Nuclear Energy: Boon or Bane?

Reassessing Nuclear Costs and

Evaluating Feasibility of Nuclear Insurance

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Abstract

In the next 20 years, the demand for energy is anticipated to grow by 40 per cent. All available energy sources would need to be leveraged in order to satisfy the growing demand, however, in reality it does not happen. The fossil fuels are considered for a gradual phase-out and the likelihood of a massive expansion of renewable energy is also doubtful. The outlook for nuclear energy is gloomy due to people's concern that it is not safe and that a nuclear disaster would cause severe damage. While the previous studies support the above, several new studies suggest the opposite. This paper assesses the cost of a nuclear disaster through a hypothesized nuclear disaster at Olkiluoto-3 power plant in Finland and finds that the previously reported nuclear costs might be overstated. Furthermore, this study analyses the international third party liability laws on nuclear energy and concludes that they have been consistently failing. Finally, this study finds that insuring against a nuclear disaster is feasible but currently not manageable. Based on the findings, this paper derives eight implications for the consideration of associated stakeholders and urges for a constructive discussion.

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List of Abbreviations and Acronyms

AP-1000	Advanced Pressurized Water Reactor
ASN	French Safety Authority
AM-1	Atom Mirny (Peaceful Atom)
BWR	Boiling Water Reactor
DBA	Design Basis Accident
DEMO	Demonstration Power Plant
DM	Deutsche Mark
EBR-1	Experimental Breeder Reactor
ECCS	Emergency Core Cooling System
ECRR	European Committee on Radiation Risk
ECU	European Currency Unit
EED	Expert Expected Damage
EPR	European Pressurized Reactor
EU	European Union
EUR	Euro
FBR	Fast Breeder Reactor
GCR	Gas-Cooled Reactor
GDP	Gross Domestic Product
GRS	Gesellschaft für Anlagen und Reaktorsicherheit (Society for Plant and Reactor Safety)
GOELRO	Gosudarstvennaya Komissiya po Elektrifikacii Rossii (Soviet Union Sate Electrification Commission)
GW	Gigawatt
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
ILW	Intermediate-level waste
I&C	Instrumentation and control system
INES	International Nuclear Event Scale
IPHECA	International Programme on the Health Effects of the Chernobyl Accident
IPPNW	International Physicians for the Prevention of Nuclear War
ITER	International Thermonuclear Experimental Reactor
Kela	Social Insurance Institution of Finland
Km	Kilometre
kPA	kilopascal
kWh	Kilowatt hour
LLW	Low-level waste
LNT	Linear No-Threshold
LWR	Light Water Reactor
mSV	Millisievert
MW	Megawatt
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission of United States
OECD	Organization for Economic Co-operation and Development
ORM	Operating reactivity margin
PC Protocol	Protocol to Amend the Paris Convention
PCA	Probabilistic Consequence Assessment
PHWR	Pressurized Heavy Water Reactor

PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Assessment
PWR	Pressurized Water Reactor
RBMK	Reaktor Bolshoi Moshchnosty Kanalny (High Power Channel-type Reactor)
SDR	Special Drawing Rights
SOARCA	State-of-the-Art Reactor Consequence Analyses
STUK	Finnish Radiation and Safety Authority
Tepco	Tokyo Electric Power Company
TORCH	The Other Report on Chernobyl
TVO	Teollisuuden Voima Oyj
TWh	Terawatt hours
UK	United Kingdom
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USA	United States of America
USD	United States Dollar
USSR	Union of Soviet Socialist Republics
VC Protocol	Protocol to Amend the Vienna Convention
VVER	Vodo-Vodyanoi Energetichesky Reactor (Water-Water Power Reactor)
WHO	World Health Organization
WW II	Second World War

Introduction

The outlook for the global energy markets is rather uncertain. The world energy consumption is rapidly increasing. The year-on-year growth rate in 2010, as it peaked at 5 per cent, was the highest since 1973. The main driving force behind the unprecedented energy demand is the cohort of the developing economies: China, India, Russia, and those in the Middle East. Assuming the medium fertility rate, the world of 7 billion people is expected to add another 1.5 billion in less than 20 years from now, which might trigger a 40 per cent further increase in the energy demand (OECD, 2011) (UN, 2010). Hence, there is no reason to anticipate that this growth will cease. Whether the world energy production capacity will be able to catch up is a disturbing question which at the moment cannot be explicitly answered. Therefore, as never before the threat of energy crisis is becoming real.

Intuitively, to meet the increasing demand for energy, one would use all available energy sources and would explore those which are not yet employed. However, the global vision for the energy sector has been shaped in a quite opposite manner, whereas phasing out fossil fuels is widely encouraged, green energy sources are expected to take over instead and nuclear energy is not expected to grow its share in the energy mix. While having highly ambitious goals is not obnoxious, it would be useful if the policy makers presented a more specific action plan on how those goals can be achieved. Since gradual abatement of fossil fuels, which currently comprise roughly 80 per cent of the global energy mix, is a question of time, the need to define potential substitutes has become urgent. From the perspective of the electricity markets, renewables cannot be an alternative to the fossil fuels because, due to their inherent intermittency problem, they do not qualify for the base-load power generation. Moreover, the renewable energy technologies are still expensive and in many parts of this world, if not subsidized, they are not economically viable. Given that more than 20 per cent of the world population does not have an access to electricity and the vast majority of those people live in the poor rural areas in the developing countries, renewable energy there will doubtfully be a priority (OECD, 2011). As by 2035 the world electricity consumption is expected to double, the only realistic candidate being able to reinforce such transition and accommodate needs for the base-load power is actually nuclear energy.

At present, roughly 6 per cent of the global energy and 14 per cent of the world's electricity are generated by the nuclear power industry. What really is appealing about nuclear energy, apart from its ability to be the base-load power, is the fact that the resources to fuel nuclear energy production are abundant – Uranium is still far from being depleted; besides virtually

unlimited reserves of Thorium can be also used. Another attractive thing about nuclear is that it has been widely admitted to be an effective tool in the fight against the climate change. Given all that, the current nuclear generation capacity seems to be modest in comparison to what it could have potentially been (NEA & IEA, 2010).

A massive expansion of nuclear energy, however, has never happened mainly due to the generally negative public attitude enhanced by a number of research papers and studies which discuss the severity of nuclear damage in case an accident takes place. Some studies report that a cost of a nuclear disaster would surpass several trillion euros (EUR) (Hohmeyer, 1988) (Ottinger & al., 1990) (Günther, Karau, Kastner, & Warmuth, 2011). As the major share of those costs is attributed to the health consequences, e.g. radiation-induced cancer, there is no wonder that it cultivates anxiety among the people. Given that generally people have vague understanding about principles of nuclear energy and radiation, their negative feelings are constantly being reinforced by their own lack of knowledge and inclination to assume the worst. As a result, nurtured by fear and ignorance, many people have developed strong radiophobia and taken a radical anti-nuclear stand, which altogether hinders development of nuclear energy.

However, the latest studies on severity of nuclear damage caused by the Chernobyl accident (1986) give grounds to suspect that the previously reported estimations are highly exaggerated (WHO, 2012a), (UNSCEAR, 2011). The initial assessment of the radiation doses after the Fukushima accident (2011) suggests the same (WHO, 2012b). If that turned out to be true, it would mean that over long decades nuclear energy has been criticized and judged unfairly. Amid the energy crisis which teaches to appreciate every available source of energy, this finding, if supported by irrefutable evidence, would be breaking news for the global energy markets. Therefore, it is high time to put aside prejudices and feelings and to reassess the validity of a claim that nuclear disaster causes severe damage.

Hence, this paper joins the quest for the truth and raises the following two research questions:

1.   What are the costs of a nuclear disaster at a modern nuclear power plant?
2.   Is it feasible to insure a modern nuclear power plant against the damage caused by a nuclear disaster?

In order to answer the stated questions, this paper studies the case of the Olkiluoto-3 EPR reactor currently being under construction in Finland. The authors of the paper hypothesize the worst case scenario for a nuclear accident at the Olkiluoto-3 nuclear power plant, analyse

what damage it can cause and derive relevant implications for the whole modern nuclear power industry.

The structure of this paper goes as follows: the background information about the nuclear power industry is firstly presented, followed by a discussion of the Finnish nuclear power industry and explanation of why Olkiluoto-3 EPR reactor was chosen for the analysis. The history and reasons of major nuclear events are then depicted, and the following section presents previous research which estimates costs and probability of a nuclear disaster. Next, existing regimes for the third party liability and compensation for nuclear damage are described; it is followed by calculation of costs and probability of a hypothetical nuclear disaster at the Olkiluoto-3 nuclear power plant, as well as feasibility of nuclear insurance which has to be paid in order to secure mobilization of necessary funds to cover damage claims of third parties, is assessed. Finally, relevant implications are derived for the nuclear policy makers, operators and other related stakeholders.

1. Present State and Promising Possibilities of Nuclear Power Industry

The emergence of the nuclear industry dates back to 1932 when neutron was discovered. Along with protons, neutrons are part of an atom's nucleus and they do not have an electric charge. The true key to the initiation of nuclear power production was the discovery that energy is released during the nuclear fission, a process of splitting the atom's nucleus into two (World Nuclear Association, 2010). The amount of heat released during this process is of approximately 200 million electron volts, or 4 million times the energy produced by burning the same amount of coal (NRG Expert, 2011). Research undertaken in 1939 found that energy was not the only by-product of the nuclear fission: additional neutrons which can cause further reactions with other atoms were also found to have been produced. This chain reaction would be then self-sustained and would ensure the release of an enormous amount of heat that can be used to generate electricity (World Nuclear Association, 2010) (NEA, 2003a). Uranium-235 (U-235) and Plutonium-239 (P-239) are the two elements found to ensure a self-sustaining nuclear chain reaction (U.S. Department of Energy, 1994).

Nuclear science has seen the most progress during the Second World War (WW II) (1939-1945) when much emphasis was put on development of the atomic bomb. Research was undertaken simultaneously in the United States of America (USA), the United Kingdom

(UK), the Union of Soviet Socialist Republics (USSR), France and Germany. The attack of Japan on Pearl Harbor in December 1941 made the USA directly engaged in the WW II. Tremendous effort was devoted to the development of nuclear weapon, and as a result, the Manhattan Project was initiated in 1942. The first nuclear reactor called Chicago Pile-1 was built in December 1942 as a part of this research project. The first atomic bomb prototype was successfully tested in Alamogordo, New Mexico on July 16, 1945. The actual atomic bombs were dropped on the islands of Hiroshima and Nagasaki in Japan on August 6 and 9 of 1945, respectively (World Nuclear Association, 2010).

1.1. Development of Nuclear Power Industry

1.1.1. Commercialization of Nuclear Energy

Following the WW II, the main goal of the nuclear research was to prove that nuclear energy can be used for civil purposes and that it can become an important energy source for commercial production of electricity and naval propulsion. A nuclear reactor called Experimental Breeder Reactor (EBR-1) with initial power generation capacity of 100 kilowatt (kW) was the first to start producing electricity in Idaho in the USA on December 20, 1951. Prompted by this achievement, the US President Eisenhower delivered a speech "Atoms for Peace" on December 8, 1953 in front of the United Nations (UN) which fostered the research and cooperation worldwide for the development of peaceful implementation of nuclear energy (U.S. Department of Energy, 1994). As a result, the first nuclear powered electricity generator Atom Mirny (AM-1), Russian for "peaceful atom", with the capacity of 6 megawatt (MW) was erected in Obninsk, the USSR, in June 1954. Consequently, it served as a prototype for the Reaktor Bolshoi Moshchnosty Kanalny (RBMK), a high power channel reactor, which was built all over the Soviet Union including Chernobyl. Nevertheless, it is the year of 1956 which should be viewed as the commencement of the nuclear industry when the first commercial nuclear power plant based on the Magnox reactor featured with a capacity of 50 MW was built at Calder Hall in the UK. Following the example of the UK, commercial-scale nuclear power plants were commissioned in the US (1958), Canada (1962), France (1963), the USSR (1964), and other countries. In conclusion, the development of the nuclear power industry from the conception to the discovery of the practical application was considerably rapid, spanning a mere 20 years (World Nuclear Association, 2010).

The Pressurized Water Reactor (PWR) was initially developed for the naval use in March 1953 in the USA. The first nuclear-powered submarine referred to as USS Nautilus was put

to sea a year later. Accordingly, the USSR was the first to develop a nuclear-powered surface vessel, icebreaker Lenin, in 1959 (World Nuclear Association, 2010).

The oil crisis of 1973 stimulated more countries to employ nuclear technologies in the energy sector to meet the growing energy demand as oil prices increased fourfold. France was the frontrunner with 56 nuclear power plants built by 1985 (Palfreman, 2006). Overall, 399 nuclear reactors were commissioned with the total capacity of 323 gigawatt (GW) within 1970-1990 (NRG Expert, 2011). During that period, on average one reactor was built every 18 days.

However, the following cut in fossil fuel prices and the overall decline in the economy deterred the expansion of the nuclear industry. The major deferment of nuclear power sector development was triggered by two accidents: the Three Mile Island accident in 1979 in the USA and the Chernobyl accident in 1986 in the former USSR (1986). These accidents caused massive anti-nuclear movements in the USA and Europe and raised safety concerns among the general public. Altogether these factors hampered further advancement of the nuclear power industry throughout the 1990s. Construction of many reactors was postponed or cancelled and 125 reactors with the total generation capacity of 37 GW were shut down by 2010 (IAEA, 2011a). Nonetheless, the contribution of the nuclear power in the world energy mix throughout these years was constant at 16-17 per cent (NRG Expert, 2011). The following part of this paper briefly discusses the evolution of a nuclear reactor which has been one of the key elements enabling nuclear power industry to sustain a stable position in the world energy mix.

1.1.2. Classification and Evolution of Nuclear Reactors

Despite the existing variety of nuclear reactor types, all of them share the same main elements: fuel, moderator, coolant and control rods.

Nowadays nuclear reactors are fuelled by Uranium, which in nature is represented by two isotopes: U-235 and U-238. While U-235 is fissile in thermal reactions and thus can be used straight away, U-238 should firstly be transmuted. However, U-235 accounts roughly for 0.7% of all Uranium global reserves, hence a relatively more expensive method of U-238 transmutation has to be widely employed (NEA, 2003a).

A moderator ensures that the neutrons produced during the self-sustaining chain reaction are slowed down in order to continue efficient fission. The most common moderator is water,

while graphite and heavy water (water enriched with deuterium isotope of hydrogen) are sometimes used as alternatives.

A coolant is needed to absorb and eliminate the excessive heat produced during the nuclear fission. The generated heat is then transported to an electricity-generating system. The most commonly used coolant is water, which as pointed out before, can be simultaneously used as a moderator. This dual usage of water is applied in the majority of modern reactors. However, heat-exchanger and heavy water, gases (helium, carbon dioxide) and molten metals (sodium and bismuth) can also serve the purpose of a coolant (NEA, 2003a).

Finally, the control rods which constitute the core of a reactor are of major importance as they control the rate of the fission process (NEA, 2003a). The three main functions of control rods are: to start and shut down a reactor; to regulate the power rate of a reactor; and to level the reactivity changes during the energy production (Britanicca, 2012).

Most commonly, classification of nuclear reactors is based on the coolant used. Firstly, there are reactors which use water as a coolant, such as Light Water Reactors (LWRs) – they represent 80 per cent of reactors currently operating worldwide (see Appendix 1, Figure 1). There are two types of LWRs: Pressurized Water Reactors (PWRs) or a Russian version of the design called from Russian Water-Water Power Reactor (VVER), and Boiling Water Reactors (BWRs). RBMK, also known as High Power Channel Reactor developed by Russians, is a water-cooled reactor, too; however, in comparison to LWRs it does not at the same time use water as a moderator. Secondly, the reactors which use heavy water as a coolant are called Pressurized Heavy Water Reactors (PHWRs). The remaining reactors use either gas or liquid metals as a coolant, those are Gas-Cooled Reactors (GCRs) and Fast Breeder Reactors (FBRs) respectively (NRG Expert, 2011) (NEA, 2003a). Appendix 1 (Table 1) summarizes details about the classification and employment of different types of reactors by different countries.

The design of nuclear reactors has been constantly evolving and to the date it has witnessed a number of innovative breakthroughs. Indeed, the evolution of a nuclear reactor has been fascinating. Four generations of nuclear reactors have so far been developed (NRG Expert, 2011). Early prototypes of **Generation I** nuclear reactors (e.g. Magnox reactor) were developed in the USA throughout 1950-1960s. Nowadays only some of them are still operating in the UK and they are expected to be shut down by 2014. When compared to the reactors of the later generations, the design and construction of Generation I reactors was

relatively more expensive and their operational life results into higher volumes of nuclear waste. Nowadays the majority of the globally operating reactors belong to the **Generation II**, of which approximately 80 per cent are PWRs and BWRs. Despite nuclear reactors of Generation I and II share many identical features, an important distinction of Generation II reactors is that they are generally safer. Reactors of Generation II were mainly built throughout 1970-1980s with a life expectancy of 40 years. However, they proved to be able to operate longer, especially in case of the LWRs, and as a result their life expectancy was extended to 60 years. It would not be a mistake to tell that the foreseeable future lies in **Generation III** and **Generation III+** nuclear reactors. The first Generation III reactor was built in Japan in 1996 and several more are currently under construction. The Generation III+ reactors are referred to as the European Pressurized Reactor (EPR) and the Advanced Pressurized Water Reactor (AP1000). At present, EPRs is currently under construction in Olkiluoto, Finland and Flamanville, France, while four more are expected in Taishan, China.

Generation III and Generation III+ reactors are considered to be more efficient and less waste intensive. They are also economically more viable than reactors of the preceding generations as they benefit from the standardization of design. Consequently, the costs related to licensing, production and construction are optimized. Perhaps, the main distinction of Generation III and Generation III+ reactors roots in the fact that they have an improved passive safety systems which limit radiological impact outside the nuclear power plant in case of a major accident, i.e. the core meltdown (Barre, 2012). Construction of the first **Generation IV** nuclear reactor is expected to take place in 2030's. This reactor will embrace a whole spectrum of innovations and technological advancements. To mention some of them, it will include additional safety systems, it will be proliferation-resistant and it will produce minimal volumes of nuclear waste. Currently, there are six technologies being tested to accommodate the expectations for the first reactors of that class (DBI, 2012) (GIF, 2012).

1.1.3. Current Status of Nuclear Power Industry

Although the renaissance of nuclear energy has recently been inhibited by the surge of negative public attitude triggered by the Fukushima nuclear disaster, there are still several factors which should foster the development of nuclear power industry. The primary factor is the increase of energy demand due to rapidly expanding developing economies. The need for energy diversification and security of energy supply is another contributing factor. Heavy dependency on such foreign resources as oil from the Middle East or natural gas from Russia makes economies of other countries vulnerable to the slightest rise of the underlying

commodities' prices. Consequently, including domestically available alternative sources into the energy mix enables countries to ensure their economic sovereignty. Another factor is that as the safer Generation III and III+ nuclear reactors became available and are financially affordable, threats associated with the nuclear industry are being reconsidered. Finally, the need for zero-emission energy sources is at the top of the age – along with sustainable development, elimination of CO_2 emissions is the worldwide utmost agenda. Altogether it is suggested that the moratorium on nuclear power which has already been cancelled, should not be imposed again (World Nuclear Association, 2010).

As of May 2012, there were 436 nuclear power plants in operation worldwide with the total power generation capacity of 370 GW or 13.5 per cent of the world's electricity demand (see Appendix 1, Table 1). More than a half of the operational nuclear reactors are 15-30 years old or are in the intermediate of their life expectancy, which was extended to 60 years instead of 40 after the engineering reassessments. The USA is the leading nuclear nation in terms of generated output in the world with 104 operating nuclear power plants; Europe is led by France with 59 operating units (World Nuclear Association, 2010).

Currently, 62 power plants are under construction in 14 countries, 150 are being designed, and around 330 have already been proposed. Most of the future nuclear energy generation capacity will come from China, Russia and India (World Nuclear Association, 2012a). In addition to the countries with nuclear energy already present in their electricity mix, the nuclear option is being considered by numerous countries, e.g. Poland, Ireland, Georgia, Chile, Thailand, Australia and others.

The share of electricity generated by nuclear power differs among 30 countries which accommodate nuclear power plants: France is the leading country with more than 75 per cent, followed by Belgium and Slovakia both with roughly 54 per cent. Half of the countries have less than 20 per cent dependency on nuclear such as Russia (17.6 per cent), India (3.7 per cent) and China (1.8 per cent). However, given the current number of nuclear reactors in the construction pipeline, the share of nuclear energy in the individual countries' energy mix might well rise in the foreseeable future (IAEA, 2011a).

1.1.4. Main Concerns and Advantages of Nuclear Energy

There are four main factors which hinder the development of the nuclear power industry: doubts about nuclear safety, limitedness of Uranium reserves, management of radioactive long-lived nuclear waste and proliferation risk.

Safety

Up to date, commercial nuclear reactors have accumulated 14,500 years of operation in 32 countries, with only two major accidents (World Nuclear Association, 2010). It is widely accepted that the damage triggered by the nuclear disasters in Chernobyl and Fukushima were devastating. However, with most of modern reactors currently in operation, the disaster that occurred in Chernobyl is not technically possible (NRG Expert, 2011). In addition, after the Fukushima nuclear disaster almost all nuclear power plants worldwide are undergoing additional safety assessments tests with the emphasis on the back-up generators and ability to withstand natural disasters. Lastly, the upgraded reactors of Generations III and IV with the focus on safety are on the way, and nuclear fusion is a promising solution in the long run. Another important aspect of nuclear safety is a possibility of a terrorist abuse. The terrorist attack of September 11, 2001 in the USA undoubtedly fuelled the concerns that an airplane can be crashed into the nuclear power plant with the intention to cause a massive release of radioactive material. As a result, several studies were undertaken to reassure the general public that nuclear reactors of current design would be resistant to such attacks (World Nuclear Association, 2012b).

Uranium Reserves

The reason why nuclear energy is not considered a sustainable resource despite being carbon free is that nuclear power plants run mostly on Uranium, which despite substantial known reserves is still limited. The two main periods of Uranium extractions took place in the 1950s, when the purpose of the extraction sought to satisfy military demands, and in the 1970s, during the upsurge of the commercialization of nuclear power.

Following this, major explorations were undertaken and several new mines were discovered (NRG Expert, 2011). According to the research conducted by the Massachusetts Institute of Technology (2009), there are sufficient Uranium reserves to fuel 1000 reactors over the next 50 years. Most importantly, Uranium reserves are well distributed among countries as compared to the limited number of oil nations. The largest Uranium producers are Kazakhstan (28 per cent), Canada (20 per cent) and Australia (16 per cent) (NRG Expert, 2011).

The limitedness of Uranium should even less be a concern if Thorium becomes a commercial success. Thorium reserves are estimated to be 4-6 times larger than those of Uranium and they are found to be relatively equally distributed around the world. Furthermore, Thorium

gives 200 times more energy than natural Uranium for the same mass and in present day reactors. Given that Thorium-fuelled reactors have smaller impact in term of nuclear waste than Uranium-fuelled reactors, commercialization of such reactors might take place sooner than anticipated (ThorEA, 2010).

