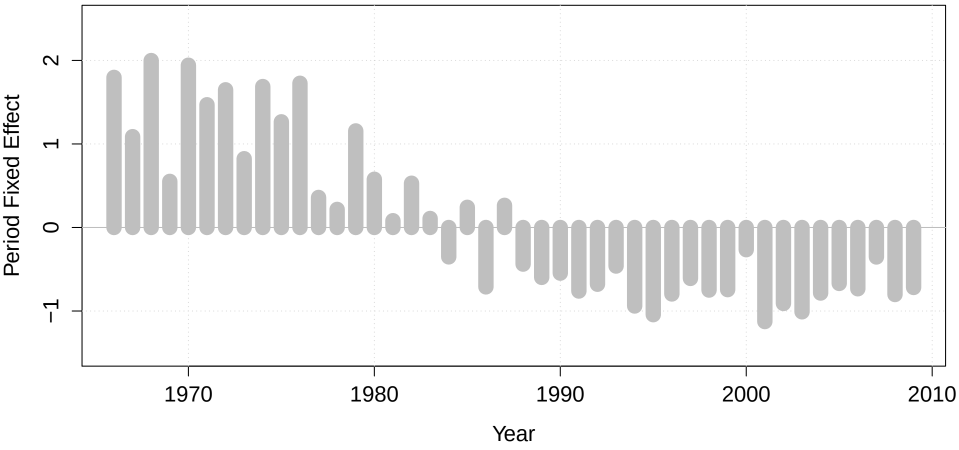

Figure 1: Period Fixed Effects (λ_t) from Accident Model I

accidents in the USSR in the sample period that would rate level 5 (Smythe (2011)), but were not made public and therefore not known at the time (Chernobyl 1982, Lake Karachay 1967). All other INES 5 or 6 accidents happened before the examined period and therefore are excluded from the dataset. In order to test the effects the above accidents have caused worldwide, it is necessary to estimate the time length of the impact, which may differ from country to country. To do this, I run individual regressions for all countries, allowing for the impacts of the nuclear accidents to last for varying times.

$$LogS_{i,t} = \beta_0 + \beta_1 logS_{i,t-1} + \beta_2 logE_{i,t-1} + \beta_3 LUC_{1-41} + \beta_4 TMI_{1-31} + \beta_5 CHER_{1-24} + \epsilon_{i,t} \quad (2)$$

I allow the Lucens dummy to take on the value of ”1” in successive time periods, allowing for differing impact extents. The variable thus takes on a positive value first in 1969, then in 1969&1970, and then progressively covers the entire sample period between 1969-2009. Similarly, I allow for the impact of the TMI accident to run from 1979 to 2009 and for Chernobyl, to run from 1986 to 2009. What the optimal impact length of an accident is, taking into account the other accidents, the constructions of the previous year and the energy consumption of the previous year, I ascertain by running the entire array of models, in this case 41*31*24=30504 regressions for each country. The optimal impact length has been determined by using the AIC sample selection criterion, and the results are found in Table 3.