Waste Management

Nuclear waste is the furthermost legitimate concern. Currently, all countries accommodating nuclear power facilities are parties to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. This document provides detailed safety requirements on management of nuclear waste through the whole nuclear fuel cycle (IAEA, 2012a).

Nuclear waste is particularly hazardous because it contains substantial radioactive substance with a long half-life period. Only 3 per cent of nuclear waste that is derived from the fission reactions contains a high level radioactive material and it amounts to 700 kg per year. Despite being the most hazardous waste generated by the nuclear industry, it accounts for less than 1 per cent of the total industrial toxic waste in all the countries with nuclear power plants. Nevertheless, its disposal is one of the main concerns that accompany the nuclear industry. The other 97 per cent of the nuclear waste, however, can be reprocessed. There are 630 reprocessing factories operating in the world, most of them are located in France and in the UK (NRG Expert, 2011).

There is a customary two-step nuclear waste disposal process. Firstly, high level waste is isolated and stored under water for 40-50 years in large pools generally located at the nuclear site. During this time period the radioactivity diminishes to one thousandth of its initial concentration. Afterwards, it is transported to the ultimate depositary hundreds of meters below the earth's surface for thousands of years. As most of the countries accommodating nuclear power plants have not yet accumulated significant amount of waste during the first disposal step, a construction of a single geological repository has not been initiated. However, it is anticipated that it will be opened by the middle of the 21st century (World Nuclear Association, 2011a) (World Nuclear Association, 2012c).

Proliferation Risk

After nuclear bombs were dropped in Japan during the WW II, concerns about the possible recurrence of such a catastrophe were raised. As a result, Treaty on the Non-Proliferation of Nuclear Weapons came into force in 1970 aiming to prevent the usage of nuclear technology

for the development of any kind of nuclear weapon. To the date, the Treaty has been signed by 189 countries; nonetheless such politically unstable countries as Iran, Pakistan, North Korea, are non-signatories (IAEA, 2012b). Initially, North Korea was a party to this agreement but in 2003 it withdrew its participation; ever since it has undertaken intensive nuclear research and has performed two nuclear weapons tests. Even though there is no existing evidence that it have obtained a working nuclear weapon, the situation is quite alarming (New York Times, 2012b). Similarly, Iran has a controversial nuclear program in place. It has refused to grant an access for IAEA inspectors to its nuclear power plants several times, which raised concerns that it might be developing nuclear weapon. In order to foster the cooperation between Iran and IAEA, the USA, Australia, the European Union (EU) and other developed countries have imposed sanctions on Iran. This resulted in the first visit of the IAEA's Director General to Iran in May 2012, during which it was suggested that the ratification of the agreement on the access of inspectors to nuclear power plants is signed in the nearest future (BBC, 2012b).

Despite all the concerns nuclear energy has raised, is has a substantial positive side too. In addition to being greenhouse gas emissions free, it has no intermittency problems as compared to the renewable sources of energy. Moreover, it is the only realistic and currently available base-load energy source which can possibly substitute fossil fuels. Base-load power is a minimum amount of electricity that should be generated to cover estimated energy demand at any taken point in time. Technically nuclear energy is a perfect source of base-load power: it takes a long time to heat up the nuclear reactor to allow its operation mode and therefore it is not cost efficient to turn it on and off to adjust to the energy peak and through. Thus, the sounder alternative is to operate it at almost full capacity all the time. There is also an economic reasoning behind why nuclear energy is considered a base-load power source. The cost of Uranium is low; it ensures low marginal costs of operation and lowest cost of electricity production. Thus, it is economically efficient for nuclear plants to run at maximum capacity all the time.

Perhaps the most neglected fact is that despite what the general public might think, nuclear power is already more economically attractive than renewable energy sources. Furthermore, if the carbon sequestration is priced, e.g. through carbon tax, the cost of fossil fuels will rocket and will make nuclear energy even more price competitive. Altogether, it will not be surprise that in the foreseeable future nuclear energy will become one of the cheapest energy sources on earth.

1.2. Future Prospects of Nuclear Energy

Thorium

There is an opinion that Thorium-fuelled reactors have a great future potential. It is supported by the facts already discussed in this paper: it is abundant, it is energy efficient and it addresses the nuclear waste concern fairly well. Thorium fuel cycle can be designed in a more efficient way than that of Uranium-238 (World Nuclear Association, 2011b). Currently, Thorium is under exploration as it can be converted into U-233 by transmutation. Uranium-233 derived from is contaminated by Uranium-232 which makes it expediently impossible to use it for nuclear weapon production. In such a way Thorium mitigates the proliferation risk as well. Consequently, Thorium is much safer and it does not require extensive monitoring, which also makes it cheaper to administer. The use of Thorium in nuclear reactors has been tested for about 40 years (e.g. Molten-Salt Reactor Experiment) and it has proved to be technologically feasible and to contribute to elimination of the long-lived transuranic waste. From the perspective of the nuclear waste, Thorium-based reactors produce very little radioactive waste and in addition to that can burn nuclear waste from Uranium-based reactors. Nevertheless, an immediate employment of Thorium in nuclear power generation cannot take place due to high path dependence within the industry: most of the commercial nuclear reactors operating today are designed for Uranium (235-U isotope) and should the commercialization of Thorium-based reactors be started, it would require huge investments (ThorEA, 2010). Nevertheless, Uranium-based reactors are inevitably ageing, and at some point in time they will require replacement which might trigger expansion and scaling up of Thorium-based reactor technologies. The first Thorium-based reactors are forecasted to be operational before 2025 (IThEO, 2012).

Fusion

Reactors of Generations I, II, III/III+ and IV are all fission nuclear reactors. It however should be noted that fusion is believed to be a scientific breakthrough which has all necessary prerequisites to solve the world's energy problem. Different from a fission reaction when heavy Uranium atoms are being split, in fusion reaction two atoms of Hydrogen merge to form a heavier nucleus (Helium). This reaction which resembles an on-going process at the core of the sun is accompanied by release of energy. Even though fusion reaction yields less energy than fission, it would still be a preferred alternative due to several reasons. The main reason roots in the fact that there is no chance a fusion reactor could possibly trigger a nuclear disaster such as those in Chernobyl or Fukushima, hence this technology is extremely

safe. Moreover, fusion almost does not overlap with the nuclear weapon technologies, which substantially mitigates the proliferation risk. Also reserves of Hydrogen are abundant and very well distributed across the world. Finally, fusion reactors would produce almost zero high-level radioactive waste, while other radioactive waste would have much shorter half-life than waste produced in a fission reaction. To sum up, better than any other nuclear technology, fusion would address the above four concerns very well (European Commission Research and Innovation, 2012).

International Thermonuclear Experimental Reactor (ITER) project was undertaken in 2007 in Cadarache, France, to assess feasibility and to explore the potential of fusion technologies. Seven stakeholders – the USA, the EU, China, India, Japan, Russia and South Korea joined hands in order to build the first fusion reactor in the world and to demonstrate that fusion can be used as a commercial energy source. The construction of the ITER is anticipated to be completed by 2019. Should the project prove to be successful, the Demonstration Power Plant (DEMO) will follow, which will start producing fusion electricity for the general grid expectedly in 2040 (ITER, 2012). Nevertheless, there is still a long way to go and while fusion technology has still not proven itself, Generation IV fission reactors might be the best choice in the nuclear power industry.

Gaps for Improvement

At the moment the development of nuclear power industry is severely constrained by multiple factors. Due to the recent nuclear disaster at the Fukushima Daiichi nuclear power plant and general radiophobia the world has developed and cherished for many years now, the public acceptance is low. This had a dramatic consequence on the nuclear science as it lacks students (especially from the Western world) (IAEA, 2010) and therefore does not accumulate sufficient competence and knowledge necessary for innovations and other technological advancements. Given the promising potential of the nuclear science, e.g. Thorium-based reactors and fusion, this is an obvious gap which needs to be covered in the future. Another issue which demands attention is the currently high risk premium which financial institutions incorporate in the lending rate for construction of nuclear facilities (MIT, 2009). Should the governmental authorities try to lower it by providing guarantees for the financing of nuclear power plants, it will certainly enhance confidence in the nuclear sector. However, it might be a very "nominal" help as two main risks – political and sovereign, are still remain an integral part of nuclear sector. The term the government officials are elected for does not last as long as the perspectives need for nuclear projects.

Therefore, even if support for nuclear power industry is provided today, it does not necessarily mean that in 20 years or so the political course will still be the same, especially if yet another nuclear accident takes place and the government withdraws from nuclear amid growing public pressure. This would definitely harm nuclear operators who, having received the green light from the government, committed to the project and made huge investments.

2. Nuclear Power Industry in Finland

This paper has a goal to assess current state of the nuclear power industry and to draw relevant implications from the analysis of costs and probability of a nuclear disaster. For that matter, the case of Finnish nuclear energy has been chosen and this choice can be justified in several ways. To begin with, it is the only country in Europe and North America that has decided to add nuclear capacity in the last decade by building the fifth reactor of the latest Generation III+ with enhanced safety design. The success of this project will be a demonstration of and reference to a new generation of nuclear reactors. Moreover, while other countries, like Germany, Switzerland and Japan, are phasing out its nuclear power plants, the Finnish government approved two more proposals for the construction of new reactors of Generation III+ design. Consequently, it is a country with strong commitment to significantly increase the share of nuclear energy in its electricity production in the nearest future. Another important factor is that Finland is leading the world in the spent fuel disposal which is the principal concern associated with the nuclear energy. Yet again Finland's accomplishment of this technological breakthrough is a critical step towards verifying that the nuclear power industry is indeed welcoming the renaissance of nuclear as a safe energy source. Finally, nuclear energy there is not as a divisive issue as in other countries, such as Austria, Denmark, Greece, Ireland and Portugal on a public and political level in Finland (Reuters, 2012) (Economist, 2011). On the contrary, Finland can be considered as an example of a country which has successfully exerted efforts into creating a conversation with its citizens on this highly debated topic, with the polls showing public's support of nuclear energy since 1980s (NRG Expert, 2011). Furthermore, nuclear energy is integrated in the foresight of Finland, with three nuclear reactors currently being in the construction pipeline. Mauri Pekkarinen, previous Finnish Minister of Economic Affairs said: "*We are giving a strong signal to the industry that it is worthwhile to invest in Finland. Granting one* [nuclear reactor] *permission is not enough.*" (Reuters, 2010), and this paper attempts to clarify if this signal has a chance to be properly heard and interpreted by the world.

2.1. Energy Consumption and Production of Electricity

The energy consumption per capita in Finland is substantially higher compared to other Western countries. It was the third highest in Europe in 2010, 10 per cent up from 2009 (World Bank, 2011). Most of this increase is attributed to the demand growth in electric space heating and energy-intensive industry, such as forestry, metals and chemicals (IAEA, 2011b). The 2010-year energy mix consisted mainly from fossil fuels (47.7 per cent), with a significant part of renewables (27 per cent) and nuclear energy (17 per cent) (Statistics Finland, 2011a). Almost two thirds of the primary energy is imported, mainly coal from Russia and Poland, and gas also from Russia (World Nuclear Association, 2012d).

Electricity production has been significantly increasing over the past 40 years and has reached 87.5 terawatt hours (TWh) in 2010 (Statistics Finland, 2011c). It is expected to further increase by at least 14 per cent by 2030. Electricity in Finland is mainly generated by hydro, nuclear and conventional thermal plants. Finnish electricity market was deregulated in 1990 and it is has also become a part of the Nordic power exchange, a common integrated end-user electricity market, Nord Pool. Therefore, depending on the net balance of its production and consumption, Finland can export and import electricity to and from the Nordic countries. For example, electricity export to Sweden increased significantly in 2010 due to the shut-down of several Swedish nuclear reactors for maintenance and as well to the shortage of water necessary for hydro electricity generation. Sometimes, however, Finland is an electricity importer. The main country it imports electricity from is Russia (Statistics Finland, 2011a) (Ministry of Employment and the Economy, 2011). However, after unpredictability of the Eastern neighbour demonstrated itself during the conflict over the gas supply to Ukraine, Finnish government expressed willingness to minimize its dependence on Russian energy commodities, which served as a strong stimulus for development of nuclear power industry (Bloomberg, 2010a).

2.2. Nuclear Power Industry

2.2.1. Development of Nuclear Power Industry

As most of the Western countries, Finland made a decision about including nuclear power into its energy mix in the late 1960s. First nuclear reactor was built in 1977, and by the 1980s four reactors were completed (Ministry of Employment and the Economy, 2011). As soon as construction of nuclear reactors started, Finland initiated work on the nuclear policies and laws. Two national legislations, Nuclear Energy Act and Nuclear Energy Decree, came into

force in 1987 and 1988 respectively. In essence, these documents state that the Finnish Radiation and Safety Authority (STUK), on behalf of Finnish Parliament, is responsible for the licensing process for such nuclear installations as power plants and waste disposals. Altogether, 70 guidelines were issued covering eight areas: general guides, systems, pressure vessels, civil engineering, equipment and components, nuclear materials, radiation protection and radioactive waste management. These guidelines are used for the safety evaluation of a nuclear reactor prior to the construction. However, after STUK grants the construction and operation licenses, it is the nuclear power plant operator who is liable for the management and safety measures on the site (Ministry of Employment and the Economy, 2012).

An important factor which made nuclear power viable in Finland was neutral public attitude. The public opinion polls have been regularly carried out by independent research groups since 1980s. Although initially it was not negative, the public attitude throughout the years kept improving even further as Finnish nuclear industry did not encounter any major accidents. An exception was the year 1986 when the Chernobyl nuclear disaster took place; however, favourable attitude was promptly restored. The survey of 2009 shows that close to 60 per cent of the respondents would like that the generation of nuclear energy is increased or maintained at the same level (Finnish Energy Industries, 2010) (IAEA, 2011b).

Nuclear power in Finland is used for generating base-load electricity and since the 1980s it has been the largest source of electricity production. It accounted for 25 per cent in 2010 (Statistics Finland, 2011c) and in 2011 nuclear electricity production increased by 1.8 per cent year-on-year (Finnish Energy Industries, 2012). Currently Finland has four operational nuclear reactors, all of them are Light Water Reactors and they are considered to be one of the most efficient in the world with average capacity factor of 90 per cent since 1983 (Ministry of Employment and the Economy, 2011). The average capacity factor is defined as "*ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period*" (World Nuclear Association, 2012d) (U.S. NRC, 2012a). The four reactors are located in two nuclear power plants, Loviisa and Olkiluoto, on the Southern and Western coasts of Finland respectively (Ministry of Employment and the Economy, 2011), which have a total capacity of 2700 MWe and provide almost 30 per cent of domestically generated electricity (World Nuclear Association, 2012d).

2.2.2. Currently Operating Nuclear Reactors

Loviisa Nuclear Power Plant

Loviisa was the first nuclear power plant built in Finland and it is located 100 kilometre (km) East from the capital city of Helsinki. The two reactors the plant accommodates are of VVER design originated from Russia. The design was supplemented by the Western computerized safety system and containment construction that limits radioactive emissions. Moreover, with a growing operation expertise and experiences from nuclear accidents occurring in other countries, Finnish operators have further enhanced safety measures. For example, fire safety arrangements and plant instructions were modified to mitigate the associated risks (Ministry of Employment and the Economy, 2011). The Loviisa nuclear power plant is operated by Fortum Power and Heat Oy. Initially Loviisa nuclear reactors 1 and 2 had a net electricity generation capacity of 440 MWe (see Appendix 2, Table 1), which with time was increased by 9 per cent. The life expectancy of the reactors was also increased from 30 years to 50, whereas safety assessment takes place every 10 years. Periodic safety reviews are performed to review such important issues as power plant design, equipment qualification, emergency planning, radiological impact on the environment and others (World Nuclear Association, 2012d) (IAEA, 2003).

Olkiluoto Nuclear Power Plant

The two reactors at Olkiluoto nuclear power plant are of Swedish BWR design and are operated by Teollisuuden Voima Oyj (TVO). Olkiluoto reactors 1 and 2 were built in 1978 and 1980, respectively. The life expectancy of both reactors has been increased to 60 years and they are planned to be shut down around 2040. The total electricity generation capacity of each reactor is constantly increasing: it was initially 690 MWe, it then grew to gross 860 MWe gross by 2006 and there is still a possibility to surpass 1000 MWe (World Nuclear Association, 2012d) (see Appendix 2, Table 1). Similarly to the safety enhancement completed at the Loviisa nuclear power plant, extra safety measures were taken at Olkiluoto whereas major accident management systems were installed in order to ensure containment of radioactive release in case of the core meltdown (Ministry of Employment and the Economy, 2011).

After the Fukushima nuclear catastrophe, STUK conducted emergency safety assessments of the Finnish nuclear reactors to evaluate their ability to withstand natural disasters. In the subsequently released report STUK confirmed that all four nuclear reactors complied with the

highest safety standards. Nevertheless, following the request of the EU Council to run stress tests for all European nuclear power plants, operators performed additional assessments on possible extreme floods, earthquakes exceeding the previously tested magnitude, loss of cooling system and others (Ministry of Employment and the Economy, 2011) (NEA, 2011). Finnish nuclear power plants have successfully completed the stress tests by November 2011, showing that the current safety measures are indeed able to withstand major natural phenomena. However, the Loviisa nuclear power plant operator mentioned that this assessment "*identified some possibilities to improve safety even further: for example, securing sea water cooling with air cooling; and securing the fuel pond cooling in case of exceptionally long lasting accident situations*" (World Nuclear News, 2011).

Nuclear Waste Management

All nuclear waste from the four Finnish nuclear reactors is initially stored in the water pools located within the territory of the respective power plants. Thereafter, low and intermediate-level waste (LLW/ILW) is transported to the disposal facility that is located 60-110 meters deep in the solid rock in Olkiluoto and Loviisa, built in 1992 and 1997, respectively. This LLW/ILW disposal will store the waste from all Finnish reactors currently operated as well as Olkuiluoto-3 which is currently under construction (World Nuclear Association, 2012d) (Ministry of Employment and the Economy, 2011). However, worth mentioning, the first spent fuel repository will be soon built in Finland by Posiva Oy, a construction and management company which is jointly owned by operators of the existing nuclear power plants, whereas TVO owns 60 per cent and Fortum Power and Heat Oy together own the remaining 40 per cent. The final waste disposal facility, called ONKALO, will be built in Olkiluoto, it will lie 400 meters deep in a 1.9 billion year-old igneous rock. The project proposal was approved in 2001. It is anticipated that in 2012 the project will be licensed by the Ministry of Employment and the Economy. The construction works are expected to take place within 2012-2020 and the beginning of fuel disposal can start upon the construction completion. According to the Finnish Nuclear Energy Act, the responsibility over all costs associated with the waste management and disposal lies with the operators of the nuclear power plants. So far TVO and Fortum Power and Heat Oy have contributed to the State Nuclear Waste Management Fund around EUR 2 billion, while the total construction cost is expected to reach EUR 3 billion (Ministry of Employment and the Economy, 2011). It is planned that spent fuel from all four operational nuclear reactors in Finland as well as from new reactors which are currently in the construction pipeline or being designed, will be

disposed there (Ministry of Employment and the Economy, 2011) (IAEA, 2011b) (NEA, 2009) (World Nuclear Association, 2012d).

2.2.3. Nuclear Reactors in Pipeline

A proposal to build the fifth reactor, named Olkiluoto-3, was approved by Finnish government in May 2002 and construction works started in 2005. Additionally to this, two more nuclear reactors have just officially received green light: one at the Lovissa nuclear power plant and one at the Olkiluoto nuclear power plant (see Appendix 2, Table 2). The design for these new reactors is to be selected and the supplier to be approved by the end of 2012, while construction works will start two years later (Ministry of Employment and the Economy, 2011) (World Nuclear Association, 2012d).

Olkiluoto-3 nuclear reactor is EPR designed by the French-German supplier consortium consisting of Areva NP and Siemens AG. The net output of the new reactor will be 1600MW and its expected lifetime is 60 years. However, given that the lifetime of Generation I and II reactors all over the globe was extended by at least 15-20 years, it is reasonable to assume that the operational life of Olkiluoto-3 will reach 80 years (World Nuclear Association, 2012d). According to Areva NP, the innovative reactor design will ensure substantial advantages: electricity generation costs are expected to drop by 10 per cent, fuel consumption – by 17 per cent, and production of high-level waste – by 14 per cent per unit of energy output (Areva, 2012).

To the date, major construction works have been completed, whereas the reactor pressure vessel, the pressurizer and three steam generators have already been installed (Ministry of Employment and the Economy, 2011). Initially it was planned to commission Olkiluoto-3 in 2009. However, it has been delayed for four years due to some construction issues and lengthy approval of technical documents, which altogether brought the overrun costs to EUR 2.7 billion (Bloomberg, 2010b) and thus doubled the cost of construction budgeted back in 2005. As of now the final launch of Olkiluoto-3 is planned to take place in August 2014 (Power Technology, 2012). Interestingly enough, the second in the world EPR reactor, currently under construction in France, has also been delayed until 2016 due to "*structural and economic reasons*" (Nuclear Engineering International, 2011). Perhaps such delays in Finland and France can be understood, given that it takes time to accumulate competence in the construction of the new reactors design. The effect of the learning curve for the new design is seen in China, where construction of two EPR reactors which started in 2007 is well

ahead of that in the European counterparts, and the first reactor should start operating in 2013 (Guardian, 2010).

Following the goal of this paper, Olkiluoto-3 nuclear reactor has been chosen for the further analysis. A nuclear disaster at Olkiluoto-3 will be hypothesized and the worst-case scenario damage will be estimated in order to raise a meaningful discussion on the current developments in the nuclear energy field.

3.   Nature of Nuclear Events: Incidents, Accidents and Disasters

3.1.   Definition of Key Terms

Prior to assessing nature of a nuclear disaster, it is firstly necessary to introduce and define the key terms associated with extraordinary situations in nuclear power plants operation, including the term of "natural disaster" itself.

Operations at nuclear facilities can be disturbed by events of different nature. Incidents resulting from use of nuclear fuel and energy are called "nuclear incidents" and are defined as "*any occurrence or series of occurrences having the same origin which causes nuclear damage*" (European Commission, 2004). The definition of "nuclear damage" has been constantly revised; it currently embraces damage to people, property, environment, as well as economic and monetary losses associated with those three, and costs of preventive measures.

The severity of accidents in nuclear facilities might substantially vary. The International Atomic Energy Agency (IAEA) together with Nuclear Energy Agency (NEA) developed the International Nuclear Event Scale (INES) in 1990 which became a remarkable tool for nuclear authorities to form judgment about the safety significance of nuclear events and to communicate this to the general public, media and other third parties. The scale was being constantly revised in order to include more information on specific topics (e.g. transportation of radioactive material and human exposure to radiation) and examples of nuclear events, while methodology has been kept fixed (IAEA, 2012c). As of today, INES is adopted in 69 countries and classifies the severity of nuclear events on the scale of 7 across the following three areas of impact:

- People and the environment: nuclear events resulting in unplanned release of radioactive material and a consequent widespread within the location of the event;

- Radiological barriers and control: nuclear events resulting in high radiation levels which, however, are limited to the nuclear facility only, hence no damage to people and the environment occurs;

- Defence-in-depth: nuclear events which do not impose direct damage to people and the environment, but for which preventive measures have proven to malfunction.

According to INES, severity of nuclear events increases from level 1 – "Anomaly", which implies minor problems and slight safety concerns, to level 7 – "Major Accident", which implies damage to people and the environment. Nuclear events of level from 1 to 3 are called incidents, while the next four levels, from 4 to 7, mark nuclear accidents which have much more severe consequences, including people's death, widespread of radioactive material, and similar. Nuclear events, according to INES carrying no significant safety concerns are classified below the scale – level 0 (see Appendix 3).

The scope of this paper is limited to the major nuclear accidents only (level 7) which are also often called "nuclear disasters". According to INES, such accidents result in "*major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures*" (IAEA, 2012c). It is generally accepted that every nuclear plant must be designed and built in such a way so as to withstand a design basis accident (DBA), sometimes also called as a maximum credible accident (U.S. NRC, 2009) (European Nuclear Society, 2012). This is hypothetically the most severe accident which occurrence is probable for a particular nuclear power plant given its design, equipment, configuration, control and safety systems, etc. The accident results from an adverse combination of various errors and failures at the nuclear site which could have been foreseen and taken care of. Not only a nuclear power plant should be able to withstand its defined DBA, but it also should do so without losses to the key systems and structures, hence no threats to public health and safety should be encountered (European Nuclear Society, 2012). Thus, a nuclear disaster lies beyond the specified DBA.

3.2.   Overview of Nuclear Events

Nuclear incidents and accidents might happen on a daily basis. While nuclear incidents are not often reported to the wide public due to insignificance of damage or threat to people and the environment, nuclear accidents are those the public gets to read and to hear about in the breaking news. The history of nuclear accidents numbers several events; the top seven are fitted into the INES classification and discussed below.

The earliest two nuclear accidents took place in 1957 in Kyshtym, the Soviet Union (currently Russia) and in Cumberland (currently Sellafield, Cumbria), the UK. Kyshtym accident is rated 6 ("Serious Accident") on the INES scale and its severity roots in the fact that a tank containing roughly 70 tons of radioactive waste exploded and triggered a substantial release of radioactive material into the surrounding environment (IAEA, 2012c) (Teeghman, 2010).

Nuclear accident in Cumberland, also known as Windscale Pile or Windscale Fire is rated 5 ("Accident with Wider Consequences") and is claimed to be the worst nuclear accident in the UK history. It occurred due to a fire in the reactor which resulted in a release of radioactive material into the environment (IAEA, 2012c).

Another nuclear accident rated 5 took place in 1979. Three Mile Island is located in Pennsylvania and is by far the worst nuclear event in the whole US history. The accident happened due to a failure of the feed-water pumps which stopped working, followed by the automatic shutdown of the turbine and the reactor (U.S. NRC, 2009). Not only Three Mile Island was a result of a series of technical failures, but also of lack of nuclear site management's knowledge and experience in handling such emergencies (Teeghman, 2010).

The next dangerous nuclear accident took a year later, in 1980, in France. Saint Laurent des Eaux accident was rated 4 ("Accident with Local Consequences") by the INES. One channel of fuel in the reactor melted, however this accident was limited to the area of the nuclear facility only (IAEA, 2012c).

The Tokaimura accident rated 4 by the INES took place in 1990, in Japan. The accident was attributed to the fact that the three on-site employees-operators were preparing a batch of fuel based on the highly-enriched uranium, which they had little experience dealing with. They exceeded the uranium amount allowed by the precipitation tank and criticality was reached and continued intermittently for roughly 20 hours, triggering a fatal overexposure of the on-site operators, whereas two of the three died (IAEA, 2012c), (Teeghman, 2010).

Indeed the history of nuclear accidents numbers several major events, from which, however, only two so far qualify for being referred to as nuclear disasters – Chernobyl in 1986 and Fukushima Daiichi 25 years later, in 2011. These two nuclear disasters, both rated 7 ("Major Accident") according to INES are most relevant for conducting the intended analysis in this paper, hence they will be studied in more detail in the following section.

3.2.1. Chernobyl Nuclear Disaster (1986)

On the 26th of April, 1986, at 1:23:45 am local time, a severe nuclear accident took place at the Chernobyl nuclear power plant, located in close proximity to the populated city of Prypiat in the Ukrainian Soviet Socialistic Republic (currently Ukraine).

As described by World Nuclear Association (2009), a shutdown of the 4th Unit of the Chernobyl nuclear power plant was scheduled for a routine maintenance on the 25th of April, 1986. The shutdown would also allow testing if the cooling of the core would still be supported by the slowing turbine in case of a loss of power. To enable the shutdown, the emergency core cooling system (ECCS) was switched off. The shutdown of the reactor was taking place as planned up until the moment when it was interrupted due to the demand for the power in the grid; at 11 pm the shutdown process was recommenced. According to the plan, stabilization of reactor had to take place at the power level of 700-1000 MWt, however as of 00:28 am, April 26, it fell to 30 MWt. By 1:03 am it was stabilized at 200 MWt level and it was decided to perform the planned test at that level. What the employees of that shift did not know is that already by 1:00 am the minimum operating reactivity margin (ORM) for the reactor of that type (RBMK) was already severely violated. By 1:22:30 am the ORM comprised eight manual control rods while the minimum permitted ORM was 15. The test was started at 1:23:04 am and a disaster was a matter of seconds. Under less than a minute from the moment the test was commenced, the power reached 530 MWt at 1:23:43 and kept rising. The steam triggered by rupture of the fuel elements acted as a catalyst for the explosion, whereas the positive void coefficient increased, the pressure in the reactor rocketed, the reactor support plate was detached and the rods got stuck before they even reached the reactor core. Finally, the reactor cooling circuit depressurisation took place due to the breakage of the channel pipes and triggered the consequent mass steam generation. This lead to the first explosion at 1:23:45 am (World Nuclear Association, 2009) whereas the sarcophagus around the reactor collapsed, water poured in and reacted with zirconium. The result of this reaction was hydrogen which caused the second explosion just several seconds later and prolonged graphite burning, while the destroyed core of the reactor was exposed to the atmosphere.

The Chernobyl nuclear accident was followed by long debates regarding what was the cause of the explosion and who was to be held responsible. While this is presented in more detail in the subsequent sections of this paper, the historical background of the USSR energy and

power sector should be briefly assessed now as it well contributes to the understanding of the path to that accident.

In the beginning of the 20th century, the electricity production in Russian Empire comprised 1.9 TWh per year, which was a very low level for a country of that size. In fact, in terms of electricity production Russian Empire was lagging well behind even Switzerland, which was 500 times smaller in area (Kuznetsov, 1964). After the revolution of 1917 the Communist Party came to power, they developed a new vision for a new country – the Soviet Union. The Communist Party switched to the planned economy and put electrification among the top-urgent priorities and in 1920 the All-Russian Central Executive Committee of the Soviet Union announced establishment of a Sate Electrification Commission (GOELRO) which would work on creation of an Electrification Plan for the country (Lenin, 1964). Both the Commission and the Plan were under direct supervision of V. I. Lenin who deeply believed that electrification is a critical process to the successful transformation and industrialization of ex-Russian Empire. A 500-hundred page Plan was presented soon by GOELRO and massive construction works of a network of regional power plants and transmission and distribution systems commenced, and with the well-known Soviet 5-year plans the targets were heavily over-fulfilled (Geldern, 2012). Even the WW II could not stop the Soviet Union's pursuit of electrification and by 1956 the Soviet Union was the 2nd largest electricity producer after the USA with its total electricity output reaching 192 TWh in that year which shows more than a 100 times increase over roughly 50 years (Kuznetsov, 1964).

However, in early 1950's it became clear that the electricity capacity was not yet sufficient for achieving all goals set by the Communist Party. Therefore, it was decided to expand into Siberia and the Far East as well as to have a closer look at the nuclear power potential (Lomakin, 2012). Worth mentioning, by that time nuclear power had already been a well-established scientific field in the USSR, however, it was considered for the military purposes only – bombs and fuel for submarines, and did not have any ready-available applications for the electricity generation. Hence, civil nuclear industry had to be developed from scratch which required huge investments into capital, knowledge and human capacity.

According to V. Legasov, who was the First Deputy Director of the Kurchatov Institute of Atomic Energy at the time of the Chernobyl accident and was appointed the Chief of the Investigation Committee of the accident, in terms of nuclear science, the Soviet Union was lagging behind the rest of the world for 10 years, so a big "catching up" challenge was awaiting (Lomakin, 2012). An extensive research and development program was initiated by

the State Committee for the Utilization of Atomic Energy to assess viability of different nuclear reactors and to conclude which reactors would be most suitable for the USSR (Semenov, 1983). Various types of reactors were considered, e.g. PWR, BWR, GCR. The research showed, however, that a uranium-graphite channel-type reactor cooled with boiling water, also known as the "Soviet design reactor" or RBMK, is the most economically appealing one. The first nuclear power plant based on this type of reactor was commissioned in 1954, in Obninsk, nearby Moscow, and in next 15 years similar nuclear power plants comprised roughly half of the total Soviet nuclear capacity (Zheludev, 1980). Worth mentioning, the USSR was particularly interested in developing fast breed reactors since such reactors were critical for realization of a large-scale nuclear programme. After almost a decade of experimenting and testing different technologies, in the second half of 1960's it was finally decided that the VVER and the already discussed RBMK will be cornerstone of the long-term nuclear programme (Semenov, 1983).

It is critical to understand the nature of the Soviet Union as a country at the time it was stepping into the civil nuclear power era. It was a country which has just gone through a massive electrification process under enormous time pressure. What other countries were doing for a century, the Soviet Union accomplished under less than 30 years. The Communist Party had the ultimate power and through its subordinates was making orders which nobody would dare to question – the hierarchy was indeed strong and strict. Abundant number of commissions, councils, reporting groups and others was created to control and monitor every industry, including nuclear power sector, however they lacked clear vision, did not communicate with each other and were not properly structured, which altogether lead to over-bureaucratization and inefficiency (Dyatlov, 2005). Worth mentioning, the working style of controlling and monitoring bodies was skewed towards punishing for what has been done wrongly, rather than incentivizing and preventing wrongdoing (Lomakin, 2012).

Furthermore, the Soviet Union was an isolated country which put an explicit boundary between itself and the rest of the world with the famous "iron curtain". While only people living in the Soviet Union knew how the country is like from the inside, the whole outside world could only see what the Soviet "public relation" offices would show them. The Soviets' pursuits for self-sufficiency and strong unwillingness of being dependant in any respect on other countries, made it "reinvent the bicycle" many times – nothing could be borrowed from the West, not even a nuclear reactor design – this was developed in-house (Lomakin, 2012). Such policy had an important negative externality: the country was lacking

funds and adequate labour force, so it had to urgently establish universities and educate necessary specialists locally while being restricted with a limited budget. This yet again put efficiency of the whole nuclear industry into question.

To sum up, the 26th of April 1986 witnessed a dreadful accident taking place in a country whose nuclear power sector was comprising 20 per cent of the whole electricity generating capacity throughout 1976-1980 (Zheludev, 1980), yet which had been developed in a rush and independently of what the whole scientific world had to offer, amid scarcity of available technologies, financial resources and adequate specialists. This should be kept in mind while evaluating probability and costs of the Chernobyl nuclear accident which is presented in the subsequent parts of this paper.

3.2.2. Fukushima Daiichi Nuclear Disaster (2011)

The year of the 25th anniversary of the Chernobyl accident witnessed yet another terrifying nuclear disaster at the Fukushima Daiichi nuclear power plant, in Japan. On the 11th of March 2011 at 2:46 pm local time, an earthquake of magnitude 9.0 Richter scale hit the North of Japan, triggering a devastating 15-meter high tsunami. The earthquake received a name of the Great East Japan Earthquake and by so far it is the most complex and severe one in the whole history of the country: not only it moved Japan a few meters to the East, but also brought down over a million buildings and collected a human death toll of roughly 20,000 (World Nuclear Association, 2012e).

Eleven reactors at four nuclear power plants (Fukushima Daiichi 1, 2, 3, and Fukushima Daini 1, 2, 3, 4, maintained by Tokyo Electric Power Company (Tepco), Tohoku's Onagawa 1, 2, 3, and Japco's Tokai) were operating at the moment when the earthquake hit. All eleven turned out to be seismically robust – they shut down automatically as they were supposed to in a case like that, however, the tsunami which followed the earthquake proved to be a much bigger danger for the nuclear reactors as it imposed a power blackout threat. While other eight operating reactors still managed to run their cooling systems with power from the grid or/and emergency power generators, Fukushima Daiichi units 1, 2 and 3, which six external power suppliers were disabled due to the earthquake, were flooded by the tsunami. As a result, water damaged the back-up diesel-based power generators located in the basement and hence disabled the heat removal process in the reactors. With a massive blackout and a subsequent cooling system failure, and despite all effort by Tepco employees, additional contractors, fire fighting and military personnel into restoring the heat removal, the three

Fukushima Daiichi units experienced a substantial core meltdown within the first three day after the accident (World Nuclear Association, 2012e). At 7:03 pm same day a Nuclear Emergency was declared followed by an order from the Fukushima Prefecture to initiate people's evacuation within the radius of 2 km from the Fukushima Daiichi which was extended to 20 km on the following day. Fukushima Daiichi units 4, 5 and 6 were not operating at the time of the earthquake, however they were still affected and the 4th unit soon became a big concern. On March 15 an explosion occurred in the 4th reactor which resulted from the hydrogen accumulating in the 3rd unit. To sum up, the melting of the fuel occurred in the units 1, 2 and 3 immediately after the tsunami, and release of the radioactive material took place actively during the first days, especially through the contaminated water which fled the reactors. Cooling down the reactors with the recycled water from the treatment plant took several months and it was only in October 2011 when the temperature in the reactors fell down to 80C. The official "cold shutdown condition" appeared almost after a year of the accident, in December 2011 (World Nuclear Association, 2012f).

The Fukushima nuclear accident at the units 1, 2 and 3 was initially ranked as level 5 according to INES, while the situation at the unit 4 ranked as level 3. However later it was reconsidered and a 7th level was attributed to units 1-3 collectively due to a substantial release of radioactive materials into the environment (American Nuclear Insurers, 2009).

4.   Costs and Probability of a Nuclear Disaster

Complex nature of nuclear accident costs and uncertainties related to them are well described in the previous studies. It is generally accepted that the costs of nuclear disasters are huge, however, the range of the amounts in question vary dramatically from source to source which will be described in detail later in this paper. Hence, it is difficult to arrive at a reasonable damage assessment even for accidents which have actually taken place, not to mention those which can only be hypothesized and modelled. This partly results from the fact that despite of a roughly 60 years long history of the world nuclear power, there still is a lack of standardized and widely accepted methodology for evaluation of nuclear damage and of consensus regarding what consequences of the nuclear accident should be taken in consideration (European Commission, 1995). What the practice shows, assessment of potential costs in case of a nuclear disaster for the same nuclear site yields different results when analysis is performed by different parties (Froggatt & Carroll, 2010). Subsequently, it

does not allow to form a unique and, most importantly, objective expert view on the potential nuclear accident damages.

The nature of nuclear disaster risks is also very distinctive. It is generally accepted that a nuclear disaster is characterized by an extremely low probability of occurrence (Günther, Karau, Kastner, & Warmuth, 2011). However, the assessment of that probability is substantially complicated by the fact that nuclear accidents do not happen frequently – to the date only two severe nuclear accidents took place, at the Chernobyl and the Fukushima Daiichi nuclear power plants; hence, there is a continuous lack of basis for such calculations. While some experts claim that evaluations of nuclear accident costs (especially the external ones) are much more sensitive to the assumptions regarding the expected off-site damages than to the measured accident probability of occurrence (Froggatt & Carroll, 2010), proper assessment of such likelihood is still a valid issue for the on-going research in general and for this paper in particular. Previous studies done in the field highlight that there is a whole range of possible different causes of a nuclear disaster, and assigning probabilities to some of those is a very complex process.

4.1.   Existing Approaches of Costs and Probability Assessment

In this section, the most widely used methodology for calculating these two values – costs and probability of a nuclear disaster – is presented.

Costs of a Nuclear Disaster

Assessment of nuclear disaster costs heavily relies on assumptions used in the analysis. The first assumption any researcher has to face is which damage has to be included into calculations. As discussed above, no single set of nuclear accident costs has yet been generally accepted, but the tendency is such that nuclear analysts attempt to incorporate all possible costs, be it local or international, direct or indirect. In short, the analysis of the nuclear disaster costs moves towards adopting a global perspective of a disaster impact (NEA, 2000), (Froggatt & Carroll, 2010).

Despite the lack of a uniform list of nuclear disaster costs, methodology for assessing some particular types of costs is well developed. NEA (2000), in their report exhaustively describes **two** types of such costs: countermeasures to reduce radiation doses and radiation-induced health effects in the exposed population:

Countermeasures to reduce radiation doses which are taken immediately in case of a nuclear disaster are assessed from a micro-economic point of view. These costs include population movement, agricultural effects and decontamination.

- Population movement cost is comprised of all costs related to evacuation from the zone of impact, provision for temporary accommodation and food for the evacuated people, foregone income and capital losses associated with the relocation, supervision of the affected area and evacuated people, as well as inconveniences and tension these people would bear. To calculate the total cost of population movement, it is necessary to define how many people and business entities may be affected by the accident and acquire a representative cost for each of the mentioned costs type.

- Agricultural losses arise from bans on production or consumption of food and water due to a nuclear disaster. It is important to understand what is the magnitude of these effects if put into perspective, e.g. how much land and water reserves are subject to contamination, how much products should be disposed, how much production capacity should be withdrawn and for how long, and how would that affect the economy of a whole country in both shorter and longer terms.

- Decontamination costs include all expenses related to cleaning up what can be cleaned and disposing what cannot be – a process which requires hiring specially trained people.

Radiation-induced health effects caused by exposure to ionizing radiation can be divided into 1) directs health care costs, 2) indirect costs which basically account for loss of income due to illness or premature death, and 3) non-monetary costs which embrace the whole spectrum of negative emotions and feelings people suffer from after a nuclear disaster. The last cost group is the most controversial of all as it is not possible to objectively express pain, grief and other non-pecuniary factors in monetary terms.

There are several approaches which deal with calculating health impacts, the most widely applied are the so called "human capital approach" and the "willingness-to-pay approach".

The human capital approach allows assessing the health effects which can be reasonably quantified and which have an obvious impact on the economy. Therefore, it makes estimation of direct health care costs straightforward because costs of treatment, hospitalization and medicines are either known or can be assumed fairly accurately. Moreover, the human capital approach defines value of an individual based on that individual's economic contribution

which is measured by expected earnings. Hence, given that adequate assumptions are made on the individual's life expectancy and salary, and how it is affected by a nuclear disaster, it is possible to estimate the indirect costs as well. To sum up, the human capital approach covers two of the three mentioned types of the costs. Despite being a widely used method it, however, has several drawbacks, e.g. the restricted ability to include non-monetary factors and uneven assessment of production potential of different population groups.

The willingness-to-pay approach deals with the third type of health costs which are derived from the affected people's emotions and feelings. This method is based on defining how much would an affected individual be willing to pay to avoid the risk of being affected or how much would this individual would be willing to receive as a compensation of that risk. Hence, this approach most often incorporates such important factor as people's preferences, as well risk aversion and utility concept. Due to the fact that still non-pecuniary factors are very subjective, the related estimations tend to vary substantially depending what kind of people is being studied and, hence, cannot be claimed ultimately accurate.

Other costs the report by NEA (2000) lists among the potential damages from a nuclear disaster are psychological effects, impact on power sector, damage to economy on a macro level, long-term social and political impact, as well as environmental and ecological damages (see Appendix 4).

An important part of calculating costs of a nuclear disaster and expressing them in the monetary terms is assessing the present value of the costs. Hence, only the costs occurring in the short term can be taken at a nominal value, while those costs which spill over in the longer time should be discounted. Therefore the idea that money has certain time value is adopted – which is reasonable since discounting enhances comparability of costs which occur within a long time horizon.

Probability of a Nuclear Disaster

As it was already pointed out, estimating risk of a nuclear disaster is a complex process since the final value of the estimated probability has to embrace probabilities of all events which might possibly trigger and/or aggravate the accident. Hence, a certain bottom-up approach has to be performed, whereas each probability has to be estimated and then all of them have to be credibly combined into the final total value. Naturally, it cannot be done unless a set of assumptions is made which yet again leads to possible confusion, just deepening the extent to which such computations are analytically challenging (U.S. Congress, Office of Technology

Assessment, 1994). Another source of problem roots in the fact that while some events leading to a nuclear accident are independent from each other, some events might be conditional upon occurrence of other events. For example, probability of a radioactive release would be conditional upon the occurrence of a core meltdown. Hence, methodology chosen for calculating the final total probability of the disaster has to be able to account for this (European Commission, 1995). Furthermore, the uncertainties related to the environmental consequences of a nuclear disaster are those which are the most hard to handle in the quantitative studies. The main reasons for that are the ambiguity of the available data and the lack of objective measures (U.S. Congress, Office of Technology Assessment, 1994). What also should be kept in mind is that due to lack of nuclear disaster frequency, statistics of the disasters do not ensure a reliable and meaningful basis for estimating the probability of a nuclear accident; hence, mathematical methods should be applied (NEA, 2003b). One of the most advocated and used tools is the so called probabilistic risk assessment (PRA), also known as probabilistic consequence assessment (PCA), or probabilistic safety assessment (PSA) which actually links costs of an accident and the probability of occurrence of those costs together.

Probabilistic Risk Assessment

PRA enables estimation of the nuclear accident cost taking two factors into accounts: 1) the magnitude of potential damages from a nuclear disaster and 2) the likelihood of every damage type to arise. Most often PRA estimations address endogenous events, that is, those events which are typical and distinctive for a particular power plant. Some PRAs deal with exogenous events as well, such as natural disasters or unique problems associated with the nuclear power plant in question, e.g. nuclear waste storage given a peculiar nature of the site geology (U.S. NRC, 2011). Nuclear analysts categorize all PRAs in the following three levels: Level I PRA calculates frequency of nuclear reactor core damage; Level II PRA defines the severity and development of a radioactive release, given that the core damage has taken place; and Level III PRA estimates health and economic losses associated with the previous two levels.

Application of the PRA tool is staged.

- Firstly, it is important to identify the potential hazards and threats which can result in the worst possible spill-over of impacts, e.g. nuclear reactor core meltdown.

- Secondly, all possible events which would cause the hazards and threats to break out have to be defined, e.g. malfunctioning of a reactor cooling system can possibly trigger nuclear reactor core damage.

- It is then crucial to attribute probability to every possible cause, e.g. define how often the reactor cooling system is expected to break down.

- Finally, it is necessary to specify all possible combinations of failures under assumption that the triggering event has taken place, e.g. that the reactor cooling system indeed has failed. The probabilities of all combinations are then calculated and probabilities of those causes which lead to the same outcome are summed up to represent a total probability of the outcome.

Damages occurring due to a nuclear disaster are expressed numerically in units (monetary, number of deaths, etc.) and their respective likelihoods, as discussed above, are expressed as probabilities; when these two values are multiplied, an expected cost is calculated. The total expected cost of a nuclear accident is therefore the sum of all expected costs (U.S. NRC, 2011). PRA implies that there are two ways to reduce the total expected costs: either to reduce the probability of an undesirable event or to reduce the magnitude of the consequences.

When it comes to interpretation of PRA results, it is not a straightforward process since they take a form of a range of potential outcomes. While nuclear analysts derive a single representative value, also known as a "point estimate", they should always bear a thought that actual risks can substantially far from that estimate.