Table 3: Accident Impact on Reactor Construction pro Country

	β_0	$logS_{t-1}$	$logE_{t-1}$	L-IL	LUC	TMI -IL	TMI	C-IL	CHER
Argentina	9,85	-0,11	-2,39	1980	-1,16	1981	1,78	1996	-0,72
	(0,02)	(0,46)	(0,03)		(0,10)		(0,07)		(0,21)
Belgium	-8,57	0,00	2,82	1971	4,20	1985	-2,34	2009	-2,96
	(0,30)	(0,99)	(0,20)		(0,00)		(0,01)		(0,00)
Brazil	-1,80	-0,30	0,52	1977	1,76	2009	-0,56	2009	-0,28
	(0,51)	(0,06)	(0,50)		(0,05)		(0,63)		(0,69)
Bulgaria	-1,26	-0,57	0,42	1974	3,57	1983	4,17	1988	3,80
	(0,73)	(0,00)	(0,73)		(0,00)		(0,00)		(0,00)
Canada	21,47	-0,32	-2,83	1969	-5,52	1979	3,41	2009	-5,42
	(0,02)	(0,01)	(0,11)		(0,01)		(0,07)		(0,00)
China	-7,73	0,40	1,70	2004	-2,66	2000	2,01	1995	-2,07
	(0,05)	(0,00)	(0,01)		(0,01)		(0,02)		(0,03)
Czech Republic	-5,92	-0,03	1,61	1986	-0,58	1979	7,52	1987	3,57
	(0,29)	(0,70)	(0,28)		(0,08)		(0,00)		(0,00)
Finland	-5,22	0,00	1,98	1975	3,52	2004	-1,54	2005	0,71
	(0,19)	(0,98)	(0,15)		(0,00)		(0,05)		(0,34)
France	-24,64	-0,10	6,22	1970	-5,76	1991	1,92	2009	-8,81
	(0,06)	(0,42)	(0,02)		(0,00)		(0,01)		(0,00)
Germany	20,92	-0,28	-2,34	1969	-6,00	1985	-5,72	2009	-7,32
	(0,42)	(0,08)	(0,60)		(0,01)		(0,00)		(0,00)
Hungary	-4,27	0,00	1,36	1974	1,48	1979	6,66	1992	-0,24
	(0,27)	(0,97)	(0,27)		(0,01)		(0,00)		(0,62)
India	-1,97	-0,02	0,51	2004	3,02	1983	-3,41	1999	-2,85
	(0,57)	(0,90)	(0,43)		(0,01)		(0,01)		(0,01)
Iran	-0,32	-0,19	0,44	1974	-1,12	1985	-1,33	2009	-1,71
	(0,84)	(0,24)	(0,33)		(0,06)		(0,03)		(0,03)
Italy	-2,09	0,00	0,44	1970	3,43	1985	-0,08	2009	-0,14
	(0,66)	(0,99)	(0,66)		(0,00)		(0,85)		(0,74)
Japan	31,03	-0,20	-4,79	1983	4,06	2007	1,80	1993	4,51
	(0,00)	(0,19)	(0,01)		(0,00)		(0,13)		(0,00)
Republic of Korea	-1,43	-0,11	1,58	1988	-2,53	2000	3,69	2005	-5,46
	(0,59)	(0,46)	(0,02)		(0,06)		(0,00)		(0,00)
Mexico	-5,28	0,06	2,03	1975	-1,98	1985	-3,56	2009	-4,46
	(0,10)	(0,70)	(0,03)		(0,01)		(0,00)		(0,00)
Netherlands	0,00	0,00	0,00	1969	6,18	2001	0,00	2009	0,00
	(1,00)	(0,91)	(0,98)		(0,00)		(0,82)		(0,42)
Pakistan	4,49	-0,26	-0,95	2004	-2,67	2006	0,80	2005	1,28
	(0,00)	(0,08)	(0,03)		(0,00)		(0,20)		(0,04)
Romania	0,64	0,19	0,05	1981	-1,38	1983	2,31	2009	-0,84
	(0,78)	(0,16)	(0,93)		(0,01)		(0,00)		(0,11)
Russia	6,73	-0,12	0,26	2005	-5,81	2007	-2,55	1986	7,68
	(0,08)	(0,01)	(0,65)		(0,00)		(0,00)		(0,00)
Slovak Republic	-4,53	-0,40	1,61	1988	2,72	1982	-2,83	1986	-3,03
	(0,18)	(0,01)	(0,18)		(0,00)		(0,01)		(0,11)
South Africa	-5,02	-0,27	1,80	1975	-1,56	1985	-2,46	2009	-3,33
	(0,20)	(0,10)	(0,09)		(0,02)		(0,01)		(0,01)
Spain	15,08	0,04	-3,11	1972	-3,55	1980	5,00	1997	-1,07
	(0,00)	(0,74)	(0,00)		(0,00)		(0,00)		(0,11)
Sweden	28,63	-0,15	-7,44	1975	5,62	1980	7,71	2002	0,54
	(0,00)	(0,07)	(0,00)		(0,00)		(0,00)		(0,27)
Switzerland	11,69	0,04	-3,01	1972	-2,86	1985	-2,12	2009	-1,64
	(0,19)	(0,77)	(0,30)		(0,00)		(0,04)		(0,18)
Ukraine	0,00	0,00	0,00	1987	6,86	1986	1,10	1989	0,00
	(0,77)	(0,00)	(0,77)		(0,00)		(0,00)		(0,00)
United Kingdom	-5,50	-0,03	2,33	2009	-6,80	1980	3,65	1988	2,23
	(0,87)	(0,84)	(0,72)		(0,00)		(0,01)		(0,05)
United States	5,37	0,22	0,30	1979	-1,05	2009	-7,72	1995	0,05
	(0,30)	(0,01)	(0,65)		(0,00)		(0,00)		(0,77)