Various computer software solutions and codes have been developed to perform the PRA and assess probabilistic consequence analysis. They estimate risk of a potential accident based on the whole range of damages and probabilities attributed to them. Such tools also allow to examine different scenarios of an accident and prepare the emergency response accordingly (Haywood, 1991). What today's probabilistic consequence assessment models focus on is the possible dispersion of the radioactive materials which to a large extent depends on the meteorological conditions and the atmospheric pathway. Another important factor taken into account is site-specific details, whereas location and surrounding are highly important for the damage assessment. Effectiveness of the emergency actions is also a point to be considered as it describes how the consequences of a nuclear accident can be mitigated. Time (season, time of a day) of a nuclear accident is crucial for the calculations as well because intensity of and ultimate damage from radioactive release depend on that (European Commission, 1995).

One of the examples of probabilistic consequences assessment codes is the one called COSYMA which was develop by the European Community Radiation Protection Programme and was used in the ExternE Project by the European Commission (1995) to estimate health and economic impacts of four different nuclear accident scenarios for France. COSYMA divides all area affected by a nuclear accident into three main zones: Near Early, Near Late and Far Late, whereas two first zones are defined as local and the last zone is regional. Other widely used computer codes dealing with the probabilistic safety assessment are CONDOR and MACCS.

4.2. Literature Review on Calculating Costs and Probability of a Nuclear Disaster

4.2.1. Modelled Nuclear Accidents

Given such distinctive nature of costs and lack of an internationally accepted objective tool to quantify them, it is not surprising that estimated nuclear accident costs tend to vary dramatically from source to source. For example, nowadays research on nuclear damages witnesses modelling of the accidents at the levels varying from as little as EUR 100 million to as much as more than EUR 8 trillion when expressed in 2011-year values (Dubin & Rothwell, 1990), (U.S. Congress, Office of Technology Assessment, 1994), (Heyes, 1995), (Greenpeace, 1994). It is thus useful to look at what assumptions and approaches different studies are based on.

One of the earliest studies is the **CRAC-II report** undertaken in 1982 by Sandia National Laboratories, widely known as Sandia Siting study. It sketches the worst possible consequences of the worst possible accident scenario occurring in any of the nuclear power plants in the USA and arrives at a cost of an average nuclear accident amounting to 26 billion United States dollars (USD) and of a large accident amounting to USD 694 billion (Sandia National Laboratories, 1982), which corresponds to roughly EUR 51 billion and EUR 1.2 trillion as of end of 2011. The Sandia report only accounts for costs associated with people's health and property damage, while all externalities are kept outside the study. The report estimates that a severe accident results into 56,600 deaths cases, 227,000 injuries and 15,600 potential cancer cases; it further assumes that the cost of each is USD 5, 0.1 and 1 million respectively, which altogether with a USD 374 billion (EUR 730 billion as of 2011) provision for property damage brings this to the mentioned USD 694 billion total loss (Sandia National Laboratories, 1982).

The research focused on nuclear damage was stimulated by the Chernobyl disaster in 1986. It took three days from the moment of the accident for the Soviet authorities to publicly admit the fact of an accident, and it took almost four months to publish the first detailed report describing the development of events, the radiation released and measures taken to address the consequences (Imanaka & Koide, 2000). Given the Soviet top secrecy and reluctance to share inside information with the rest of the world, the content of the publication has been doubted by many nuclear researches. However, in the lack of more reliable data, the early studies dealing with nuclear disasters adopt many assumptions from the Soviet reporters.

Another early study worth mentioning is the one completed by **Hohmeyer** in 1988 who hypothesizes a nuclear disaster in Biblis, Germany, in attempt to quantify the consequences of a nuclear reactor accident. The only costs the study includes into analysis are those associated with cancer; hence, other types of damage are kept outside the study. Assuming that the radiation dose of population is 2.4 million person-sieverts (adopted from the USSR Report 1986) and probability of getting cancer is 10 per cent per sievert, and taking factor 10 to account for denser population of Bibles with its 3 million inhabitants as compared to Chernobyl with 0.1 million inhabitants in the immediate areas, Hohmeyer calculates an expected amount of cancer cases to be 2.4 million. He then attributes an economic loss of 1 million deutsche marks (DM) to each fatal cancer case and twice less to a non-fatal cancer case, assumes 50 per cent mortality rate and, finally, arrives at a loss from a nuclear disaster amounting to DM 1.8 billion, which is equivalent to EUR 1.37 trillion as of 2011 (Hohmeyer, 1988) (Günther, Karau, Kastner, & Warmuth, 2011). Two years later Hohmeyer introduces a factor of 5 to increase the provision of the collective radiation dose of population which resulted in the 12 million person-sieverts population dose (Hohmeyer, 1990).

Research by **Ottinger et al.** in 1990 expands Hohmeyer's methodology even further: not only the authors perform monetary evaluation of health effects but they also proceed with estimating agricultural losses. The modelled accident takes place in the USA; the authors assume 2.4 million person-sieverts as radiation dose of the population, 7.7 per cent per sievert risk factor and 75 per cent mortality rate, which lead to a result of 140,000 fatal and 45,000 non-fatal cancer cases. When the monetary values have to be attributed, they apply the so called hedonic pricing method which allows estimating value of environmental effects. This approach results into USD 4 million for a fatal and USD 400,000 for non-fatal cancer case. The total damage, hence, was estimated to be USD 579 billion, which is equivalent to EUR 629 billion as of 2011 (Ottinger & al., 1990).

Ewers and Rennings (1991) hypothesize a nuclear disaster at the same Biblis type reactor as does Hohmeyer. They use the Hohmeyer's approach to estimate health damage and they also expand the scope of costs to consider economic losses which accompany the agricultural production, closure of areas, and resettlement. For calculating the health damage, the authors use same factor of 10 for population density adjustment and risk factor 10 per cent per sievert, however the population radiation dose is assumed to be twice as high – 4.8 million person-sieverts. This yields total health damage at a level of DM 3.6 trillion. In addition to this, the authors calculate the cost of locations losses and resettlement to be DM 1.09 trillion and cost of agricultural losses to be DM 50 billion. Hence, the total cost of nuclear accident sums up to DM 4.74 trillion (EUR 3.67 trillion as of 2011).

A year later **Ewers and Rennings** (1992) make a follow-up assessment of a nuclear disaster, whereas they abandon the previously used 10 per cent per sievert risk factor and introduce new risk factors: 5 per cent per sievert for fatal cancer cases, 1 per cent per sievert for non-fatal cancer cases, and 1.3 per cent per sievert for severe genetic damage. Another input they modify is the adjustment factor for population density – 7 is assumed instead of 10. Hence, when the health effects are estimated, 1.68 million fatal and 336,000 non-fatal cases, as well as 436,800 cases of severe genetic damage are anticipated. The authors then apply the hedonic pricing method, previously used in Ottinger et al. research, to find the monetary valuation of the fatal cancer cases which turns to be DM 10.08 trillion. Non-fatal cancer cases and severe genetic damage are assessed with the human capital method and are estimated to be DM 386.4 billion. Finally, the authors run different scenarios for property damage and arrive at DM 231 billion in anticipated cost. Altogether, the reviewed study by Ewer and Rennings show that the cost of a nuclear disaster in the Federal Republic of Germany would be DM 10.679 trillion (EUR 8.28 trillion as of 2011).

Krupnick et al. (1993) published one of the early articles recognizing the necessity to incorporate external costs of nuclear power into analysis of a nuclear disaster. The authors question if reliance on what they call Expert Expected Damage (EED) approach, which in essence was used in majority of previous studies to monetize direct expected consequences, is sufficient for picturing the whole impact of a nuclear disaster. The further discussion focuses around the three main issues the EED approach fails to address, namely:

1) individual aversion to risk, whereas money and satisfaction are assumed to be proportionally related, which is criticized by the authors of the article;

2) ex ante perspective in decision-making, whereas the EED approach is more ex post, that is, it evaluates the losses from an accident if it occurred with certainty, while the authors argue that decisions under uncertainty have to be considered;

3) risk perception of lay public, whereas the lay public has a complex multi-dimensional opinion about the nuclear risks and, hence, reckons that the cost assessment performed with the EED approach is too low. Altogether, the authors insist that these three conceptually important issues are to be addressed in the nearest future.

The same year report prepared for the U.S. Secretary of Energy's Advisory Board by the **Fuel Cycle Peer Review Panel** (1993)**,** also states the necessity of dealing with nuclear fuel cycle externalities. Apart from criticizing the existing approaches used by the studies and stating that they are not appropriate for addressing the new objectives of the nuclear researchers, the report also makes a set of crucial recommendation for the future research. Firstly, importance of incorporating qualitative factors and consequences, e.g. environmental and social costs, into the nuclear accident analysis is highlighted. Secondly, the authors reckon that a site-by-site approach and statistical averages which are representative and sound for a particular region should be used when assessing the nuclear fuel cycle and possible accidents, since location and surrounding environment substantially differ across nuclear power plants. Finally, the report urges for a necessity to develop and employ objective screening methodology for deciding which environmental effects should be considered for the analysis, again given region-specific features and policies implemented there.

The report also elaborates on adequacy of health effects assessment, which until 1990's had been the main concern of all studies on consequences of nuclear disasters, and finds substantial imperfections in the existing methodology. For instance, it is argued that the willingness-to-pay approach leads to underestimation of health (and economic) consequences because this approach has limited abilities to deal with contingent valuations which are critical for measuring health disorders. Furthermore, the paper discusses the appropriateness of the 50 km radius which limits the zone of nuclear disaster impact. Having studied the nature of airborne effluents, the authors arrive at the conclusion that this limit should be abated in favour of a site-specific analysis.

Once the urgency of considering external costs of a nuclear fuel cycle in general and in the case of an accident in particular has established its appeal and most of the world well-known nuclear authorities started talking about it, a new era of nuclear damage research has begun. The first attempt to assess external costs of an accident was performed by the **ExternE**

Project by the European Commission in 1995, whereas most recent developments and achievements in the economic and environmental research were used in order to create a comprehensive methodology which would enable to quantify the maximum costs of a nuclear disaster (European Commission, 1995). Since then a big effort was put into refining and reviewing that research, yet the nature of nuclear accident costs remain problematic and, as the ExternE team concluded: *"The subject is one of the most difficult to be faced in the project: indeed despite earlier extensive research a clear solution to the problem is still to be identified"*. What the ExternE team did was developing a so called impact pathway approach for the whole nuclear fuel cycle which would be comparable with other fuel cycles. The ExternE team used the French nuclear fuel cycle for demonstration of the methodology. The nuclear cycle was broken down into the following stages: mining and milling, conversion, enrichment, fuel fabrication, electricity generation, reprocessing, waste disposal and transportation. All relevant impacts which appear along the whole cycle were evaluated and attributed a monetary equivalent, whereas the main priority was given to those impacts derived from the releases of radioactive material to the surrounding environment (e.g. health effects and material costs occurring from loss in agriculture and similar). The electricity generation stage is the most relevant one as it considers and accommodates four scenarios for a severe nuclear accident, run by COSYMA (European Commission, 1995).

The report runs the following four accident scenarios: 1) core melt down with a severe breach of containment; 2) core melt down without a breach of containment; 3) and 4) intermediate levels of releases of radioactive materials, both scenarios used for demonstrating the sensitivity of results. The scenario 1 is the most relevant to the focus of this paper as it deals with the worst possible damage caused by a nuclear disaster. The total costs from a nuclear accident in the ExternE Project are broken down into health effects and material costs (food bans, evacuation and relocation). While methodology for assessing health damage is being kept the same as in the studies discussed above, assumptions are slightly modified: 5 per cent per sievert for fatal cancer cases, 12 per cent per sievert for non-fatal cancer cases, and 1 per cent per sievert for severe genetic damage. The collective population dose is borrowed from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (1988) prepared by the United Nations and constitutes 291,200 person-sieverts which is a substantially smaller number from previously seen 2.4 and 4.8 million person-sieverts. The fatal cancer cases are then evaluated to be at the level of European Currency Unit (ECU) 2.6 million per case, which is based on the willingness-to-pay approached developed by the

ExternE Project Volume 2. The cost of a non-fatal cancer case is adopted from the US study by Oak Ridge National Laboratoty and is assumed to be ECU 250,000. Hence, the total health damage cost is estimated to be ECU 54.1 billion (EUR 74.1 billion as of 2011). The material costs are measured using COSYMA and the following estimates are acquired: food bans ECU 27.6 billion, and evacuation/relocation ECU 1.5 billion. Summing all costs up, the total cost of the worst-case scenario nuclear accident comes to ECU 83.2 billion (EUR 114 billion as of 2011) (European Commission, 1995). However, the decontamination costs which are excluded from this analysis would have added a substantial amount on top of that. Furthermore, the ExternE report admits that the study is limited to the extent that often it is impossible to perform economic valuation of the costs due to high level of uncertainty with respect to estimating the impact of the accident and the efficiency of countermeasures. Moreover, the COSYMA code used for the ExternE Project does not deal with the potential long-term damage to the ecology. Back in 1995, when the study was done, this limitation was explicitly stated and it was highly recommended that such costs are investigated and included into the analysis in the future (Froggatt & Carroll, 2010).

Report by **NEA** (2000) made a substantial contribution to the discussion of methods to calculate external costs of large nuclear accidents. This report has a "generic nature", that is, it is not country-specific and it does not take circumstances of an accident into account. As the authors underline, "*this report represents the current state-of-the-art thinking in the area of economic consequence assessment methodologies and that it should be used as guidance for further work in this area*". Similarly to previous studies, it is argued that nuclear accidents result in huge off-site consequences which mainly include health impacts, environmental effects, protective countermeasures as well as economics losses in affected areas. Apart from that, this report is one of the early birds in recognizing the necessity to internalize short-term and long-term psychological, social and political impacts. However, the authors admit that in majority of cases such costs would be "unquantifiable".

Another report by **NEA** (2003b) looks at the question of internalization of the external costs of a nuclear fuel cycle from a slightly different angle. Apart from specifying the main external costs (for example, disposal of radioactive waste, decommissioning and dismantling of nuclear facilities, health effects and environmental impacts caused by releases of radioactivity during daily operation of nuclear site) which are subject to quantitative analysis, the report also concludes that the majority of them has already been incorporated into the price of electricity produced at nuclear power plants. With respect to qualitative factors, e.g.

politics, macro-economic and social issues, the report admits that a standardized view on how to estimate and incorporate them into the cost of a nuclear fuel cycle still does not exist. However, as the authors argue, the impact of qualitative factors is not anticipated to change the final cost dramatically. Regarding the damage arising from nuclear disasters, the authors argue that since the third party liability system was established, external costs of accidents have been also incorporated into the insurance system, hence, into the final cost of electricity. The report suggests that, when assessing the total external costs, only radiological effects from nuclear accidents should be taken into consideration since evaluation of non-radiological impacts in monetary terms is insignificant. The previously described ExternE Project methodology is discussed and the authors notice that apart from direct costs of a severe nuclear accident estimated by the Project, indirect costs should be also taken into account as they will substantially change the accident aftermath. Hence, a multiplying factor of 1.25 is assumed to address the macroeconomic conditions and another multiplying factor of 20 is assumed to reflect risk aversion. These two factors are then used to adjust the ExternE Project calculations which imply a cost of nuclear accident amounts to EUR 0.0046 EUR per kWh (derived from the total nuclear accident cost ECU 83.2 billion as of 1995, divided by electricity output and translated into EUR as of 2011) and a new cost of nuclear accident amounting to EUR 0.12 per kWh is suggested for consideration instead. Furthermore, the authors argue that any country with a nuclear power industry and its neighbours have to bear the incremental costs necessary for preventing and preparing for a nuclear disaster, however yet again such costs are argued to be insignificantly small.

One of the most recent studies attempting to evaluate costs and probability of a nuclear disaster was completed in 2011 by **Versicherungsforen (Insurance Forum) Leipzig**, a spin-off of the University of Leipzig. Appalled by the severity of the Fukushima accident, German authorities raised debate about reliability and safety of nuclear industry in Germany. In fact, the decision of the German government to extend life of the nuclear power plants taken in 2010 was seriously doubted and in June 2011 Angela Merkel announced phasing out nuclear power by 2022, so 17 nuclear reactors have to be closed. Consequently, nuclear power lost its potential in Germany to serve as a bridge technology from fossil fuels to sustainable energy, as it was discussed by the politicians before. In essence, the mentioned study was completed in order to see if the authorities' decision to abate nuclear power is justifiable. Based on the previous research in the field, the authors define the probability and the maximum damages from a nuclear disaster which might happen in any of the 17 nuclear reactors in Germany.

The minimum damage amount is estimated and rounded to be EUR 150 billion. The expected worst case scenario cost from a nuclear disaster, however, is estimated to be EUR 5.9 trillion. Differently from the previous research, this study goes further and calculates an insurance premium which nuclear operators would need to pay in order to cover the maximum damages borne by the third parties in case an accident takes place. For that, the so called Extreme Value Theory is used which, as the authors argue, deals well with events described by an extremely low probability of occurrence and extremely high potential losses at the same time. Running several scenarios with different assumptions regarding operational time period of a nuclear plant, the insurance premium is estimated to lie within the range of EUR 0.14-67.3 per kWh. If this premium is incorporated into the price of electricity generated from nuclear power plants, it would trigger a dramatic price change which would not be desired by consumers. At the same time, having said that, the authors highly question whether it is possible to insure against the nuclear risks due to low insurability of such risks in general.

4.2.2. Probability of a Nuclear Disaster

It was not until the Chernobyl disaster took place in 1986 that the scientific world realized an urgent necessity to reassess the likelihood of a severe nuclear disaster. Indeed, the Chernobyl accident laid solid grounds for elaborated research of reasonable probability to be attributed to a nuclear event of such magnitude. Several nuclear experts took an attempt to look at the Chernobyl disaster retrospectively and to assess its probability. Given the complexity of the disaster consequences and insufficient data released by the Soviet authorities, naturally, a uniform opinion regarding the probability does not exist. Most of the studies find that the value would be greater than 10^{-4}, which is more frequently than once in a 10,000-year operating time, e.g. $2*10^{-4}$ (Hirschberg, Burgherr, & Hunt, 2004) and $3*10^{-4}$ (NEA, 2003b).

What, however, should be kept in mind while assessing probability of the nuclear disaster in Chernobyl is that intricacy of such calculations is aggravated by the fact that the reactor was located in a very peculiar country, the USSR. As it has been already discussed in this paper, development of the Soviet nuclear power industry development was aggressive, and it presumably contributed to the occurrence of the Chernobyl accident. There are at several versions of what could have possibly led to the disaster. The official version publicly spread by the Soviet media after the disaster accused the personnel of the night shift in wrongdoing (Rhodes, 1993). There is also a conspiracy theory which suggests that the reactor design was flawed and that it was known to the authorities who, however, chose to hide it from the reactor personnel (UNICEF, 2007). Indeed, in his book Dyatlov, who was the vice chief

engineer of the Chernobyl nuclear power plant, confessed after the disaster that not only the personnel did not possess all important information regarding the reactor safety, but even the Regulations of the reactor exploitation contained many gaps and contradictions and proved to be useless for managing emergency situations (2005). Altogether, several reports by independent investigation commissions available about the Chernobyl accident, as well as interviews with the personnel who were on duty during that fatal night, suggest that the 4th reactor possibly had an inferior design. They also pinpoint agency problems existing within the highly bureaucratized energy sector. Furthermore, they conclude that information shared between the senior management and regular personnel was highly asymmetric and the response to the problem was slow. While the truth is perhaps still being sealed and buried in the Soviet archives, it is important to realize that the context of the Chernobyl accident is not unequivocal and that most likely it has contributed to the likelihood of the disaster to the extent which, unfortunately, cannot be reliably measured. Another version of the accident stated that the accident could have been triggered by an earthquake of magnitude of 3-4 Richter scale; however, this did not find any proof. An important implication is that given the design of current reactors, qualification of personnel, safety control techniques and readiness to operate in emergency situations, what happened at the Chernobyl nuclear power plant in 1986 would be highly unlikely to happen today.

In his study, Hohmeyer assumes the probability of a nuclear disaster to be within the range of $5*10^{-4}$ to $5*10^{-5}$. The author, however, argues that the upper value is to be used to calculate the most likely cost of nuclear disaster in Germany (Hohmeyer, 1990).

The Phase B of the German risk study on nuclear power plants published by Gesellschaft für Anlagen und Reaktorsicherheit mbH (Society for Plant and Reactor Safety) (1989), or GRS for short, uses Biblis B type reactor to assess the probability on a nuclear disaster, that is, when a major release of radioactive material takes place. The study also distinguishes between two possible scenarios – when accident management measures for backing up security systems in case of emergency, are successfully implemented and when execution of such measures is not done. The suggested probability equals to $3*10^{-5}$ or once in 33,300 operating years if accident management measures do not take place and to $3*10^{-6}$ or once in 280,000 operating years if such measures are taken. Ten years later GRS looks at the German advanced pressurized water reactors and finds that estimated probability attributable to a nuclear disaster is 10^{-8}, which corresponds to one disaster every 100 million years.

ExternE report states that the probability of a nuclear reactor core meltdown is $5*10^{-5}$, or once in 20,000 years of operation. However, assuming that only 19 per cent of the accidents will actually result in the radioactive release, the disaster probability would be more than 5 times smaller, which brings the probability of a nuclear disaster to $9.5*10^{-6}$, or one accident in a time of 105,000 operating years (European Commission, 1995).

An important attempt to assess the probability of a nuclear disaster was undertaken by Versicherungsforen (Insurance Forum) Leipzig in 2011 (Günther, Karau, Kastner, & Warmuth). The authors revise previous studies and claim that many factors have been omitted from the analysis. They further incorporate a whole variety of events and conditions which theoretically increase the likelihood of a nuclear disaster in Germany. For example, the study suggests including ageing of nuclear reactors into account – that is, the older the reactor is, the higher probability of a technical failure is. As all German nuclear reactors were built in 1970-80's, this seems rather logical. Furthermore, a possibility of terroristic attack is taken into account. The authors conclude that a terroristic act is a very real threat, given the fact that many nuclear facilities have already been a target of terrorists and other criminals in several countries. A terroristic attack can take a variety of forms: an airplane can be hijacked and crashed into a nuclear facility or an anti-tank missile can be used. Alternatively, terrorists can conceal their purposes, get employed in the nuclear power plant and organize sabotage from inside. The events of September 11, 2001, in the US indeed proved that the above mentioned threat is a real one and should hence be taken into consideration. Another cause of deliberate damage, according to the study, can be a computer virus. The recent events with the Stuxnet virus attacking the nuclear facility in Iran suggest that a cyber-attack can be a real threat. The authors also discuss a possibility of a human error which might trigger a nuclear disaster. Given the complexity of operation of a nuclear reactor, this threat is very real as well. Finally, a scenario of an earthquake is brought into the general picture which has, for instance, triggered a nuclear disaster in Fukushima in 2011. Altogether, the authors make at attempt to attribute numerical values to these potential threats and thus modify the overall probability of a nuclear disaster in Germany. Their results suggest that a modification factor for the ageing reactor lies in a range 2-18, for computer virus – in a range 1.1-1.5, while a human error is estimated to increase the probability by 1.1. Probability of a terroristic attack is estimated to be 10^{-3}.