[*] Source: Own Calculation, S_t =construction starts in year t, E_t=primary energy consumption in year t, LUC= Lucens accident impact, TMI=Three Mile Island Accident Impact, CHER=Chernobyl accident impact, IL=lenght of impact pro country. P-values are in parenthesis.

Clearly, some of the results, picked up by the AIC criterion, are highly questionable. It is unlikely that Lucens had a lasting impact on Chinese, or Russian nuclear energy expansion. It is the economic and political situation, and the fact that nuclear power plants have been built only much later in China that the regression fails to model. Another serious bias we are facing is that Russian and Ukrainian primary energy consumption data are only available from 1985 on, therefore earlier years have been ignored by the regression for these countries. Lithuania and Kazakhstan have been excluded due to missing data. As next, I test each of these accidents with differing impact lengths for significance, while controlling for the autoregressive component of power plant constructions, primary energy consumption, and the other accidents. The coefficients from these regressions as well as the corresponding p-values in brackets can be seen in Table 3.

In interpreting our results, caution is advised. We assume that the driving factors of nuclear power capacity development could have been different in economies where the nuclear industry was in private hand from the beginning on, such as the US, and in planned economies, with large state ownership. The effects of central party decisions or of inherent energy security considerations are econometrically very difficult to model. Significant positive impacts of "accidents" mean that the years after the accident have not in fact caused a negative impact on construction, but brought an increase with it. This is logical in case of 1969, which marked the middle of the Cold War, and the beginning of the nuclear boom, and in case of 1979 as well, which was the first year of the second oil crisis. We see however, that the model attributes a very strong significant negative effect to TMI in the United States, which is consistent with the prevailing literature, and is a result that we have expected from the beginning on.

The case of France deserves also an explanation, as by the middle of the 1980s approximately 65-70% of French electricity production was covered by nuclear energy, with the nuclear power plants occasionally being temporarily ran down to avoid overcapacity. The decrease in nuclear power plant construction in France thus could be more due capacity issues than Chernobyl. Lester and Rosner (2009) also note that by today the French nuclear capacity exceeds baseload demand. To avoid the ambiguous situation of interpreting the results individually, I construct a pooled variable for each accident dummy, including the optimal impact length for each country, and run the regression in a panel setting once again:

$$LogS_{i,t} = \beta_0 + \beta_1 logS_{i,t-1} + \beta_2 logE_{i,t-1} + \beta_3 LUC_{i,t} + \beta_4 TMI_{i,t} + \beta_5 CHER_{i,t} + \mu_i + \epsilon_{i,t} \quad (3)$$

The results (Table 2) without period fixed effects show a slightly positive effect of the Lucens accident on reactor constructions. This implies that there was no negative worldwide effect of Lucens, but the years following the accident have brought an increase in nuclear power plant constructions. TMI had no worldwide effects at all. The coefficient is slightly negative but highly insignificant, confirming the general view that TMI had mostly impacted on the US nuclear industry but not on the rest of the world. Of most interest is the Chernobyl dummy, which is not only negative as expected, but highly significant, meaning that all other effects held constant, without Chernobyl there would have been on average 82 % more new power plant capacities in construction per year over the affected period. The length of the Chernobyl impact differs pro country, as seen in Table 3, but it often runs until the end of our sample period. The results including a time trend instead of the period fixed effects can also be seen in Table 2.

$$LogS_{i,t} = \beta_0 + \beta_1 logS_{i,t-1} + \beta_2 logE_{i,t-1} + \beta_3 LUC_{i,t} + \beta_4 TMI_{i,t} + \beta_5 CHER_{i,t} + \mu_i + \beta_8 t + \epsilon_{i,t} \quad (4)$$

We see that the trend is negative and significant, as is the Chernobyl dummy. Based on these results, we would conclude that of all the examined accidents Chernobyl had a lasting and negative consequence on worldwide nuclear power plant construction. An interesting question is the length of the impact. We see that the significant negative impact of Chernobyl stops for the countries China (1995), India (1999), and South Korea (2005) after a time span of nine-nineteen years. We cannot find a negative effect of the Ukrainian accident on Japan. Gourley and Stulberg (2010) also note that Japan and Korea were building at a substantial rate when others were not. This implies that next to the question of energy dependence, the issues of physical constraints on pipeline/transmission may compound the significance of the national energy security question.

The significant negative effect of Chernobyl does not stop until the end of the sample period (2009), for the countries Belgium, Canada, France, Germany, Mexico, South Africa, whereas France, as mentioned earlier has almost full nuclear capacity to supply its electricity needs. The dominance of European countries in this group could be perhaps attributed to the proximity of the accident. Other European countries such as Italy, Spain, Slovak Republic, Hungary, Romania and Switzerland also have negative coefficients for the Chernobyl dummy, although these effects are not statistically significant, and the impact length is varying. An interesting case is Finland, where not Chernobyl, but TMI is the variable carrying a significant negative impact, which lasts until 2004. Finland was the first country to decide upon the construction of an EPR in 2005, due to issues of energy security and environmental concerns. Another noteworthy case is that of the United States, where in fact the construction of the first plants since TMI (Vogtle 3 &4) has started, although this construction is not covered by our sample due to data availability reasons. This could possibly–if the sample could be extended—end the effect of TMI after thirty-three years. There were twenty-two reactors planned for construction in the USA as of the end of 2010. Although these numbers are subject to change, the order of magnitude shows that the United States, thirty-years after TMI is actively considering the nuclear energy option.

We see that the impact of an accident is likely to have a long lasting negative effect in the country where the accident happened, and possibly in countries which were affected by the direct consequences (nuclear fallout of the accident), or subject to severe public pressure. This is true for the United States after TMI, but also for most of Europe after Chernobyl. No plant constructions have followed Chernobyl in the Ukraine up to now, and the first NPP in Russia was built after twenty years in 2006. Next to the United States, Russia presently also holds ambitious plans with thirty-eight reactors planned for construction at the end of 2010. However, a correlation analysis of the years of negative impact with the distance of capital cities to Prypiat has shown no discernible pattern.

4.3 A note on interest rate and inflation

The main reason for testing inflation and real interest rates where possible,—as many previous studies, among others Cohen (1990) suggested–is the large financing requirement of a nuclear power plant. These variables have been widely regarded by renowned authors to be of special interest in market economies, where the nuclear industry has faced open market conditions. A nuclear plant has to be authorized, built, connected to the grid, before it can start producing cash flows. This meant at the beginning of the 1970s that utilities partly had to finance approximately four years construction time. Inflation in the US has been already high starting in 1973, with the first oil crisis. Real interest rates began to rise however in 1979 and stayed comparatively high throughout the 1980s and even in the 1990s (Ebinger (2011)). TMI had certainly a regulatory aftermath in the United States that foresaw stricter control and authorization process for nuclear power plants. Coupled with resistance from the local population, this lengthened the construction time and increased the construction costs of those plants that were already started before Three Mile Island considerably (Harding (2007)). Presently, construction times in China, Japan or South Korea are comparable to those of the US and EU standards at the beginning of the 1970s, despite of the much higher safety requirements regarding the site and the passive safety systems. The real costs of an NPP in the USA and Europe have increased from approximately 1700$/KW to 4500$/KW in the last three decades. In these regions, the high investment and financing requirements are often blamed to make nuclear energy uncompetitive against natural gas or shale gas. On the other hand, the costs of nuclear power plants in the Asia-Pacific region is considerably lower, around 2300-3000$/KW. This is partially due to different ownership and financing structures, but also to lower labour and engineering costs and standardisation. Joskow and Parsons (2009) note that with the accumulation of significant construction experience everywhere in the world, construction costs are possibly going to decline significantly. A good example is France which maintained low costs by working with large economies of scale and a few suppliers (Morton (2012)).