The Fukushima nuclear disaster substantially contributed to the understanding of likelihood of such events and raised urgency of reassessing nuclear risks as such. Kenichi Ohmae

(2012), the PhD from the Massachusetts Institute of Technology in nuclear engineering, claims that the Fukushima events has shown that the probability theory fails as it assumes that an accident of that scale is highly unlikely and hence leads to substantial underestimation of the probability value. Indeed, the Japanese nuclear industry seems to have made a poor effort in assessing the probability of a nuclear core meltdown triggered by a natural disaster – obviously, the likelihood of such occurrence was underestimated and could have been anticipated (Perrow, 2011). The area surrounding the Fukushima Daiichi nuclear power plant can be classified as a natural disaster prone area – a long history of major earthquakes and tsunamis suggests that the disaster which took place in 2011 should not come as a surprise. What, however, does come as a surprise is the on-going discussion about the unsafe practices of Japanese nuclear industry among which are data falsification, concealment of nuclear accidents from the public, lack of safety monitoring, etc. While no one knows the truth and Tepco, the Fukushima nuclear power plant operator, still has not publicly given answers to many crucial questions, the report issued by the Japan's parliament brings some clarity into the general picture. According to the report, the main reason of the nuclear disaster roots in Japanese culture itself, or more precisely in reluctance to apply best public safety practices – hence, it is a "man-made" mistake (Telegraph, 2012). Therefore, it is not perhaps the probability theory which has failed but rather the application of that theory because it was adjusted for the specifics of the country. In Japan, where earthquakes and tsunamis are not a rare occurrence, probabilistic assessment, with no doubt, should incorporate all possible triggers and conditions of a disaster of that scale. An important step towards comprehending the probability of a nuclear disaster at the Fukushima Daiichi nuclear power plant was done during the PSAM11 & ESREL 2012 conference hosted by International Association for Probabilistic Safety Assessment and Management and European Safety and Reliability Association in June 2012. Not only have the experts reaffirmed the importance of probability-based risk assessment methods for nuclear power plants around the globe, but they also have developed a list of previously omitted factors which can trigger a nuclear disaster, which must be included into analysis (STUK, 2012). The most straight forward implication should be that hopefully the nuclear industry has learnt a lesson and now it is ready to reasonably evaluate all the risks involved.

4.2.3. Actual Nuclear Disasters

The history of nuclear power generation numbers two events which triggered severe consequences – nuclear reactor meltdowns in 1986 in Chernobyl and in 2011 in Fukushima.

While it seems that it is easier to assess nuclear damage post-factum when fewer assumptions are required and more factual data is available, the reality proves it is not exactly the case.

Quantifying the aftermath of the Chernobyl nuclear disaster has been a very challenging mission for the recognized world nuclear and health authorities. The early studies indicate that the minimum short-term damage would be around USD 15 billion (EUR 22 billion as of 2011), while the long-term damage would lie in the range of USD 75-150 billion (EUR 109-218 billion as of 2011) (Presidential Commission of the USA, 1990). Yuri Koryakin, the chief economist at the Research and Development Institute of Power Engineering of the Soviet Union, predicted the damage for the most radiation affected countries to be around USD 300-350 billion (EUR 437-510 billion as of 2011) within the medium-term period of 14 years after the disaster (Hudson, 1990). However, the early estimations should be considered with caution as they were performed in the lack of reliable data on the accident which the Soviet authorities did not share properly, hence they might not reflect the true impact.

Indeed, as mentioned before, the Soviet Union was not particularly transparent regarding the possible radioactivity amount released into the atmosphere, nor was it cooperative in assessing the damages the accident triggered. This substantially hindered attempts of the world authorities to evaluate the severity of the nuclear disaster and to put a final price on it. An important milestone in the post-Chernobyl nuclear studies was the report **by UNSCEAR** estimating the collective radiation dose to be 600,000 millisievert (mSv) (1988), of which 40 per cent, or 240,000 mSV, was distributed within the USSR. The collapse of the Soviet Union in 1991 marked a beginning of meaningful and so much needed cooperation, whereas World Health Organization (WHO) together with other institutions from the disaster affected areas launched the International Programme on the Health Effects of the Chernobyl Accident (IPHECA). The main goal of IPHECA was to help build capacity for national health care institutions in Ukraine, Belarus and Russia, which were recognized to be the most severely radiation affected countries, as well as to enhance collection of post-disaster data (WHO, 1995). Altogether it took nearly a decade after the Chernobyl disaster to arrive at a preliminary and rather precarious estimation of the individual radiation doses and health consequences, which was documented in the **IPHECA report** (WHO, 1995).

The one and only damage the report studies in detail is the one related to health. The main radionuclides in the radioactive cloud over Chernobyl were Iodine-131, Caesium-134 and Caesium-137. The former one, Iodine-131 despite having the shortest half-life (eight days) had the greatest impact on health of the exposed people: this isotope is accumulated in the

thyroid and causes alterations in its functions which in turn can develop into cancer. The other two radionuclides are known to have longer-term impacts. The report confirms that 444 people were at the nuclear site when the disaster occurred; 2 persons died instantly, 300 were hospitalized and 134 were consequently diagnosed with acute radiation sickness of whom 28 died within the first three months. As a consequence of the Chernobyl disaster, 135,000 people were evacuated, 270,000 people were offered relocation and went through compulsory health monitoring, 580,000 people went through special health monitoring and 4 million people − through regular health monitoring. The IPHECA report concluded with the following findings: a sharp increase in thyroid cancer was detected, especially among children aged 0-14 years living in the contaminated areas; some evidence was found suggesting cases of retarded mental development and behavioural/emotional deviations; no significant increase of leukaemia incidence was observed which, however, as the report argues, may be attributed to short time frame of the study; no increase of oral diseases was detected. Additionally, severe physiological effects were observed which, however, could not be attributed to the nuclear disaster itself but rather to the lack of information the wide public had access to in the first days after the accident, as well as stress from compulsory evacuation and relocation (WHO, 1995).

The so called **Chernobyl Forum**, an initiative by IAEA in cooperation with WHO, United Nations Development Programme (UNDP), United Nations Environment Programme (UNEP) and other organizations, was established in 2002 to enhance clarity on the Chernobyl accident and to assess the associated damage with a strong focus on the socio-economic impact (Chernobyl Forum, 2003-2005). The report also deals with some common beliefs the wide audience formed around the Chernobyl accident. For example, it reveals that only a small portion (around 1,000 people) of nuclear power plant employees and emergency workers who were on the site during and after the accident, received substantial doses of radiation, while the rest of them as well as people living in the contaminated territories were exposed to a radiation dose equivalent to the background radiation accrued over 20 years, which is considered to be reasonably low. Another interesting fact the report mentions is the death toll: it is argued that an opinion that Chernobyl accident caused thousands deaths was severely exaggerated. As the study claims, the wide public mistakenly attributed deaths of emergency and recovery workers to the radiation after the Chernobyl accident, when in fact they resulted from other unrelated natural causes. The report also estimates additional cancer cases − if most radiation-affected people are taken into account (about 600,000 people), up to

4,000 people are expected to develop fatal cancer. While there are still lots of cancer related questions left unanswered up until this day, the Chernobyl Forum report back in 2005 emphasized that the link between the individual radiation doses and additional cancer cases is not obvious, especially when talking about people outside the highly contaminated immediate area; therefore, jumping into quick conclusions should be avoided.

The study confirmed that 4,000 cancer cases detected among children, with the vast majority of them being curable, could indeed be attributed to the Chernobyl accident. However, there is no sufficient basis to suspect that other forms of cancer were triggered by the accident, too. The report also elaborated on accident impact on agricultural areas, forestry, aquatic systems and biodiversity. The study finally concluded that the estimated cost of the Chernobyl accident if accumulated over 20 years and if direct, indirect and opportunity costs of foregone electricity supply are taken into account, would not be less than hundreds billion of EUR, which imposed huge holes in the national budgets of three most affected countries – Ukraine, Belarus and Russia (Chernobyl Forum, 2003-2005).

Surprising it might seem, not so many researchers in late 1980's, throughout 1990's and up until early 2000's tried to elaborately quantify the costs of Chernobyl nuclear disaster. The nuclear disaster of 1986 showed the necessity to incorporate countermeasures, emergency planning and management assessment into the cost analysis, yet it was absolutely clear that those costs are small, if not insignificant, when compared to the health damage. However, while methodology to express health costs and deaths in monetary terms (e.g. based on individual economic contribution as seen in the preceding parts of this paper) was already well developed prior to the Chernobyl in the studies assessing different hypothetical nuclear disaster scenarios, once a real disaster took place, it seems the public resonance and the extent to which this issue was sensitive hindered the attempts to quantify short-term and long-term health consequences. Indeed, nobody really dared to put a price on a human life or health and to arrive on a final cost of the accident (NEA, 2000). The way all Chernobyl-related studies present the accident costs is in form of a huge monetary range whereas the lower and the upper boarders differ at least tenfold. Nevertheless, the studies of the previous two decades indicate that the maximum damage triggered by the Chernobyl accident would not amount less than EUR hundreds billions, most of which is attributable to the costs triggered by health consequences, and this should be viewed as an important milestone in the post-disaster assessments (Froggatt & Carroll, 2010).

Now, 26 years after the Chernobyl disaster, no one still seems to be able to tell with sufficient certainty how much the disaster cost. However, the latest studies in the field suggest some new insights into how the Chernobyl aftermath looks in reality, with a particular emphasis being put on the health consequences.

The **media release by WHO in conjunction with IAEA and UNDP** rang the first bells about the true scale of the disaster already in 2005 by revealing the fact that the predicted 4,000 additional deaths directly attributable to high radiation doses in reality turned into fewer than 50 as of mid-2005 (Finn, 2005). Dr. Burton Bennett, the chairman of the Chernobyl Forum and a well-known nuclear scientist, confirmed: "*This was a very serious accident with major health consequences, especially for thousands of workers exposed in the early days who received very high radiation doses, and for the thousands more stricken with thyroid cancer. By and large, however, we have not found profound negative health impacts to the rest of the population in surrounding areas, nor have we found widespread contamination that would continue to pose a substantial threat to human health, within a few exceptional, restricted areas.*" (WHO, 2012a). The WHO also commented on the 4,000 thyroid cancers triggered by the nuclear disaster – except for nine deaths, all cases turned out to be curable. Altogether, the assessment suggested that radiation-induced increase in cancers does not surpass 3 per cent. This finding came as a big surprise for the general public and it yet again spurred debates regarding whether Chernobyl accident resulted in a significantly higher cancer rate in the contaminated areas. The Linear No-Threshold (LNT) model, widely applied for calculating additional cancers caused by the disaster, predicts high numbers (Günther, Karau, Kastner, & Warmuth, 2011). However, this model employs a linear dose-effect relationship – an assumption which has recently been criticized by several scientists who are convinced there is no basis to claim such linearity. For example, Charles L. Sanders, who has published several books on radiology and cancer, finds that low radiation doses can result in the all-cancer mortality. The author also points out the reluctance of the LNT model advocates to address the biases which the controversial linearity assumption introduces to the analysis. If they had taken effort to finally incorporate new reliable data into the calculations, the results of their assessments would have been much less tragic (Sanders, 2009).

Three remarkable assessments of Chernobyl nuclear disaster followed in 2006, all of them highly criticizing findings by WHO, IAEA and UNDP. The **report by Greenpeace** represents an extensive study on the health consequences of the Chernobyl disaster which people from the radiation affected areas are destined to suffer from for the rest of their lives

(2006). The tone of the report is rather categorical: while the authors claim that the previous studies published by IAEA and WHO substantially understate the number of children thyroid cancers, they also assure that a great variety of other diseases, including leukaemia and other types of cancer, was triggered by the disaster of 1986. The report summarizes quite a number of papers published on the number of expected additional number of fatal cancer cases, whereas the maximum number hits a threshold of 6 million additional deaths from cancer within the next 70 years as argued in the report by the European Committee on Radiation Risk (ECRR) of 2003 as compared to predictions by IAEA and WHO of 4,000 and 8,930 additional fatal cancers respectively. Without putting a final price on the Chernobyl disaster, the report by Greenpeace concludes that the available body of research on health consequences is sufficient to claim that it triggered and will continue to trigger a substantial number of morbidity and mortality in all the contaminated regions.

Another attempt to summarize the extent of Chernobyl disaster damage was undertaken by **International Physicians for the Prevention of Nuclear War (IPPNW)** in the same year (2006) and, similarly to Greenpeace, it yet again suggested that the future would witness a high number of additional fatal and non-fatal cancers, other diseases and health disturbances.

The report called **"The Other Report on Chernobyl" (TORCH)** commissioned by Rebecca Harms, a Green Party member of the European Parliament, added to the critics of the results reported by WHO, IAEA and UNDP (Nuclear Information and Resource Service, 2006). While Michael Mariotte, the executive director of Nuclear Information and Resource Service, called those results a "*political document intended to downplay the on-going consequences of the Chernobyl disaster, presumably for the interest of the nuclear power industry*", Harms noticed that such results was a "dishonour to those who have and will suffer as a result of Chernobyl". Altogether, TORCH predicted 30,000-60,000 additional deaths directly attributed to exposure to high radiation doses during and after the Chernobyl accident.

However, the subsequent years of extensive research conducted to assess the real cost of Chernobyl nuclear disaster suggest that perhaps the extent of the earlier reported number of additional cancers caused by the disaster (up to 6 million as pointed out above) has been exaggerated. It was not until 2011 when amid the 25th anniversary of the most dreadful nuclear disaster in human history and just after another nuclear disaster in the Fukushima Daiichi nuclear power plant took place, new reports by the world recognized authorities were released. Although for example the update by IPPNW (2011) consistently call the results reported earlier by IAEA "obviously wrong" and predicted severe health consequences for

the aftermath of the Fukushima nuclear accident, there are other studies which actually suggest that in reality much less severe health-related damage have been documented than anticipated by many nuclear industry stakeholders and the public.

The **report by UNSCEAR**, which was conducted in close cooperation with nuclear scientists from the most radiation affected countries, reconfirms that radiation doses the general public was exposed to during and after the Chernobyl accident were relatively low and thus people should not "*live in fear of serious health consequences*". The report also concludes that by 2005 6,000 cases of thyroid cancer, 15 of them were fatal, were documented which, in essence, is the only evident and directly health consequence attributable to the Chernobyl nuclear disaster. Overall, the UNSCEAR (2011) study assures that the major damages the disaster triggered are those related to socio-economic losses and psychological impact.

These findings are in line with an independent **research conducted by United States Nuclear Regulatory Commission (U.S. NRC)** which applies a newly developed method called "State-of-the-Art Reactor Consequence Analyses" (SOARCA) for modelling major nuclear accidents and assessing potential health consequences they cause. Although this study does not evaluate the post-Chernobyl damage, it incorporates latest innovative approaches and simulates nuclear disaster in various locations of the US. SOARCA allows concluding that offsite impact such as public health consequences is substantially smaller than estimated in the studies conducted throughout 1990-2000's. Moreover, SOARCA calculates that long-term risk of fatal cancer caused by a nuclear disaster is million times lower than the general risk of a person to develop fatal cancer in the US (U.S. NRC, 2012b).

Probably the latest remarkable report on nuclear disaster costs is the one **published by WHO** after the accident at the Fukushima Daiichi nuclear power plant in 2011. Having gathered together more than 30 competent and experienced nuclear experts, the study evaluates the radiation doses the general public got exposed to during and after the accident. The study concludes that only two locations in the Fukushima prefecture witnessed effective doses within the range of 10-50 mSv while doses in the rest of the prefecture fall within the 1-10 mSv range. The estimated effective doses in the neighbouring prefectures are within 0.1-10 mSv, in other parts of Japan they do not surpass the level of 1 mSv, and in the rest of the world they are less than 0.01 mSv. The presented effective doses are considered to be small and, according to the report, international community should not fear and panic (WHO, 2012b). The **dose assessment undertaken by UNSCEAR's working committee** consisting of roughly 70 nuclear experts confirms the WHO's findings (Brumfiel, 2012). While the

media did remarkable job throughout 2011 informing the public about the massive radioactive fallout triggered by the Fukushima accident, two highly authoritative world institutions have just questioned the massiveness of that fallout and the radiation doses the wide audience got exposed to, so perhaps their voice should not be ignored.

Worth mentioning, in case of the Fukushima nuclear disaster, one of the most precisely calculated nuclear damage costs to the date is the decontamination effort. The short-term clean-up cost has been reported to surpass EUR 2 billion (Times, 2011), whereas the costs over the next 30 years will sum up to EUR 14 billion (Bloomberg, 2011). Even though these values attributed to the decontamination measures seem to be relatively insignificant when compared to the above described health consequences, they should not be neglected. If the previously reported health damage, estimated to be hundreds billions of EUR, is eventually classified as and proved to be a overstated, as several studies have already suggested, the decontamination and similar costs might find themselves in the same cost magnitude range as those connected to health.

5. Third Party Liability and Compensation for Nuclear Damage

Throughout the commercialization process of the nuclear power industry which started back in 1950's, society has become aware of the risks associated with the operation of nuclear power plants. The main concern was the fact that a nuclear chain reaction might go wrong and as a consequence radioactive contamination would spread over a vast territory. Therefore, an urgent necessity for the liability regime emerged, that would guarantee sufficient compensation in case of a nuclear accident and at the same time would ensure smooth development of the promising nuclear power industry. The latter could have been achieved only if private investors were protected from the uncertainty over the amount of liability claims they would face in case of an accident.

Two main conventions were adopted to balance the above stated two needs: the Paris Convention on Third Party Liability in the Field of Nuclear Energy (hereafter the Paris Convention) and the Vienna Convention on Liability for Nuclear Damage (hereafter the Vienna Convention). The fundamentals of these Conventions defined the national legislation in most of the countries which employ nuclear energy technologies (Swiss Re, 2003) (American Nuclear Insurers, 2009) (Froggatt & Carroll, 2010). This section looks at the development of the third party liability laws.

5.1.   Paris and Vienna Conventions

Organization for Economic Co-operation and Development (OECD) shaped the first international nuclear legislation for the third party liability – the Paris Convention, in 1960, which entered into force in 1968 and had fifteen contracting parties[1]. As the Paris Convention was limited only to OECD countries, IAEA tried to unite the rest of the world via the Vienna Convention in 1963 (OECD, 2006a). However, since OECD includes most of the developed Western European countries which also account for the majority of nuclear energy production, the success of the Vienna Convention was far smaller than expected. Not only it came into force only 14 years later, in 1977, but unlike the Paris Convention, it also has not witnessed less development over time (OECD, 2006b).

The Paris and Vienna Conventions are similar and share a number of common features. In case of a nuclear accident, legal and economic liability is channelled exclusively to a nuclear power plant operator. Therefore, the operator should have mandatory insurance to cover the liability amounts defined by the international legislation in case of an accident. Both Conventions imply that only a court of the country where an accident happens has exclusive rights for jurisdiction of the submitted damage claims. Nevertheless, the liability is limited in terms of the amount, time and type of damage with a sole exception when the accident happens due to "*acts of armed conflict, hostilities, civil war or insurrection*" (OECD, 2006a).

However, there are also differences between the two Conventions, whereas the main one roots in the minimum amounts of liability set by the international laws. Under the Vienna Convention the minimum liability amount was initially fixed at USD 5 million, whereas under the Paris Convention the range was Special Drawing Rights (SDR) 5-15 million or USD 5-15 million (as of 1960). The reason for choosing an artificial currency was to eliminate the dependency on one single currency and in such a way to avoid any exchange rate related fluctuations of the liability amount. Once the parties to the Paris Convention realized that this provision would not suffice to cover the costs of a nuclear accident, the amount was amended by the 1963 Brussels Supplementary Convention to provide additional public funds for the compensation. The Installation State, the country where the liable nuclear operator is domiciled, had to ensure SDR 175 million, and the Contracting parties, the countries which signed the Brussels Supplementary Convention, had to provide altogether additional SDR 125 million. The amendment came into force in 1974 with 12 OECD parties

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[1] Belgium, Denmark, Finland, France, Germany, Greece, Italy, the Netherlands, Norway, Portugal, Slovenia, Spain, Sweden, Turkey, the United Kingdom

ratifying it[2] (NEA, 2012b) (OECD, 2006a). Consequently, in countries which are parties to the Paris and Brussels Supplementary Conventions nuclear plant operators were liable for up to SDR 300 million in damage claims if a nuclear accident occurs.

5.2.   Changes in Legislation after Chernobyl Nuclear Accident (1986)

A number of shortcomings of the international legislation on the third party liability became obvious in the aftermath of the Chernobyl accident. First of all, clearly damage caused by the disaster could not have been covered by the liability amounts stated in the Paris, Vienna and Brussels Supplementary Conventions, even if combined together. Secondly, many countries which were pursuing nuclear energy at that time were still not parties to any of the two Conventions, e.g. the USSR. Thirdly, the Chernobyl accident proved that the term "damage" was not well defined and did not incorporate many important aspects. For example, while effect on the agriculture land from the nuclear disaster proved to be substantial, costs related to environment, ecology and preventive measures were not included in the list of the damage. Moreover, victims outside the country of an accident were not sufficiently protected due to the fact that their countries of origin or residence were not parties to the Conventions. Indeed, the neighbouring countries of the USSR, realized that in case of a nuclear accident the consequences were not limited to the geographical borders of one country because radiation spreads over substantial territories. Finally, the time allowed for claiming compensation − 10 years − was too short as some consequences of a nuclear accident, such as cancer caused by exposure to high radiation doses, could not be tracked and estimated immediately or in the short-term (OECD, 2006a). Therefore, having showed the inconsistencies and imperfections in the legislation of those days, Chernobyl accident triggered significant modernization of the two Conventions, which is described below.

5.2.1. Joint Protocol

It was expected that Chernobyl nuclear disaster would induce the USSR and other Central European countries to join Vienna Convention. To further increase the motivation, in 1988 the Vienna and Paris Conventions were linked by the Joint Protocol in order to bring together the geographical scope of the two and to address the lack of membership coverage (OECD, 2006a). The Joint Protocol suggested that if an accident takes place in the country which is party to the Paris Convention, victims in the affected countries are compensated to the extent specified by the Paris Convention, as long as they are party to either of the two Conventions.

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[2] Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Slovenia, Spain, Sweden, the United Kingdom

Analogously, if the accident takes place in the country which is party to the Vienna Convention, specifications of the Vienna Convention are applied under the same condition (World Nuclear Association, 2012e).

The Joint Protocol entered into force in April 1992 and its success was far less than expected because only 18 Central and Eastern European[3] countries joined the Vienna Convention and only 11 countries[4] from those joined the Joint Protocol. The Protocol had theoretically extended the number of people who would be protected in case of a nuclear accident; however the practical implementation was not sufficiently good as it did not address a critical problem of insufficiency of the liability amount (OECD, 2006a) (Froggatt & Carroll, 2010). Hence, a new round of amendments to the Vienna and Paris Conventions was initiated.

5.2.2.   Amendments to Vienna and Paris Conventions

Negotiations on the Protocol to Amend the Vienna Convention (hereafter the VC Protocol) started in 1990 and were concluded seven years later. Among the main changes, the compensation limit was increased from USD 5 million to SDR 300 million (or USD 600 million as of 1991), whereas the country participating in the Vienna Convention could decide whether and to what extent to limit the liability amount for the nuclear power plant operator, or to impose an unlimited liability. However, the amendments explicitly stated that if the state sets the minimum liability amount below the proposed SDR 300 million and a nuclear accident occurs in that country and results into damage exceeding that amount, the state would have to cover the lacking difference (OECD, 2006b). Moreover, the amendments addressed the need to ensure sufficient funds for covering broader territory and bigger range of damages. In addition to this, the period for compensation of personal injury or loss of life was extended from 10 years to 30 years. The damage was supposed to be covered wherever suffered, except for the countries which run nuclear power plants but do not have national legislation ensuring comparable funds available in case of an accident within their territory. Nevertheless, the VC Protocol was not signed by a sufficient number of states. Therefore, it came into force only in 2003, when Argentina, Belarus, Latvia, Morocco and Romania ratified it, which however was very nominal help since these most of these countries have an immature nuclear power industry and some of them do not have it at all (OECD, 2006a).

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[3] Belarus, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Macedonia, Moldova, Montenegro, Poland, Romania, Russia, Serbia, Slovak Republic, Ukraine
[4] Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovak Republic, Ukraine

The Paris Convention was revised in the 2004 Protocol to Amend the Paris Convention (hereafter the PC Protocol) and it witnessed similar changes as the Vienna Convention did, including the broader definition of nuclear damage and geographical coverage, expansion of the time period allowed for making damage claims up to 30 years, as well as higher provision for liability amount. The maximum compensation amount was increased from SDR 15 million to EUR 700 million. The provisions under the Brussels Supplementary Convention were changed, too, whereas Installation State had to provide EUR 500 million, and the public fund, established by the collective state, had to contribute EUR 300 million. Altogether, the amount of EUR 1.5 billion was made available. However, it has not yet entered into force because of lack of quorum: out of eighteen only two countries, Switzerland and Norway, officially accepted the amendments, whereas at least 12 countries are required to pass the amendments (OECD, 2006a).

Perhaps it is exactly the drastically increased liability amounts under both Conventions which hindered a broader ratification process. Unwillingness and/or inability to mobilize the above stated amount of funds to cover damage in case of a nuclear accident have resulted in hesitation to sign the convention and lack of general commitment to address the problem. Hence, while the objectives of both Conventions were obviously to harmonize the legislation and provide a better platform for the stakeholders' collaboration and communication, the reality has showed that these documents just contributed to the confusion and made nuclear operations even more difficult to carry on. Even the Fukushima nuclear accident did not foster the ratification of the Conventions as it was expected. It can probably be explained by the fact that all the direct damage from the disaster was limited to the territory of Japan due to its remote location, and thus it did not affect the neighbouring countries.

5.3.   Levels of Commitment

Despite the doubtful success of the Paris and Vienna Conventions, the general picture of the countries' commitment to adopt some kind of legislation regarding nuclear power industry is not that depressing. In fact, all countries in the world can be divided into three groups with respect to what levels of commitment they have assumed.

First of all, there are countries which simultaneously are party to one of the two international Conventions and have their own national nuclear legislation (e.g. Finland, France, Germany, Russia, and Ukraine), which, however, sometimes clash and add confusion. The nature of national legislations across the countries in this group can be very different, e.g. as little as

EUR 50 million provision is made by the Lithuanian national nuclear law while Germany, Switzerland and Japan demand unlimited liability (Froggatt & Carroll, 2010).

Secondly, there are countries which are not party to any of the two Conventions but they have their own national nuclear legislation (e.g. Canada, China, India, Japan, Korea and the United States). The USA boasts the highest number of nuclear reactors in operation nowadays and it has its own third party liability legislation – Price Anderson Act. It was created in 1957 and amended in the following years. The nuclear operator in the USA is liable for USD 375 million; in addition it should provide USD 111.9 million for the collective industry pool. Given that money is being pooled for 104 reactors, it leaves the US nuclear power industry with a total provision of USD 12 billion (U.S. NRC, 2012c) which is the largest third party liability amount in the world. Perhaps, the fact that the US itself was on the edge of a nuclear catastrophe (the Three Mile Island Accident) made it more eager to secure more funds than any other country in the world does. China adopted the nuclear liability legislation in 1986, called "Reply to the Ministry of Nuclear Industry, The National Nuclear Safety Bureau and the State Council Atomic Energy Board in respect of Handling Nuclear Third Party Liability" (hereafter the 1986 Reply). It was supplemented by "Reply to Questions on the Liabilities of Compensation for Damages Resulting from Nuclear Accidents" in 2007. Chinese legislation has all the main principles of the Paris and Vienna Conventions, however, the minimum provision for compensation was put at a substantially lower level – USD 44 million for the operator and USD 117 million for the State (Zhoua, Rengifoc, & Chen, 2011). This is quite worrying as China has the most number of nuclear reactors under construction – 25, in addition to the currently 14 in operation (Guardian, 2012).

Finally, there are countries which are not party to any of the two Conventions and they do not have their own national legislation on the third party liability. These are countries which have no nuclear power plants on their territories. While it might be reasonable for Australia to abstain from adopting national or international nuclear legislation because its isolated location substantially minimizes risk of being affected by radiation in case a nuclear disaster takes place somewhere else in the world, it is alarming that such countries as Luxembourg and Austria who have boarders with main European nuclear producers, abstain, too.

5.3.1. Commitment of Finnish Nuclear Power Industry

Finland signed the Paris Convention and the Brussels Supplementary Convention in 1972 and 1977 respectively; it was also one of the few countries to sign the Joint Protocol and the PC

Protocol. Moreover, Finland has its own national nuclear legislation, called the Nuclear Liability Act, which was adopted in 1987 and subsequently amended in 1972, 1986, 1989, 1994, 1999 and 2002. Finally the last changes took place in 2005, when the amendments to the PC Protocol and Brussels Supplementary Convention were incorporated into the Nuclear Liability Act. The changes will enter into legal force as soon as both documents are ratified (OECD, 2008). Meanwhile, the Finnish Parliament issued Act on temporary amendment of the Nuclear Liability Act which came into force on January 1, 2012. The Act introduced the unlimited liability of the operator within the territory of Finland and a provision of maximum of SDR 600 million (equivalent to roughly EUR 735 million) for the damages suffered outside the Finnish boarders (Edilex, 2011). In addition to this, under the Brussels Supplementary Convention, all contracting parties have to provide additional SDR 125 million (equivalent to roughly 150 EUR million) in a joint effort (NEA, 2012a). To support the nuclear power industry, Finnish Insurance pool was established in 1956, and in 2002 it was merged with the Swedish and is called Nordic Nuclear Insurers (Atompool, 2012).

5.4.   Opportunities for Nuclear Insurance Industry

As already discussed, the success of the international legislation has so far been quite doubtful. However, the continuously revised and increased third party liability amount is not the only factor contributing to reluctance to ratify the Convention. Another crucial impediment is a lack of a mechanism which would enable mobilization of funds necessary for third party liability coverage in case of a nuclear disaster. As of now, the understanding of what kind of institution could assume a responsibility to collect and manage those funds is very vague. Insurance industry might be a solution as it theoretically has necessary knowledge and capacity to evaluate risks and design the way funds can be accumulated (Froggatt & Carroll, 2010). Indeed, the nuclear power plant operator cannot handle the uncertainty related to the likelihood of a nuclear disaster. In other words, it is not up until the accident takes place when the operator finds him/herself in a big financial crisis imposed by the responsibility to cover the related damage. However, even operating in the accident-free times is very hard due to inability for the long-term financial planning, investments, etc. Therefore, insurance industry would be of great help; nonetheless, despite an already existing track-record of nuclear insurance activities, the required infrastructure for developing a nuclear insurance market is not in place yet. An important issue requiring attention is that a nuclear disaster triggers substantial damage, hence liability amounts due are huge. This means that an insurance institution has to be large and financially strong to be able to afford

paying for the nuclear damage. Another thing is that as of now, insurance companies willing to provide nuclear insurance services are not able to establish a worldwide portfolio to outweigh the implied nuclear risks. In other words, there are not enough nuclear reactors in this world which, given the probability of a nuclear disaster, would be able to secure a sufficient pool of money to cover nuclear damage if a disaster occurs. Therefore, to meet the underlying obligations, not only a nuclear insurance institution has to be large, but it also has to be supported by a range of diversified businesses. Altogether, an individual insurance company is highly unlikely to be able to provide nuclear insurance services; hence there is a need for non-traditional insurance mechanisms and insurance pools (Swiss Re, 2003).

As defined by the American Nuclear Insurers (2009): "[An insurance pool is a] *group of insurance companies that pool assets, enabling them to provide an amount of insurance substantially more than can be provided by individual companies to insure large risks such as nuclear power reactors.*" (World Nuclear Association, 2012f). First insurance pools were created in the mid 1950's and currently there are 26 nuclear insurance pools worldwide. In general, it has been a very good business for the insurers as, in the absence of frequent severe nuclear disasters, all premium collected go directly to the profits (Nuclear Pools, 2012). The first national nuclear insurance pool was established in London, the UK in 1956 and is still functioning as Nuclear Risk Insurers Limited. Other countries which have nuclear installations, designed their insurance pools similarly (World Nuclear Association, 2012e).

6. Cost of a Nuclear Disaster at Olkiluoto-3

As discussed in the Literature Review section, multiple nuclear experts and researchers have attempted to model a nuclear disaster and to estimate the probability of its occurrence and all related costs. Although none of the studies claim to have arrived at the ultimately precise and reliable calculations, they nevertheless provide some valuable insights in how big is the likelihood of such event and what is the potential amount of damage it would theoretically trigger. The gap between what has so far been discovered and learnt about the real cost of a nuclear disaster and what needs to be explored and proved is still tremendous: for starters, as of now even the causality between the high radiation exposure and cancer is not as obvious as many speculative papers try to present it. In reality, no scientific proof exists which would enable us to make this link. The data from the past nuclear disaster at the Chernobyl and Fukushima nuclear power plants is not complete and sufficient and thus does not provide thorough answers. Moreover, since no international agreements have been signed to tap the

global impact of a major nuclear accident, the complete damage amount cannot be calculated. However, all this does not mean that the cost of a nuclear accident is something the researchers should give up trying to study more and deeper. It still remains an intriguing topic and attempts to explore it more should be brought further.

For this paper, Olkiluoto-3 nuclear reactor which will soon be commissioned in Finland was chosen for the reference. This section assumes that the worst possible nuclear disaster occurs at Olkiluoto-3 nuclear power plants and tries to quantify the potential damage it would trigger. Once the damage is calculated, the authors of this paper assess the feasibility of the nuclear insurance.

6.1.   Safety of European Pressurized Reactor Design

Prior to hypothesizing a nuclear disaster at Olkiluoto-3, it is necessary to understand the main features of the reactor in question. The nuclear reactor currently being under construction at the Olkiluoto nuclear power plant is of the EPR design and it belongs to the Generation III. To the date, construction of EPR was approved by safety regulators of Finland (STUK) and French Safety Authority (ASN), whereas the certification process is underway by Health and Safety Executive (HSE) in the UK and Nuclear Regulatory Commission (NRC) in the USA.

The initial EPR design was completed in 1998 when Siemens, Areva and several utility companies of Germany and France joined hands and together leveraged their expertise and knowledge gained from the previous nuclear accidents (Areva, 2010). The Three Miles Island accident put an emphasis on a need to improve design of the control room in order to account for human factors. As a result, EPR interface is fully computerized, but at the same it is time user-friendly and ensures efficient communication between the plant operating system and the employees (Power Engineering, 2011) (Barre, 2012).

The experience accumulated after the Chernobyl nuclear disaster was of utmost importance, too: ever since that accident nuclear reactor design has been constantly evolving. Consequently, modern reactors, including EPR, include the reinforced containment with inner and outer concrete walls 1.3 m thick each. The "core catcher" was also added to retain and to cool down molten corium in case of a partial or a full core melt down, thus bringing radioactive release into the environment to the minimal level. The thick outer shell is able to withstand not only internal high pressure but also the large commercial aircraft crash and external explosions of 10 kilopascal (kPa) explosion pressure wave (UK EPR, 2009a). In addition to this, due to incorporating passive systems and cooling systems which do not need

external power, the EPR design has an improved backup system. The main safety system of a EPR consists of six emergency diesel generators. Moreover, four backup cooling systems are able to shut down the entire plant safely independently of each other. They are located in four different buildings to avoid simultaneous failure and to increase security of shutting down a power plant in case of a disaster (Power Engineering, 2011) (UK EPR, 2009a). Finally, all of these constructions (reactor and fuel buildings, waste storage, four safeguard buildings, two emergency power diesel generators, nuclear auxiliary building and the turbine building) are located on a six-meter thick concrete base mat, resistant to seismic vibrations (UK EPR, 2009a). Therefore, according to Areva reports, EPR reactor would be able to withstand tsunami of magnitude 9.0 Richter scale and a following earthquake similar to the on back in March 2011 in Japan (Reuters, 2011). However, the latter statement has been questioned by Greenpeace which stated that EPR would indeed be able to withstand up to 24 hours without electricity, however the Fukushima accident showed that the power outrage can last for 11 days and it is thus questionable if EPR would be able to resist that long (Greenpeace, 2012).

Another important concern of the EPR design is the interdependence of digital instrumentation and control system (I&C) which was pointed out in a joint letter by STUK, ASN and HSE to Areva in 2009. The safety system and the control platform used for every day operations are interconnected by the initial design and thus might fail simultaneously in case of an accident (ASN, 2012) (Bloomberg, 2010c). Areva took this into consideration and proposed a solution by installing a simple automatic hardwired back-up I&C system that will work autonomously in case a digital system fails (Independent Nuclear News, 2011). So far only French regulators have removed the reservations regarding I&C issue while others continue the technical examination (ASN, 2012). Besides, during the technical assessment of the EPR design, the British Health and Safety regulator identified additional 29 safety issues related to civil engineering, internal/external hazards, structural integrity, electrical engineering, reactor chemistry and human factors. Areva and EDF are working on the plan for resolving these issues and which they will submit to the authorities according on the predetermined schedule (Independent Nuclear News, 2011). Several problems related to the civil construction work were also identified by the safety authorities of Finland and France. Deformations in the concrete foundation of containment building and the welding of steel on the Olkiluoto-3 and Flamanville-3 have been found. Consequently, STUK and ASN suspended all the construction work until Areva and EDF submitted plans for improvement of construction quality control (World Nuclear News, 2008) (Thomas, 2010).

Nevertheless, despite the technical concerns, it is important to remember that all the discussed improvements in the EPR safety design made it possible to decrease the probability of a nuclear disaster to $6.1*10^{-7}$, which is by a factor of 10 lower than that of the formerly designed reactors (UK EPR, 2009b) (Areva, 2009). Therefore, it is widely accepted that EPR has one of the safest designs developed to the date, and it is ready for the commercialization (Time, 2009).

6.2.   Assessment of Damage Caused by a Nuclear Disaster

Following the suit of the previous studies, this section presents an attempt to hypothesize a nuclear disaster at the Finnish nuclear reactor, Olkiluoto-3, and to quantify the damage it would result into within the territory of Finland. The worst case accident is considered in the calculation, that is INES level 7 accident classified as "Major Accident". The calculations are built upon the list of possible nuclear damage summarized in the NEA report (NEA, 2000). Once the costs of the hypothetical nuclear disaster are evaluated, the feasibility of nuclear insurance is assessed. It should be noted that this paper considers only those costs borne by the third parties, which are privately insurable. Hence, the original list of types of nuclear costs compiled by NEA (2000) was reviewed and only those costs which can possibly be insured were taken into account. Once the annual insurance allocation is found, it is divided by the total annual power generation capacity (in kWh) of the Olkiluoto-3 nuclear power plant in order to see the annual per one kWh insurance premium. This will provide grounds for further discussion about feasibility of the nuclear disaster insurance. A sensitivity analysis will be introduced in order to see how the costs and the calculated annual insurance allocation change in response to modification of underlying assumptions.

It should be emphasized that calculations presented in this section do not claim to be completely accurate, exhaustive and reliable. Given the lack of consensus on estimating nuclear disaster costs even among the world top nuclear experts, this paper does not have an ambition to find the ultimate truth. One should rather view it as an attempt to hypothesize the economic consequences of a nuclear disaster at a specific nuclear power plant within geographical borders of one country, which altogether will subsequently provide an opportunity to assess the current status of the nuclear power industry and to derive valuable implications for the involved stakeholders, including but not limited to the nuclear insurance industry.

6.2.1. Description of Data

Several sources were used to obtain the data necessary for calculating the costs of a hypothetical nuclear disaster at the Olkiluoto-3 nuclear power plant. All economics related inputs (e.g. population, gross domestic product (GDP), average wage) were taken from the Statistics Finland database. STUK was used for gathering all information related to the Olkiluoto-3 nuclear reactor and legislation on construction and operation of a nuclear power plant in Finland. The distances between Olkiluoto-3 and nearby cities Turku and Tampere were identified using Google Maps application. Gardiner & Theobald, an international construction consultancy company, and KTI, a national provider of independent research and analysis services for the Finnish real estate sector, were chosen for collecting data on retail/office/industry space per person and construction costs of those in Finland. Social Insurance Institution of Finland (Kela) and Cancer Society of Finland were used to define necessary medical costs and cancer treatment costs, respectively. The rest of the data was obtained from the following sources: Finnish fuel price tracking web site Polttoaine.net, bus hiring company Mennaanbussilla, cost of living database Numbeo.com.

The main limitation of the data collected roots in the fact that various sources used do not necessarily observe the same data collection methods. Moreover, while the year 2011 was chosen to be the reference year, it was not possible to obtain all needed data for that year. In cases when the data was not provided for 2011, the last given data was brought to 2011 by the means of inflationary adjustment. Finally, often regional data was not available, thus the data for the Western region where Olkiluoto-3 is located or the national averages were taken as the best proxy.

6.2.2. Applied Methodology

Despite the lack of a uniform widely recognized list of nuclear disaster costs, methodology for assessing some particular types of costs is well developed. As it has already been mentioned, the report by NEA (2000) Methodologies for Assessing the Economic Consequences of Nuclear Reactor Accidents suggests to the date one of the fullest list of nuclear costs. In essence, the list consists of seven types of costs which supposedly cover all issues emerging before, during, immediately after and in the long-term after a nuclear disaster (see Appendix 4). This paper adopts the list as a main reference point for this research aimed at identifying costs triggered by a nuclear accident. However, only two types of costs are considered for the calculations of damage associated with a theoretical Olkiluoto-3 nuclear disaster: the application of countermeasures to reduce doses and radiation-induced health

effect in the exposed population. This can be explained by the fact that, as the NEA report states, there is no readily available methodology for dealing with the other five types of costs and developing such methodology is not within the scope of this given paper. Moreover, according to the Finnish nuclear law, these costs are not included in the definition of nuclear damage. Although the extended definition of nuclear damage includes certain types of economic loss and reinstatement of impaired environmental in the amended 2004 Paris Convention Protocol (NEA, 2004). However, Finland has not ratified it yet, hence such costs are excluded from the compensation systems, and thus would not be subject to insurance premium. Since this paper focuses only on the costs which are insurable, the mentioned five types of costs do not qualify for the analysis, which also intuitively makes sense as there is no any comprehensive way to insurer again such abstract occurrences as fear, depression, long-term socio-political turbulences, ecological catastrophes, etc.

Due to the fact that the NEA (2000) paper has a purely descriptive character and does not offer any elaborated methodology on how to proceed with estimating the nuclear damage, other sources were used for identifying the most appropriate approaches. As thoroughly discussed in the Literature Review section, previous studies on consequences of a nuclear disaster primarily focus on the health impact while other types of impact are studied to a much smaller extent. Therefore, Hohmeyer's approach (1988) used as a basis for many subsequent studies, is adopted for assessing the health impact while the estimation of the countermeasures to reduce radiation doses is based on the authors' own assumptions and methods.

The assessment of the insurance feasibility is based on the study by Versicherungsforen Leipzig (Günther, Karau, Kastner, & Warmuth, 2011), described in the Literature Review section. It should be explicitly stated that the authors of this paper do not have either the capacity, or the objective to calculate a nuclear insurance premium which the operator of Olkiluoto-3, TVO, would need to pay in order to cover the third party claims. The feasibility of nuclear insurance is assessed in the following way: the total amount of the calculated nuclear damage is spread over the life-time of the reactor to see the annual allocation one would need to make in order to accumulate the amount necessary for covering the damage. It is later expressed in the EUR per kWh value which gives a preliminary understanding of whether the number falls within the feasible range, and in fact it yields the highest possible amount of an insurance premium an insurer would charge, assuming the same time period. In reality, an insurer would proceed with the calculations and adjustments which would take into

account the extremely low probability of a nuclear disaster occurrence. Therefore, an insurer would arrive at a substantially lower value than the one calculated in this report.

6.2.3. Limitations of the Analysis

As stated above, the calculations presented in this paper should be viewed as rough estimations only and the authors are aware of that they are not flawless and they fully admit that. A complex nature of a nuclear disaster imposes lots of limitations to any study of that kind as a whole set of highly uncertain assumptions has to be done which, if done imprecisely, leads to very imprecise results too. The lack of uniform comprehensive methodology on how to capture and estimate the impact of a nuclear disaster is another significant problem. For example, while it is clear that a nuclear disaster would trigger certain ecological, environmental, psychological changes, it is still not certain how to quantify those.

Furthermore, if the release of radioactive material takes place into the environment, consequences of such nuclear accident are not limited to one country only: radiation does not recognize geographical borders and contamination area is dependent on different exogenous factors, such as, for example, the direction and strength of wind. Coupled with a fact that radiation is invisible to the eye and might not be expected in other countries unless authorities of the country where the accident takes place share proper and timely information internationally, this feature of the radiation makes it extremely difficult to have an accurate estimation of the costs implied. However, even if symmetric information about the accident among the countries is assumed, costs of nuclear accidents cannot be compared across the countries involved due to the country-specific issues. Another limitation is imposed by the fact that some costs occur in the short term, usually within one year after the accident, while others, such as latent cancer cases, emerge later in time. Therefore, estimations become more complicated as time goes on and as discounting factor has to be incorporated. Coupled with the fact that cost calculations are sensitive to assumptions regarding the discount rate, cost evaluation process can be misled. Finally, additional effort needs to be undertaken to avoid double counting, for example in case of cost of damage and cost of replacement of the assets.

Calculations of expected value of a nuclear disaster are limited, too, due to the complex nature of the implied probability. One limitation roots in the fact that the likelihood of a nuclear disaster is perceived differently by experts and general public. While experts assure that no relevant inferences can be made for the probability assessment for today's nuclear reactors in Western Europe from the Chernobyl disaster in 1986 because what happened in

that case cannot possibly occur here, the lay public who is generally has less expertise in nuclear energy has a different opinion with that respect.

Another issue is there are two types of risks for any given nuclear power plant: those which are related to the nuclear reactor and the facility itself and are thus endogenous for the nuclear site, and those which are not related to the nuclear site and hence are exogenous. Endogenous risks describe probability of a nuclear accident due to a mistake in the design and/or construction process of a nuclear site, a technical failure of a reactor or equipment, errors of the personnel and similar. This probability is relatively straight forward to calculate because the causes of a possible reactor core meltdown or other malfunction are reasonably known. Exogenous risks describe probability of a nuclear accident triggered by any reasons and events which are not related to the operation of the reactor and the nuclear site and hence they are much more complex to deal with. Most often, naturally, such exogenous risks have to be left unaccounted as there is no possible way to incorporate all of them into the analysis. Finally, nuclear risks should be viewed through a prism of whether the accident is indeed accidental or it has deliberate causes behind it.