At the same time the issue of political regulation surrounding the nuclear industry is also essential (Toth and Rogner (2006)), as political decisions supporting one or the other energy form are usually less “loud” and apparent than the German nuclear exit, but may play an important role in future investments. The questions of the authorization process, government guarantees, fixed electricity purchase prices, and the regulation when the costs of a new plant can be charged to the customers are all critical in shaping the energy landscape and policy of a country. As an example, the licensing process for building nuclear plants has been changed to make it more efficient in the United States in the past years (Joskow and Parsons (2009)). The concerns of energy security, (Fuhrmann (2012), Gourley and Stulberg (2010)), climate change (Joskow and Parsons (2009)) and the share of own resources may in case of many countries also play an important role in policy as we see in China, South Korea or Japan, but also in the United States. While keeping in mind the sociological and political environment of nuclear energy, I have tested where the data availability allowed, the joint impacts of inflation and real interest rates on new power plant construction, while controlling for energy consumption, persistence and the major accidents.

$$LogS_t = \beta_0 + \beta_1 logS_{t-1} + \beta_2 logE_{t-1} + \beta_3 LUC_t + \beta_4 TMI_t + \beta_5 CHER_t + \beta_6 r_t + \beta_7 infl_t + \epsilon_t \quad (5)$$

A full time series is available for the United States and for South Africa for the period between 1965-2009, while a partial series for France (1965-2004), Sweden (1970-2005), and for Japan (1971-2009). Many other Western countries have statistics only starting in the 1980s. Another problem is that due to the political transitions, most of the countries of the ex-Warsaw Pact only have data starting after the mid-1990s, which results in serious loss of information and a clear bias. The results can be seen in Table 4.

Table 4: Impact of Inflation and Real Interest Rate on Reactor Construction

	β_0	$logS_{i,t-1}$	$logE_{i,t-1}$	LUC_t	TMI_t	$CHER_t$	$r_{i,t}$	$infl_{i,t}$	μ_i
United States	4,35	0,22	0,44	-1,14	-7,83	0,07	0,00	0,02	
	(0,48)	(0,02)	(0,58)	(0,00)	(0,00)	(0,72)	(0,99)	(0,55)	
Japan	1,51	-0,25	-2,10	6,06	3,13	5,88	-0,55	-0,24	
	(0,59)	(0,13)	(0,64)	(0,01)	(0,04)	(0,00)	(0,09)	(0,14)	
France	-1,13	-0,15	3,28	-5,87	1,91	-5,74	-0,18	0,26	
	(0,48)	(0,25)	(0,33)	(0,00)	(0,06)	(0,01)	(0,48)	(0,23)	
South-Africa	-6,63	-0,33	2,14	-1,69	-3,16	-3,86	0,07	-0,01	
	(0,10)	(0,05)	(0,06)	(0,01)	(0,00)	(0,00)	(0,15)	(0,87)	
Sweeden	6,03	-0,10	-1,56	4,37	7,83	1,28	-0,03	-0,03	
	(0,01)	(0,28)	(0,01)	(0,00)	(0,00)	(0,09)	(0,67)	(0,57)	
Panel sample	2,08	0,48	-0,19	0,01	-0,37	-0,87	-0,01	0,00	incl
	(2,67)	(0,00)	(0,62)	(0,99)	(0,12)	(0,00)	(0,37)	(0,68)	

* Source: Own Calculation, S_{t-1} =construction starts in year t-1, E_{t-1}=primary energy consumption in year t-1, LUC_t= Lucens accident impact, TMI_t=Three Mile Island Accident Impact, $CHER_t$=Chernobyl accident impact, $r_{i,t}$= real interest rate, $infl_{i,t}$=inflation rate, μ_i=country fixed effects. P-values are in parenthesis.

For the countries examined above the individual regression usually shows the coefficients of both the real interest rate and the inflation variables to be negative as expected, but non-significant. A panel regression including the same variables for the entire dataset also results in non-significant coefficients with coefficient values around zero. A test of the real oil prices for the panel dataset also brings non-significant regression results.

4.4 A note on real income, economic growth, energy security and nuclear proliferation

The primary purpose of the paper is to test the consequences of major nuclear accidents on worldwide power plant construction. However, a few other issues that have been extensively discussed in literature deserve a short explanation. One is the case of real income (Y), which is claimed to be a major driver or nuclear energy, and was also found to be a significant positive driver of nuclear plant construction by Fuhrmann (2012).Therefore after fixing the basic model (Accident Model II), I have tested if including real income or economic growth changes my results significantly.

$$LogS_{i,t} = \beta_0 + \beta_1 logS_{i,t-1} + \beta_2 logE_{i,t-1} + \beta_3 LUC_{i,t} + \beta_4 TMI_{i,t} + \beta_5 CHER_{i,t} + \beta_9 logY_{i,t-1} + \mu_i + \epsilon_{i,t} \tag{6}$$

$$LogS_{i,t} = c + \beta_1 logS_{i,t-1} + \beta_2 logE_{i,t-1} + \beta_3 LUC_{i,t} + \beta_4 TMI_{i,t} + \beta_5 CHER_{i,t} + \beta_{10} \Delta logY_{i,t-1} + \mu_i + \epsilon_{i,t} \tag{7}$$

The results of these regressions can be seen in Table 5.

Table 5: Impact of real GDP on Reactor Construction

	β_0	$logS_{i,t-1}$	$logE_{i,t-1}$	$LUC_{i,t}$	$TMI_{i,t}$	$CHER_{i,t}$	$logY_{i,t-1}$	$dlogY_{i,t-1}$	μ_i
GDP Model I	5,92	0,36	1,07	0,14	-0,09	-0,89	-0,74		incl
	(0,04)	(0,00)	(0,00)	(0,48)	(0,61)	(0,00)	(0,02)		
GDP Model II	-0,38	0,38		0,12	-0,02	-0,80	0,10		incl
	(0,86)	(0,00)		(0,55)	(0,91)	(0,00)	(0,53)		
Growth Model I	-1,29	0,38	0,48	0,31	-0,02	-0,87		2,24	incl
	(0,12)	(0,00)	(0,01)	(0,15)	(0,92)	(0,00)		(0,15)	
Growth Model II	0,82	0,39		0,13	0,05	-0,69		2,22	incl
	(0,00)	(0,00)		(0,53)	(0,77)	(0,00)		(0,15)	

* Source: Own Calculation, S_{t-1} =construction starts in year t-1, E_{t-1}=primary energy consumption in year t-1, $LUC_{i,t}$= Lucens accident impact, $TMI_{i,t}$=Three Mile Island Accident Impact, $CHER_{i,t}$=Chernobyl accident impact, $logY_{i,t-1}$=real income in year t-1, $dlogY_{i,t-1}$=economic growth in year t-1, μ_i=country fixed effects. P-values are in parenthesis.