Regarding the assessment of the nuclear insurance feasibility, one should realize such analysis is limited too. Nuclear insurance industry is not yet well established and there are many on-going discussions about whether nuclear risks are insurable in the first place. Therefore, this paper is one of the pioneering attempts to raise a constructive discussion.

6.2.4. Quantifying Costs of a Nuclear Disaster

This section presents calculations of the maximum potential damage of a nuclear disaster at Olkiluoto-3 nuclear power plant. As discussed above, two types of costs are considered for the calculations: countermeasures to reduce doses are assessed first and costs associated with radiation-induced health effects among the population exposed to radiation release.

Application of Countermeasures to Reduce Doses

According to the Finnish Ministry of the Interior Order, the emergency planning zone for Olkiluoto-3 nuclear power plant extends up to 20 km around the plant and it is required that a detailed rescue plan is developed for this area. Hence, the calculations are based on the assumptions that in case of a nuclear disaster the area lying within the 20 km radius should be deserted, e.g. population should be evacuated, businesses and industrial facilities should be relocated and agricultural products should be banned. One year is assumed to be sufficient for complete relocation of residential, commercial, office and industrial space.

Population movement

Even though the full version of the rescue service plan for the emergency preparedness area is not publicly available, it is widely known that the plan describes how the authorities should mobilize their resources in order to evacuate the population within the 20 km radius at a reasonable quick pace when the conditions dictate so (STUK, 2000). There are two major population centers in the close proximity to the Olkiluoto-3 nuclear power plant – Rauma and Eurajoki, respectively 13 and 16 km away from the site. According to STUK estimates, there are 46 000 people living within the 20 km radius from the Olkiluoto power plant (2009). It is assumed that in case of a nuclear disaster, when evacuation takes place, people will not be able to return to their homes and they will need to be relocated somewhere else, which should be fully compensated by the liable party.

- **Transport away from the affected area and supervision of the evacuated area**

Assuming that the emergency plan developed for Olkiluoto-3 nuclear power plant is accurate, evacuation of the population inhabiting the area within the 20 km radius around the site will be completed in 24 hours after the disaster takes place. Given there are 46,000 people requiring evacuation, around 2,000 people per hour should be ready to leave the area. It was estimated that 920 buses with a loading capacity of 50 people each would be necessary for the evacuation operation. Each bus would be used for 24 hours and would make two fully loaded trips to the nearest cities – Turku (110 km away) and Tampere (150 km away). A fully loaded bus means 25 people and luggage which they will be allowed to pack swiftly in this emergency case.

Additionally, as suggested by NEA study (2000) the supervision of the evacuated area is included into the overall transportation costs. Assuming that one person will be hired per 230 people subject to evacuation, in total 200 people will be hired to fulfil the supervisor's duties and they will be paid a country-average hourly wage.

Altogether, the transportation costs associated with the evacuation of 46 000 people living in the 20 km radius from Olkiluoto-3 sum up to approximately **649,000 EUR** (see Appendix 5, Table 1).

- **Temporary accommodation and food**

After the evacuation people have to be accommodated for a short term at first. Although definitely some evacuated people would be able and willing to stay with their friends and

family members who live outside the emergency area, following the worst case scenario logics, it is assumed that all 46,000 people have to be provided a temporary accommodation. Furthermore, it is assumed that the temporary accommodation is needed for one month, and for that matter a hotel is chosen as an accommodation option. The average hotel price in 2011 in Finland was 90 EUR per night per room (Statistics Finland, 2012a). It is assumed that every person will be accommodated in a separate room. Although this might not be a realistic assumption since many people would most likely prefer to stay with a friend or a family member, however, sharing the same room for a month can be psychologically difficult. This assumption is also in line with a goal to calculate the maximum possible cost imposed by the nuclear disaster. Therefore, altogether the temporary accommodation costs sum up to **124 million EUR** (see Appendix 5, Table 2).

The food expenses for the first two weeks are included into the calculations. As suggested by NEA study (2000), these costs should not be included as food expenses are the general expenses of people, which should not differ very much within Finland, either it is Rauma or Turku. Nevertheless, first fourteen days people are assumed to be fed and the costs are 6.85 EUR/person that are needed for a balanced diet (2000 kcal/day) (Numbeo, 2012). Altogether the total costs associated with short term accommodation and food is circa **4.4 million EUR** (see Appendix 5, Table 3).

- **Monitoring of people's health**

Evacuated people need to go through a health check, hence at least one visit to a hospital is required. A 20-minute visit to the general practitioner costs 27 EUR (Kela, 2012), which sums up to approximately **1.24 million EUR** (see Appendix 5, Table 4).

- **Loss of income**

The best proxy of income is assumed to be GDP. There are at least two approaches which allow approximating the income lost due to a nuclear disaster. The first one is to take a GDP per capita value and multiply by the population which is relocated from the 20 km radius area. The second one is to take a GDP per square kilometre value and multiply by the area (expressed in km) within the 20 km radius. The loss of income (in form of wages, corporate and municipal income, rents, etc) is calculated for the one year which as mentioned before is necessary for full relocation. Both approaches are applied, the first approach yields a result twice as high as the second approach yields. Nevertheless, following the logics of the worst

case disaster scenario, the highest cost is considered to be a rough estimate of the GDP loss – **1.66 billion EUR** (see Appendix 5, Table 5).

- **Loss of capital**

It is assumed that all real estate abandoned within the 20 km radius around the Olkiluoto-3 due to the relocation will be replaced, that is equivalent amount of space will be built somewhere else to accommodate needs of evacuated people, corporate sector and alike. Data on the average area of each type of real estate in square meters per person is publicly available and was obtained for the sake of this calculation. The space per person value is consequently multiplied by the number of evacuated people and the total area of each real estate type which needs to be replaced is defined. The construction cost of 1 square meter of different real estate types is also publicly available. It was obtained and multiplied by the total number of square meters which are needed to be built in order to fully replace the foregone properties.

The average residential space per person is 39 square meters; assuming every relocated person needs to be provided with this space, roughly 1.8 million square meters have to be constructed. The assumed construction cost of the residential space is 2500 EUR per square meter, which altogether brings the total construction of new residential space to 4.5 billion EUR (Gardiner, 2011) (Statistics Finland, 2009). To double check this, another calculation method is applied to estimate the total cost of residential space which has to be additionally provided. In Finland, around 75 per cent of population lives in a household of an average size of 2.79 people, the remaining 25 per cent represent the 1-person households (Statistics Finland, 2012b). If the same living pattern is assumed to be preserved, 46,000 evacuated people will need 23,866 new flats. The cost of a flat in the municipality with 20,000-50,000 inhabitants has the price index for a dwelling of 1,703 EUR per square meter in the Western part of Finland and the average floor flat area is 79 square meters (Statistics Finland, 2012c) (Statistics Finland, 2009). Therefore, the total cost of additional residential space amounts to roughly 3.2 billion EUR. Yet again, following the logics of the maximum cost, the higher value is considered, that is the construction cost of new residential space amounting to 4.5 billion EUR. Also intuitively it makes sense as it is highly doubtful that in case of a nuclear disaster at Olkiluoto-3 the residential real estate market of Finland would be able to provide 23,866 flats straight away – definitely, at least some construction of new residential space would take place in order to meet the unexpected demand.

Additionally, each of new flats needs to be fully furnished and ready for moving in. Therefore, a consumer durable goods allowance amounting to 10,000 EUR is assumed to be provided for each new flat, which in this case is a proxy of a new household. Additionally, every evacuated person is offered a personal expenditures allowance amounting to 5,000 EUR in order to buy new clothes, personal care items and similar. Altogether, the costs of new residential space and allowances for settling down sum up to **4.95 billion EUR** (see Appendix 5, Table 6).

Analogously, the replacement costs for the real estate in different real estate segments (office, retail, industrial) were calculated. Due to limited data, the refurbishment of the newly built space is not included into the analysis. Altogether these costs amount to approximately **192 million EUR** (see Appendix 5, Table 7).

Finally, the construction cost of the waste disposal on the territory of Olkiluoto power plant is considered as it represents an investment which in case of a nuclear disaster will not be fully recovered. At the moment it is already under construction and its total cost is estimated to be **3 billion EUR.**

- **Psychological effects of worry and upheaval**

These costs are considered to be non-quantifiable and non-insurable due to the lack of comprehensive methodology to assess and put a price to such abstract concepts as people's emotions and feelings. Different sets of values and beliefs among people do not let to come up with a standardized approach to quantify such things. Therefore, these costs are not included into the calculations in this paper.

Agricultural restrictions and countermeasures

There are no significant farming sites within the radius of 20 km around the Olkiluoto nuclear power plant (STUK, 2008). Moreover, all major GDP contributions within the affected territory have been already included in the calculations of income losses under subsection a); hence double-counting should be avoided.

Decontamination

The decontamination costs are difficult to estimate prior to the actual accident, therefore, a reference is made to the recent disaster at the Fukushima nuclear power plant which decontamination process cost was reported to be around **2 billion EUR** (Times, 2011). Even though the magnitude of consequences in case of Olkiluoto-3 is expected to be smaller due to

lower population density as compared to prefectures surrounding the Fukushima Daiichi nuclear reactors, this paper uses this full amount for calculations yet again as a worst-scenario number.

To sum up, the total cost of countermeasures to reduce doses appears to be approximately 12 billion EUR.

<u>**Radiation-induced health effects in the exposed population**</u>

The total costs related to radiation-induced health effects represent a sum of direct costs of fatal and non-fatal cancer treatment and indirect health costs which are less obvious than the direct one but which at the same time are expected to be much more severe. The indirect costs are economic costs the society would have to bear in case of a nuclear disaster from the fact that many people with dramatically affected health would not be able to work. In other words, these costs represent a sum of all economic contributions which people who develop cancer will not able to make. For the sake of calculating direct and indirect costs, Hohmeyer's study (1988) is used. Even though the study assesses solely the indirect health costs, the introduced assumptions are found to be valid and useful for assessment of the direct costs.

The underlying assumptions in the Hohmeyer's study of 1988 are as following: the total person-sieverts radiation dose is assumed to be 2,400,000 which was the radiation dose reported by the Soviet authorities after Chernobyl; 10 per cent risk of getting cancer which lies within the range of 2-74 per cent according to International Commission on Radiological Protection; 10 factor to account for higher population density in Germany as compared to Chernobyl; 10 years of employment foregone in case of a non-fatal cancer; 20 years of employment foregone in case on a fatal-cancer; 50% mortality rate in case of cancer. With a single exception for the factor to account for different population density which in this paper is assumed to be 0.8 as population density around Olkiluoto-3 is lower than in the immediately affected area of Chernobyl, all other assumptions made by Hohmeyer are observed.

The computation of direct costs is rather straight forward. It is assumed that cancer can be treated in one year. The number of additional cases of cancer is found to be 240,000; the average cost of cancer treatment is known – 30,000 EUR (Cancer Society of Finland, 2012). Altogether, the direct health costs are estimated to be **5.76 billion EUR** (see Appendix 6, Table 1).

The computation of indirect costs is more cumbersome as it involves a longer time horizon which in turn requires that discounting principles are used.

The long-term inflation rate in Finland is assumed to be 1.6 per cent based on the 20-year historical average (Worldwide Inflation Data, 2012). The discount factor is assumed to be 2 per cent, which is the 2012-year average yield of the Finnish government bond with 10 years to maturity (Bloomberg, 2012). In fact, this yield is a proxy of a risk-free rate. Perhaps the real discount factor analysts would use in their assessments of Finnish financial market would be higher as it would also incorporate the market premium, which in this case is assumed away. However, consistently with the attempt of this paper to calculate the maximum possible damage a nuclear disaster at Olkiluoto-3 would trigger, a smaller discount factor means less discounting, hence, higher costs. The annual salary in Finland as of 2011 was 36,480 EUR (Statistics Finland, 2012d) and it is assumed to grow along with the anticipated long-term inflation rate.

Net Present Value approach is used for estimating the cost of cases of non-fatal and fatal cancer, whereas the year of the accident is omitted from the analysis. This is done in order to avoid double-counting as the foregone wages of the first year after the accident have already been incorporated into the loss of income. Altogether the indirect health costs are estimated to be **100 billion EUR** (see Appendix 6, Table 2).

Summing up the direct and indirect health costs brings the total costs of the radiation-induced health effects up to roughly 106 billion EUR.

Worth mentioning, a year later after his first study was published Hohmeyer suggested that the person-sieverts radiation dose should be increased from 2.4 million to 12 million. This was based on the results suggested by the German Risk Study on Power Plants, Phase B which suspected that the Chernobyl radiation release was five times higher. Should this assumption be incorporated into the above calculations, the total costs of the radiation-induced health effects surpass **528 billion EUR**.

To provide a sanity check for the above calculations of the radiation-induced health effects, Ottinger's calculations (1990) which are based on the hedonic pricing method, were reconstructed as well. The total costs of the radiation-induced health effects reach **570 billion EUR** (see Appendix 6, Table 3).

Thus, the total cost of a nuclear disaster at Olkiluoto-3 sums up to be:

- 118 billion EUR if Hohmeyer's assumptions from year 1988 are assumed to be correct;
- 540 billion EUR if Hohmeyer's assumptions from year 1990 are assumed to be correct;
- 582 billion EUR if health costs are calculated according to Ottinger.

6.2.5. Expected Value of a Nuclear Disaster and Insurance Liability Allocation

The expected value of a nuclear disaster is calculated as total cost of the disaster multiplied by the probability of an accident. The probability of a core damage frequency at Olkiluoto-3 is estimated to be $6.1*10^{-7}$ (UK EPR, 2009b). However, since the EPR reactor design is still going through the process of upgrading, it was conservatively decided to increase the probability to $6.1*10^{-6}$, which also is in line with the ExternE and GRS assumptions, as discussed in the Literature Review section.

Thus, the expected value of a nuclear disaster at Olkiluoto-3 is estimated to be:

- 717,000 EUR if Hohmeyer's assumptions from year 1988 are assumed to be correct;
- 3,296,000 EUR if Hohmeyer's assumptions from year 1990 are assumed to be correct;
- 3,550,000 EUR if health costs are calculated according to Ottinger.

The total annual power generation capacity of Olkiluoto-3 is expected to be roughly 14 TWh. When expressed in the per kilowatt hours (kWh), the defined set of expected values yields the following results:

- 0.000051 EUR/kWh if Hohmeyer's assumptions from year 1988 are assumed to be correct;
- 0.000235 EUR/kWh if Hohmeyer's assumptions from year 1990 are assumed to be correct;
- 0.000254 EUR/kWh if health costs are calculated according to Ottinger.

In theory, the expected value would be the starting point for an insurer for estimating the nuclear insurance premium he/she would need to charge a nuclear plant operator in order to provide a damage coverage in case of a nuclear disaster. In reality, however, it is not that straight forward – when assessing the so called Damocles risks, whereas the probability of occurrence is extremely low but the damage is extremely high, multiplying the probability by the estimated damage does not give an answer. Hence, the insurer would make further

adjustments which would enable the coverage of the damage in the case of an accident. Therefore, the calculated expected value of EUR per kWh represents a preliminary assessment of what a nuclear premium would potentially look like before all the insurer's considerations are properly taken care of.

To further increase the understanding of whether nuclear insurance is feasible, the annual allocation is calculated which would ensure accumulation of funds necessary to cover the damage triggered by a nuclear disaster. The study by Versicherungsforen Leipzig (Günther, Karau, Kastner, & Warmuth, 2011) discussed in the Literature Review section represents an attempt to calculate a nuclear insurance premium for German nuclear reactors. It assumes a 2 per cent actuarial interest rate and lets the crediting of interest happen at the year end. The time period assumed by the paper varies from 10 to 100 years. In order to make a preliminary estimation of what is the highest possible nuclear insurance premium would be for the case of Olkiluoto-3, the authors of this paper adopt the same assumptions regarding the actuarial interest rate and the time of the interest crediting. The authors assume 60 years to be the accumulation period, which is the estimated lifetime of an EPR. The future value approach is used to find what annual premium payments should be made in order to accrue the necessary coverage amount at the end of the selected period. However, it should once again be emphasized that the full-scale calculation of a nuclear insurance premium an insurer would charge the operator of the Olkiluoto-3 reactor is beyond the scope of this paper and, hence, does not take place. Assuming that the identified earlier damage amount is insurable, the following annual insurance allocations are derived:

- 1.03 billion EUR if Hohmeyer's assumptions from year 1988 are assumed to be correct;
- 4.74 billion EUR if Hohmeyer's assumptions from year 1990 are assumed to be correct;
- 5.11 billion EUR if health costs are calculated according to Ottinger.

When these annual insurance allocations are expressed on a per kWh basis; they yield the following results:

- 0.074 EUR/kWh if Hohmeyer's assumptions from year 1988 are assumed to be correct;
- 0.339 EUR/kWh if Hohmeyer's assumptions from year 1990 are assumed to be correct;

- 0.364 EUR/kWh if health costs are calculated according to Ottinger.

The calculations presented above give an indication of what range the damage from a hypothesized nuclear disaster at Olkiluoto-3 can possibly fall into, as well as they show what implied expected value of the disaster and annual insurance allocations would be like. The next section of this paper will question the assumptions made here, perform a sensitivity analysis intended to assess the impact of different assumptions on the final results, as well as it will compare the results to the previous studies and discuss where the differences in findings might come from.

6.3.   Discussion of Results and Sensitivity Analysis

As the frequency of nuclear disasters is low and statistics on real damage is lacking, this paper attempts to make the best use out of the research available in the field. However, the studies on nuclear accidents which have been conducted up to date are often based on ambiguous assumptions and doubtful methodologies – an issue which has already been addressed in the Limitations part. Nevertheless, given the complex nature of a nuclear disaster, the uncertainty is a factor which in this case is impossible to mitigate fully. Therefore, an analysis performed by the previous researchers in general and in this paper in particular still gives a useful insight into the magnitude of costs a severe nuclear accident can trigger, and in such manner it serves as a good starting point for the discussion. It should, however, be clarified that the differences in methodologies used for conducting the analyses make the cross-paper comparison difficult and, to some extent, unreliable. Thus, it is not the absolute numbers which should be viewed as crucial, but rather the general trend they shape. All the numbers presented below are translated into the 2011-year values.

Discussion of the Results

The calculations of the maximum damage a nuclear disaster at the Olkiluoto-3 reactor can possibly cause within the territory of Finland concluded with a range of EUR 118-582 billion, of which countermeasures to reduce radiation doses (EUR 12 billion) comprise 10% at a maximum. Naturally, this result does not give a clear picture because, for example, EUR 200 billion and EUR 500 billion, while being within the same range, represent a substantial difference, which the stakeholders of the nuclear power industry would certainly like to know more precisely. Unfortunately, given the complex nature of a nuclear disaster and lack of consensus on how to measure the nuclear damage, this may well be the best available answer for today. While the absolute numbers perhaps do not yield the ultimate truth, what, however,

is important is that the obtained range of EUR 118-582 billion is substantially lower than similar calculations of other researchers. For instance, Sandia National Laboratories (1982), Hohmeyer (1988) (1990), Ewers & Rennings (1991), Versicherungsforen Leipzig (Günther, Karau, Kastner, & Warmuth, 2011) obtain results which altogether form a range of EUR 1.2-8.28 trillion if translated into the 2011-year values. Even though the majority of the above researchers base their studies on the German nuclear reactors while this paper refers to the Finnish Olkiluoto-3, even intuitively the difference in the results is tremendous. However, once the approaches used in the mentioned studies are examined, it becomes clear where the difference might have come from. The Sandia National Laboratories evaluate the nuclear disaster cost to be around USD 694 billion in 1982. However, when adjusted to 2011-year value, it yields EUR 1.2 trillion. Hohmeyer' study (1988) predicts that 2.4 million of additional cancer cases would be triggered by a nuclear disaster in Germany. Ewer & Rennings (1991), in essence, replicate Hohmeyer's approach but go even further with respect to the assumption of an additional number of cancer cases – they assume it to be twice higher. Given the findings presented in the newest research on the consequences of nuclear disasters by WHO in conjunction with IAEA and UNDP (Finn, 2005), (WHO, 2012a) and UNSCEAR (2011), also discussed in the Literature Review, these assumptions seem to be exaggerated. Therefore, there is a reasonable doubt that the final results of these authors are reliable. The study by Versicherungsforen Leipzig (Günther, Karau, Kastner, & Warmuth, 2011) suggests that a nuclear disaster in Germany might trigger roughly EUR 6 trillion of the disaster related damage. Despite the fact that it is a relatively new paper, it does not pursuit an independent evaluation of the nuclear damage. Instead, based on the assumptions from the previous papers, including those by Hohmeyer, Ewer & Rennings and others, the authors derive twenty amounts of nuclear damage which are subsequently used for calculating one single final amount. In fact, a weighted average is used, whereas 50 per cent share is allocated to the highest cost, found to be EUR 7.5 trillion, which altogether perfectly explains how such high total cost is obtained.

Some studies arrive at a range of the maximum nuclear damage which is comparable to the one obtained in this paper. The estimated EUR 629 million nuclear costs by Ottinger et al. (1990) do not lie far from the upper boundary of the cost range found in this paper – EUR 582 billion. The ExternE Report (European Commission, 1995), however, estimates the total cost of the most severe nuclear disaster to be around EUR 114 billion as of 2011, which appeals to the lower boundary of the same cost range – EUR 118 billion. The costs caused by

the Chernobyl nuclear disaster found by such reports by Presidential Commission of the USA (1990), Hudson (1990), (Froggatt & Carroll, 2010), Chernobyl Forum (2003-2005), advocate the lower boundary, too.

There is one study discussed in this paper – the one undertaken by Versicherungsforen (Insurance Forum) Leipzig in 2011, which goes beyond evaluations of the cost of a nuclear disaster and attempts to estimate a potential insurance premium an operator of a nuclear reactor would need to pay in order to cover all costs related to a disaster. When expressed on the per kWh basis, the nuclear insurance costs are estimated to lie within the range of EUR 0.14-67.3 per kWh, with the assumed time periods necessary to accrue the liable amount varying from 10 to 100 years. The current paper makes an attempt to assess the feasibility of nuclear insurance, too. When the probability of a nuclear disaster at Olkiluoto-3 power plant is assumed to be $6.1*10^{-6}$ the expected value of a disaster is estimated to be within the range EUR 0.717-3.55 million, or EUR 0.000051-0.000254 per kWh, which appears to be insignificantly small numbers. Furthermore, allocating 60 years for accumulation of the necessary funds, this paper finds an amount of an annual insurance allocation to lie within the range of EUR 1.03-5.11 billion per annum, which an individual nuclear operator, most likely, would not be able to afford. When expressed on the per kWh basis, the values are within the range of EUR 0.074-0.364 per kWh. Therefore, if the accumulating of funds for covering the damage caused by a nuclear disaster was passed to the electricity demand side, the Finnish consumers would eventually need to pay somewhat 62-300 per cent more, assuming electricity price in Finland equals to EUR 0.12 per kWh (Statistics Finland, 2011b). Altogether, it would be a dramatic increase in the electricity price and Finnish consumers and respective regulatory commissions would not allow this to happen.