A test of the natural log of gross domestic product for the panel dataset brings in the absence of primary energy consumption insignificant results, and in the presence of the energy consumption variable negative significant correlation. It would be dangerous to assume however, that nuclear power plant constructions are negatively driven by real income. The reason for the negative coefficient could be that real GDP and primary energy consumption were cointegrated over the examined period (Csereklyei and Humer (2012)), and so due to a misspecified multicollinear model, the real GDP takes on a large negative, while primary energy consumption a large positive coefficient. These results imply that a proper model specification would not include both real income and primary energy consumption. While real GDP might be causing primary energy consumption, it is likely that primary energy consumption is the variable that contributed directly to nuclear plant construction, and not real GDP. The coefficients on the accident variables are practically unchanged. The insignificant coefficient on real income in the absence of the energy variable is in contrast with the findings of Fuhrmann (2012), as well as of Gourley and Stulberg (2010). A panel regression of economic growth on reactor constructions brings also insignificant results, with or without the presence of energy consumption. Another crucial topic to consider is the question of energy security, discussed by Fuhrmann (2012), Miller and Sagan (2009), Gourley and Stulberg (2010), Nelson (2010). Energy security is considered as a strategic issue, not only relevant for the economy but also for national security. In case of diplomatic or military hostilities a country that is heavily energy import dependent may be adversely disadvantaged without proper energy supply. Many decisions about nuclear strategy, such as those of France might have been driven by energy security considerations. Therefore I test the impact of energy security alongside with the effect of nuclear accidents on power plant constructions to see how the results presented in Table 2 might change. The basic model tested together with the energy security variable gives following results:

Table 6: Impact of Energy Security on Reactor Construction

	β_0	$logS_{i,t-1}$	$logE_{i,t-1}$	$LUC_{i,t}$	$TMI_{i,t}$	$CHER_{i,t}$	$ENSEC_{i,t-1}$	@t	μ_i
Energy Sec. I	-4,36	0,30	1,11				-0,33		incl
	(0,00)	(0,00)	(0,00)				(0,21)		
Energy Sec. II	0,53	0,34	0,01	0,13	-0,09	-0,79	-0,90		incl
	(0,59)	(0,00)	(0,96)	(0,55)	(0,61)	(0,00)	(0,00)		
Energy Sec. III	-2,05	0,29	0,95	-0,29	-0,23	-0,51	-0,53	-0,06	incl
	(0,05)	(0,00)	(0,00)	(0,19)	(0,20)	(0,00)	(0,04)	(0,00)	

[*] Source: Own Calculation, S_{t-1} =construction starts in year t-1, E_{t-1}=primary energy consumption in year t-1, $LUC_{i,t}$= Lucens accident impact, $TMI_{i,t}$=Three Mile Island Accident Impact, $CHER_{i,t}$=Chernobyl accident impact, $ENSEC_{i,t-1}$ = energy security measure in year t-1, @t=time trend, μ_i=country fixed effects. P-values are in parenthesis.

While the coefficient on the energy security variable is significant and negative, meaning that energy dependency (insecurity) contributes to nuclear power plant construction, the impact of accidents or the magnitude of their coefficients is almost unchanged. This outcome is in line with the expectations. My results thus support the view that nuclear power plant constructions worldwide have been mostly driven next to the increasing energy demand, by historical circumstances, political and economic policy, as well as energy security considerations, rather than economic factors. A simultaneous panel regression of the energy secuirty and real income variables has not brought a change in either the signficance or the direciton & magnitude of the coefficients. The Chernobyl accident seems to have caused an enormous worldwide decrease in new nuclear plant constructions for decades, with the exception for countries where physical barriers to energy imports made nuclear power to be a crucial national energy source.

The question what impact the possibility of nuclear proliferation has on energy policy is beyond the scope of the study. Many studies identify the problems of possible nuclear proliferation (Miller and Sagan (2009), Socolow and Glaser (2009), Fuhrmann (2012)) as a potential challenge and constraint for the future of nuclear energy, especially if non-democratic countries were to acquire nuclear technology.

5 Conclusion and implications for the future of nuclear energy

In this paper I investigate the effects of nuclear accidents on energy policy with the help of a panel dataset of 31 countries from 1965-2009, using annual data about the capacity of reactors under construction, primary energy consumption, as well as three nuclear accidents scaled INES five or higher by the International Atomic Energy Agency. After determining the extent of the accident impact in the different countries, I find that neither Three Mile Island nor Lucens had a worldwide negative effect on construction starts, while Chernobyl did. The effect of Chernobyl is however shown to wear-off in certain geographical clusters, after ten to thirty years. Thus, an accident is likely to have a negative and long lasting impact in the country where it happened, and possibly in countries which were affected by the direct consequences, such as the nuclear fallout, or where governments are subject to severe public pressure. I also find that nuclear capacity enlargement shows a significant persistence, but it was also significantly driven by primary energy consumption in the past five decades. After the test of real interest rates jointly with inflation, gross domestic product and oil prices, I find the effect of these variables insignificant.

Recently, the Economist (Morton (2012)) published an article about nuclear energy, titled “a dream that failed”. To the question why nuclear energy has not continued worldwide to gain considerable share in electricity generation after the 1970s, the answers are complex, and often interrelated. The golden age of nuclear power was certainly not only due to the inevitably increasing energy demand, but also to political, military, security and strategic considerations. As the political and sociological landscape changed, so did the environment surrounding the nuclear industry. Massive anti-nuclear sentiments rose from the public following the TMI and Chernobyl nuclear accidents, that resulted either in clear policy decisions against nuclear energy, or less visible political measures such as the support of other energy forms over the nuclear option.

Nuclear energy certainly has to battle with a number of obstacles. One serious hindrance is the widespread public perception. Nuclear power is frequently considered as a dreaded and uncontrollable risk by the general public, without the necessary awareness for the safety record and features of nuclear power plants, and without a basic understanding of the technology. Severe public protests and voting behaviour may create for private utilities a changing and uncertain policy environment, which might be highly discouraging. The enormous financing requirements and long constructions times for a power plant are an equally potent stumbling stone. The Economist (Morton (2012), page 3) argues that “in liberalized energy markets, construction of nuclear power plants is no longer feasible.” Other energy forms with less safety requirement, faster construction times, and much less regulatory requirements offer faster and safer return on investment.

Has nuclear energy a future then? This is the point where we have to look a bit farther than immediate investment decisions or next-month elections. Nuclear energy is the only energy source which is both resistant against resource price fluctuations, has abundant resources and a secure base load output. From the point of energy security it provides independence to many states from energy imports, high price fluctuations and undisrupted energy supply in case of an emergency. But even more importantly, nuclear energy provides clean energy. The impact of climate change is not yet adversely felt in many regions of the world, however with the steadily increasing primary energy demand from developing countries, the consequences of global warming will be inevitably felt. To keep the temperature increase under two degrees Celsius, a drastic decrease in energy consumption and serious improvements in energy efficiency would be needed. Princeton University estimates, among others that deploying the double of the current global nuclear capacity to replace coal based capacity would have the potential to reduce global carbon emissions by at least one billion tons per year by 2060, or one wedge (Princeton University (2011)). The economic damage caused by the increase of sea levels and by adverse weather conditions are very difficult to estimate. Next to best possible deployment of renewable energy sources, the performance of which is not only fluctuating, but also land-intensive, nuclear energy, given that the problems of waste handling and proliferation are competently addressed, offers a secure and concentrated long-term energy option, with a potential to mitigate impending climate change.

These are the points that policy makers have to keep in mind also in the wake of Fukushima. We have seen that the empirical results of this paper support the evidence of a strong negative reaction of nuclear power plant construction to the Chernobyl accident. At the same time, the radioactive contamination in case of Fukushima is estimated considerably less than that of Chernobyl, and is concentrated closer to the damaged power plant. The conclusions of this paper indicate that at least in Japan, the accident would have an aftermath on the number of new constructions. In fact, on September 19^{th}, 2012 the Japanese cabinet agreed on a nuclear exit strategy, however without committing itself to any specific date (Reuters (2012)). This policy move is one, that was indicated by our findings. Where and how far the negative policy impact of Fukushima might spread will now depend on the objectivity of the media coverage, on the depth of technology understanding in the public, whether or not there are existing nuclear infrastructures and know-how in a country, but also on the existing political structures. We have seen that the impact-length of an accident can, but need not "wear off" anywhere between ten to thirty years.

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