Sensitivity Analysis

The sensitivity analysis is performed to show how the values of the radiation-induced health costs and, eventually, the nuclear insurance premium respond to changes in the underlying assumptions. Since the costs of the countermeasures to reduce radiation doses proved to be much smaller than the health related costs, they are omitted from the sensitivity analysis. Furthermore, while Hohmeyer's approach used in 1988 is fully replicated, his subsequent study of 1990 where a five times higher person-sieverts radiation dose is assumed is not pursued anymore. This is justified by the fact that the fivefold increase in the total radiation dose does not seem to have any reliable basis. Ottinger's (1990) approach is omitted as well as main assumptions of his study were adopted from Hohmeyer (1988).

- **Radiation-induced health effects in the exposed population**

Although many researchers predicted that the radiation release from the Chernobyl accident would trigger tens or even hundreds of thousands of additional cancers, in reality the scientific proof for that is still missing. Moreover, a possibility that medium and low doses of radiation do not cause cancer has been discussed by several reports, including those by WHO in conjunction with IAEA and UNDP (Finn, 2005) and UNSCEAR (2011). These studies collectively suggested that under no circumstances the number of additional fatal cancers caused by the Chernobyl accident can be higher than several thousand (4,000 or 8,930). A great number of other studies suggested a much higher number of deaths – up to 6 million, as it was discussed in the Literature Review part. The reality, however, witnessed fewer than 50 deaths as of 2005 which could be directly attributed to the Chernobyl nuclear disaster (Chernobyl Forum, 2003-2005). Altogether, this gives a reasonable basis to assess the assumption related to the number of additional cancers a nuclear disaster has a potential to cause. So far it has been estimated to be 192,000, whereas the total person-sieverts dose and the risk of the developing cancer were adopted from the Hohmeyer's study (1988). It is now assumed that the total person-sieverts dose is decreased from the currently used 2.4 million to 291,000, as suggested by UNSCEAR (1988) and ExternE Report, (European Commission, 1995). The risk to develop a cancer, which is assumed to be 10 per cent, should be modified as well. The recent assessments suggest that in case of a nuclear disaster a radiation-induced increase in the number of cancers will not surpass 3 per cent (Finn, 2005) (UNSCEAR, 2011), hence this new information is taken into account (see Appendix 7). As a result, the additional number of cancers is estimated to be roughly 7,000, which in turns dramatically reduces health related costs: the direct health costs drop from EUR 5.76 billion to EUR 210 million (see Appendix 7, Table 1) and indirect costs – from EUR 100 billion to EUR 3.64 billion (see Appendix 7, Table 2). Altogether, the costs of radiation-induced health effects in the exposed population sums up to roughly **EUR 4 billion**, which is 26 times smaller than the lowest estimation of the total health related costs in the conservative analysis.

Taking the costs of the countermeasures to decrease radiation doses into account, the overall cost of a nuclear disaster occurring at Olkiluoto-3 is estimated to be **EUR 16 billion**.

- **Probability and Expected Value of a Nuclear Disaster at Olkiluoto-3**

The reported probability of a severe accident for EPR is $6.1*10^{-7}$, which is ten times lower than the value assumed in the conservative calculations (UK EPR, 2009b). The EPR design

incorporates the main defence-in-depth principles related to prevention and control of severe nuclear accidents, whereas the core-catcher should not allow a release of radioactive material even in a the worst possible force majeure, e.g. an earthquake or a plane crash, which gives a reasonable basis for the authors of this paper assume that this estimation is correct. Besides, the fact that this probability has been also confirmed by HSE (2011) further enhances the validity of such assumption. The expected value of a nuclear disaster is immensely sensitive to the assumption made regarding the estimated probability. Once the new value $(6.1*10^{-7})$ is assumed and EUR 16 billion is taken as a total cost of a nuclear disaster, the expected value is found to be equal to roughly EUR 10,000. This translates into EUR 0.0000007 per kWh, which is an insignificant number.

- **Liability Insurance Allocations**

Once the total cost of a nuclear disaster at Olkiluoto-3 reactor is estimated to be EUR 16 billion, the implied annual liability insurance allocation is estimated to be EUR 138 million or EUR 0.009857 per kWh, which is seven times lower than in the initial conservative analysis. While the liability amount still might not be financially bearable for an individual nuclear operator, it is more likely than before that a final electricity consumer will agree to pay this cost. If the mentioned per-kWh cost of the insurance allocation is incorporated into the current electricity cost, it would hardly result in a more than 8% price increase which, if communicated properly, can be passed on the society.

6.4. Summary of Results

To sum up, this paper assumes that the most severe accident takes place at the Olkiluoto-3 nuclear reactor and it calculates all possible related costs in the most conservative way. The range of nuclear damage is found to be within the range of EUR 118-582 billion. The implied insurance allocations which are needed to be done over 60 years for covering all estimated damages from a nuclear disaster is found to be within the range of EUR 1.03-5.11 billion per annum, which is not financially manageable for a nuclear operator. The per-kWh allocation is found to be in the range of EUR 0.074-0.364, which is considered to be unaffordable for a final electricity consumer. Therefore, given this state of affairs, it is not possible to identify a party who would be capable to pay the proposed liability insurance amount. However, as the sensitivity analysis shows, the picture significantly changes when the underlying assumptions of this paper are revised and data from the latest studies is considered.

In the sensitivity analysis, three most crucial assumptions are modified: the total person-sieverts dose is assumed to be 291,000 (instead of previously applied 2.4 million); the risk of getting cancer after a nuclear disaster is assumed to be 3 per cent (instead of previously applied 10 per cent); the probability of a nuclear disaster at Olkiluoto-3 is assumed to be $6.1*10^{-7}$ (instead of previously applied $6.1*10^{-6}$). The changes in the calculations are tremendous: the total health related costs decrease by 26 times and are equal to EUR 4 billion, thus cutting the total potential cost of a nuclear disaster to EUR 16 billion. The expected value of the nuclear disaster drops to EUR 10,000 as compared to EUR 717,000 before. The annual liability insurance allocation is estimated to be EUR 138 million or EUR 0.009857 per kWh, when the 60 year time period is assumed. It might still not be possible for a nuclear operator to afford that big annual allocation. The final electricity consumer, however, most likely would be able to cover this cost as it would represent up to 8 per cent increase in the electricity price. Given that the electricity price in Finland is one of the lowest across the whole EU (Eurostat, 2010), the mentioned increase is not expected to be dramatic. Moreover, if the costs of countermeasures to reduce radiations doses (EUR 12 billion), which were excluded from the sensitivity analysis, are assessed more accurately and realistically, the final cost of the potentially worst nuclear disaster at Olkiluoto-3 would be even lower than the currently estimated EUR 16 billion. This would further enhance feasibility of the liability insurance.

7. Implications

The position of the nuclear power industry has never been secure due to the adverse public attitude but after the Fukushima event it has been significantly shaken. While several countries consider phasing out nuclear energy, this paper studies the case of the Olkiluoto-3 and finds that reasoning behind such decision is not supported by sufficient evidence, thus it might not be rational. For that matter, this section once again states the main findings of the present paper and puts them forward by deriving relevant implications for the current and future state of the nuclear power industry.

Finding 1: Previously reported estimations of nuclear disaster costs might be severely overstated.

Lack of reliable methodology and data to estimate the costs of a nuclear disaster must have been the main factor which shaped the general belief that nuclear accidents trigger severe consequences, especially those related to health. In the absence of proved theoretical and

empirical grounds, researchers took a radical stand and assumed the worst. While doing so amid high uncertainty is in human nature, the latest studies, however, suggest that even the least conservative assumptions are, in fact, utterly pessimistic. These results have not yet received public acknowledgement and the world keeps revolving around the idea that nuclear energy is ultimate evil. However, if it can be imagined for a while that the true nuclear damage is substantially lower than the reported one, it will become clear that the society pays a high cost for believing in wrong numbers. First of all, the reported dramatic costs of a nuclear disaster create fear and anxiety in the society, whereas the most affected people would be those who live in proximity to nuclear power plants. Definitely, the fear and anxiety will grow stronger if an incident/accident is reported to have taken place. While there might be virtually a zero chance of being affected by the nuclear event, people will not stop fearing, worrying and being stressed. What should be understood is that an average person is poorly educated about the principles and mechanics behind nuclear energy, and he/she does not know much about radiation either. Therefore, an average person will not try to rationalize his/her fear but will rather fall in despair and prepare for the worst – to develop cancer and in the most severe case, to die. Imposing such moral pressure on people is not only unfair, but also inhumane. Another negative externality of believing in exaggerated costs, especially those related to health, is that it encourages opportunism among the so-thought affected people. If it is generally believed that nuclear disaster results in high release of radiation and radiation causes cancer, there will be people who will seek compensation, claiming they developed cancer due to a nuclear disaster even if their cancer case is not disaster-related. Although no official proof exists, this is believed to have happened after the Chernobyl accident. Finally, public fear enhanced by reports overstating the true cost of a nuclear disaster, can be a manipulation tool in the hands of politicians. In order to increase chances to win elections, politicians often adjust their agenda to the interests of the electorate and dismiss it as soon as elections are over. Hence, what can be easier for a politician, who does not necessarily have best society's interests at heart, than going radically anti-nuclear to impress the nuclear adverse voters, win the elections and abuse the voters' trust?

To address the above stated issues properly, the following is recommended for consideration of the policy makers, researchers and other related stakeholders:

1. While there are plenty anti-nuclear and several pro-nuclear studies, the room for objective research is certainly huge. Impartial experts should come together and conduct an in-depth study, especially of the so much discussed health related costs. It is also

crucial to improve cooperation and knowledge exchange between organizations with substantial expertise and capacity to perform qualitative analysis, e.g. UN, IAEA and WHO. Besides, radiation effects on the environment should be assessed as well because excluding such costs from the analysis is certainly an ignorant decision. Altogether, nuclear experts should finally arrive at consensus on how to calculate nuclear damage.

2. The myths of society regarding radiation and nuclear energy should be dispelled. To rationalize their fear and to form an objective opinion, people should have impartial and complete information. There are different means to achieve this: awareness campaigns can be implemented, central and local governments can engage relevant stakeholders and initiate the dialogue, etc. Furthermore, nuclear energy should not be a political tool. Hence, it is crucial to minimize ability of politicians to exploit it for their own benefit. No games and manipulation with people's mind should be tolerated.

3. R&D in nuclear science should not be abated, on the contrary, it should be increased and other nuclear technologies should be explored, e.g. Thorium. Since there is always a chance that Uranium-based nuclear reactor will explode, no matter how safe it is, why not to pursue a much safer technology which still can fulfil a function of the base-load power source? Given the advantages of Thorium-based reactors, it seems this technology has been undeservedly neglected.

Finding 2: International nuclear third party liability laws have been consistently failing.

Despite nuclear power industry is more than 60 years old, international legislation related to nuclear energy is unexpectedly immature and highly disorganized. Even more surprising it is in the light that there is so much controversy going around nuclear energy whereas many experts and researchers claim it is the most unsafe energy source the humankind has ever created. One would expect that if nuclear energy was indeed so dangerous and the costs of disaster were so high, the world legal authorities would impose very strict third party liability laws and they would increase the liability provisions to match the estimated costs of nuclear damage. In fact, they could have even tried to ban it completely. The reality, however, shows that current nuclear legislation is lax, not harmonized, not enforceable and discouraging for the countries who comply with it and for those who consider complying. Finally, the damage provisions under the current legislation are much smaller than the costs of a nuclear disaster reported in the previous studies and this paper. This suggests that a proper coverage of nuclear damage would not take place in case of a major accident.

Therefore, to enhance enforceability of the nuclear energy related legislation, the following is recommended for consideration of the policy makers, legislators and other related stakeholders:

4. Harmonization of the nuclear laws across countries is required. One globally applicable legislation should be created, whereas all terms would be explicitly defined, importance of compliance would be communicated and uniformity of response to a nuclear disaster would be ensured. The legislation should call for commitment and offer necessary guidelines for making this commitment. To achieve this, several steps should be taken: awareness about importance to join hands in shaping universal nuclear law among the nuclear operating countries should be raised, the step-by-step action plan should be compiled and the deadlines should be settled, the stakeholder engagement map should be clearly defined, the incentives to attract and convince potential signatories should be shaped.

5. Stakeholders representing both supply and demand of nuclear energy should be engaged into the work on legislation. While urgency of nuclear-related issues is not always recognized by the governmental institutions, producers and consumers are more motivated to finalize laws which appeal to them the most. Therefore, to foster harmonization of nuclear laws, representatives of the nuclear energy markets should work closely together with the governments, whereas independent consultants should be appointed to ensure that best interests of the society are taken into account.

Finding 3: Insuring against nuclear disaster is feasible but currently is not manageable.

Plausibility of the nuclear insurance is highly dependent on the legalization of the third party liability. At the moment, the grounds for creating a well-functioning nuclear insurance industry are not sufficient, not to mention that the provisions for satisfying the third party claims under current legislation are far below a reasonable level. However, even if the legislation is harmonized and is efficiently enforceable, the main impediment still roots in the fact that nuclear damage estimations are highly overstated. Insurance premium a nuclear operator would need to pay is directly linked to the amount of damage the insurance covers; and as seen in the calculations before, the financial burden for a nuclear operator will be enormous, if previously reported nuclear costs are assumed to be true. At the same time, if the nuclear damage estimations are reassessed, as it was showed in the sensitivity analysis, the nuclear insurance becomes financially feasible – if not for a nuclear operator, then most likely for a final consumer of electricity. Not only the ability to insure against nuclear disaster

would be beneficial for the nuclear operator, it would also contribute to minimizing people's radiophobia and anxiety about whether the related costs will be covered in case the disaster occurs.

Therefore, to help design a well-functioning nuclear insurance industry, the following is recommended for consideration of the policy makers, insurance companies and other related stakeholders:

6. The payment of a nuclear insurance premium should be thoroughly thought over. If it is a nuclear operator who has to pay the premium, it should be decided if he/she can further pass the cost of the premium to the final consumers. It is likely that incorporation of the nuclear insurance premium into the electricity price is feasible, given it would not increase the electricity price beyond the reasonable level. For this, the relevant demand and price elasticity should be examined, as well as consumers' willingness to pay little extra for their own safety should be estimated. If it is nuclear operator who needs to bear the costs of an insurance premium, this should not be imposed on a compulsory basis – this way it will probably be lost in debates initiated by operators, and hence will never succeed. Instead, nuclear operators should have incentives to insure against a nuclear accident. The government, perhaps, should be the initiator of such incentives, whereas it could possibly support those operators who assume such commitment.

7. Restructuring of the existing nuclear insurance industry is inevitable. At present, insurance companies do not have adequate financial capacity to cover nuclear damage even if the most optimistic damage estimations are applied. The reality proves that domestic nuclear insurance pools are not well equipped to handle a nuclear damage, too. Therefore, new insurance products should be designed to address the nuclear risks, as well as higher level of cooperation on a national level between insurance companies and government and on an international level between all nuclear insurance companies/pools should be achieved.

8. Other alternative insurance mechanisms should be developed, too. For example, nuclear operators can pool their own funds and make them available in case of an emergency, in such a way creating a sort of "in-house" insurance facility. Even though freezing substantial amounts of money is not rational from a business perspective, what matters is that it would still remain within the company and if managed properly, would even grow at a rate of inflation. Therefore, while the goal of mobilizing funds when a disaster strikes would still be fulfilled, nuclear operators would save a great sum of money which

they otherwise would have to pay to an insurer. Another option is to engage the capital markets with a proposal to issue nuclear bonds – analogously to the catastrophe bonds which have already been placed. Finally, since governments seek cheap but at the same time green and reliable energy sources and nuclear energy sector can accommodate this need; the two parties should increase the extent of their cooperation and partnership.

To sum up, this paper calls for reconsideration of the current state of the nuclear power industry. Given the latest findings in the field, it would only seem logical to reopen and objectively reassess what can be called the nuclear case. It is time to stop being ignorant.

Conclusion

The current situation in the world energy markets can be well described as a struggle: there is a clash between what the society aspires to achieve – that is, sustainable world fuelled by green and, most importantly, abundant energy sources, and what the society has to deal with – that is, the demand for energy outstripping the supply. While having ambitious goals is not obnoxious, it is also important to stay grounded, focused and able to mobilize resources for facing the challenge. The threat of an energy crisis has become real and it is crucial to make an inventory of all energy sources the world has at its disposal, including nuclear technologies which have always been suppressed by people's radiophobia, but after the recent events in Fukushima have been placed under consideration for a phase-out.

Abatement of nuclear technologies, however, might be a luxury the world will not be able to afford. Phasing out nuclear energy would be a very expensive process due to time and capital required for a proper handling of dismantlement and nuclear waste. What, however, is worse – given that renewable technologies are still immature and they cannot accommodate the need for the base-load power, abating nuclear energy would also mean decreasing the chances of living in the world fuelled solely by green, yet sustainable energy. While the world is obviously not willing to say such tough goodbye to its aspiration, the latest studies on the damage caused by nuclear accidents suggest that it will not be necessary. Reports by several nuclear world authorities claim that the previously reported costs associated with the nuclear disaster in Chernobyl as well as radiation doses after the nuclear disaster in Fukushima, are highly exaggerated.

This paper hypothesizes a nuclear disaster at Olkiluoto-3 power plant and finds that in the worst case the cost would fall within the range of EUR 118-582 billion, which is a much

lower number compared to the previous studies. This paper also assesses the feasibility of the nuclear insurance industry. The authors conclude that the expected cost of the disaster would not be a reliable basis for calculating the insurance premium as it does not incorporate the complexity of a nuclear disaster. However, when the annual allocation necessary to accumulate the necessary amount to cover damage from a nuclear disaster is calculated, it turns out to be in the range of EUR 1.03-5.11 billion per annum, or EUR 0.074-0.364 per kWh. Furthermore, when several crucial assumptions are modified to accommodate the findings of the most recent assessments, the cost of such nuclear disaster drops to EUR 16 billion, and the corresponding insurance allocation drops to EUR 138 or roughly EUR 0.01 per kWh.

While the authors of this paper do not claim they have found the ultimate truth, they nevertheless insist that the analysis yields several important findings. Firstly, the previously reported estimations of nuclear disaster costs might be severely overstated, and finding the true value is of utmost importance. Moreover, the international third party liability laws have been consistently failing to accommodate the needs of the nuclear power industry. Should the costs of a nuclear damage be reassessed, it will foster the enforcement of better compliance with the third party legislation related to nuclear energy. Finally, the nuclear insurance appears to be feasible but given the current state of the insurance industry, not yet manageable, which however might be changed if the costs of a nuclear disaster are reassessed and are found to be much smaller than the society has thought before. Based on these findings, the authors of the paper derive eight implications aimed at raising a constructive and objective discussion.

Therefore, this paper can be viewed as a call for reconsideration: it might be the case that nuclear energy has been overdramatized and as a consequence the potential of nuclear energy may have been significantly undervalued. Amid the energy crisis the price of such ignorance is inexcusably high to pay. Hence, it is time to put fear and prejudice aside, to reassess the costs and probability of a nuclear disaster and to see how the findings can be put forward. It may well be the case that while the world has been searching for a miracle cure to balance the energy demand/supply equation, the solution has always been there.

Further Research

The room for the further improvement of this paper is substantial. Given the limitations of this study, the further research should be undertaken to reconfirm the underlying assumptions and the methods used for calculating costs of countermeasures to reduce radiation doses and health related damage. It is also necessary to define if any measurable costs related to a nuclear disaster have been omitted from the analysis. Moreover, an assessment of global consequences triggered by a nuclear disaster at Olkiluoto-3 power plant should be conducted in order to understand what would be the cost borne by the global society. Finally, a deeper study is needed to examine feasibility of the nuclear liability insurance. Given that safety is the main concern people share about nuclear energy, correct assessment of the insurance premium is ultimately important. If a nuclear disaster appears to be insurable, it will not only enhance the feeling of security, but will also give a so much needed support to the nuclear power industry.

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Appendix 1. Types of Nuclear Reactors Operating in the World
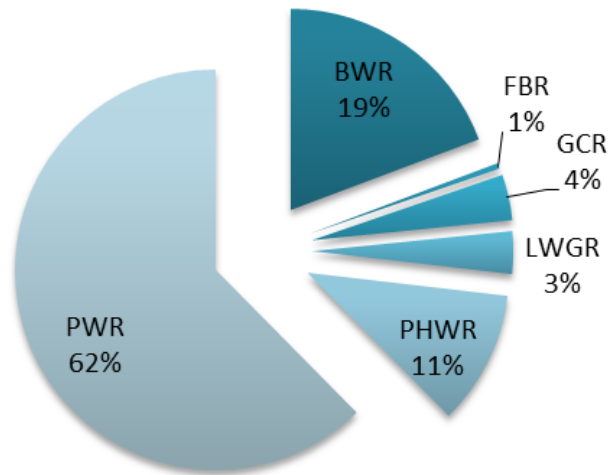
Figure 1. Employment of different types of nuclear reactors operating in the world.
Compiled by authors using (IAEA, 2011a).

Reactor Type	Number/GW	Main Countries	Coolant	Moderator	Fuel
Pressurized water reactor (RWR, VVER)	272/250	US (68), France (58), Japan(24), Russia (16)	Light water	Light water	Enriched uranium
Boiling water reactor (BWR)	84/78	US (35), Japan (30), Sweden (7)	Light water	Light water	Enriched uranium
Light water graphite reactor (RBMK)	15/10	Russia (15)	Light water	Graphite	Enriched uranium
Pressurized heavy water reactor (PHWR)	47/23	Canada (18), India (18)	Heavy water	Heavy water	Natural Uranium
Gas-cooled reactor (Magnox, AGR, UNGG)	16/8.5	UK (18)	CO_2	Graphite	Natural or enriched uranium
Fast breeder reactor (FBR)	2/0.5	Russia (2)	Liquid sodium	none	Plutonium and enriched uranium
Total	436/370				

Table 1. Types of nuclear reactors operating in the world.
Compiled by the authors using (NRG Expert, 2011), (IAEA, 2011a).

Appendix 2. Nuclear Power Plants in Finland: Operating, Under Construction & Planned

	Type	MWe net	First power	Expected shutdown
Loviisa 1	VVER-440/V-213e	488	1977	2027
Loviisa 2	VVER-440/V-213e	488	1980	2030
Olkiluoto 1	BWR	885	1978	2039
Olkiluoto 2	BWR	880	1980	2042
Total (4)		**2741**		

Table 1. Finland's operating nuclear power reactors. Compiled by the authors using (World Nuclear Association, 2012d).

	Type	MWe net	MWe Gross	Construction start	Commercial operation
Olkiluoto 3	EPR	1600	1720	May-05	Aug-14
Olkiluoto 4	EPR, ABWR, ESBWR, EU-APWR, or APR -1400	1450-1650	1500-1770	2014-15	about 2020
Hanhikivi 1	EPR or ABWR	1550-1650	1600 to 1800	2014	By 2020
Total (3)		4600-4900	ca. 4800-5300		

Table 2. Finland's nuclear power reactors under construction and planned. Compiled by the authors using (World Nuclear Association, 2012d).

Appendix 3. International Nuclear Event Scale

A **C** **C** **I** **D** **E** **N** **T**	**7** Major Accident
	6 Serious Accident
	5 Accident with Wider Consequences
	4 Accident with Local Consequences
I **N** **C** **I** **D** **E** **N** **T**	**3** Serious Incident
	2 Incident
	1 Anomaly
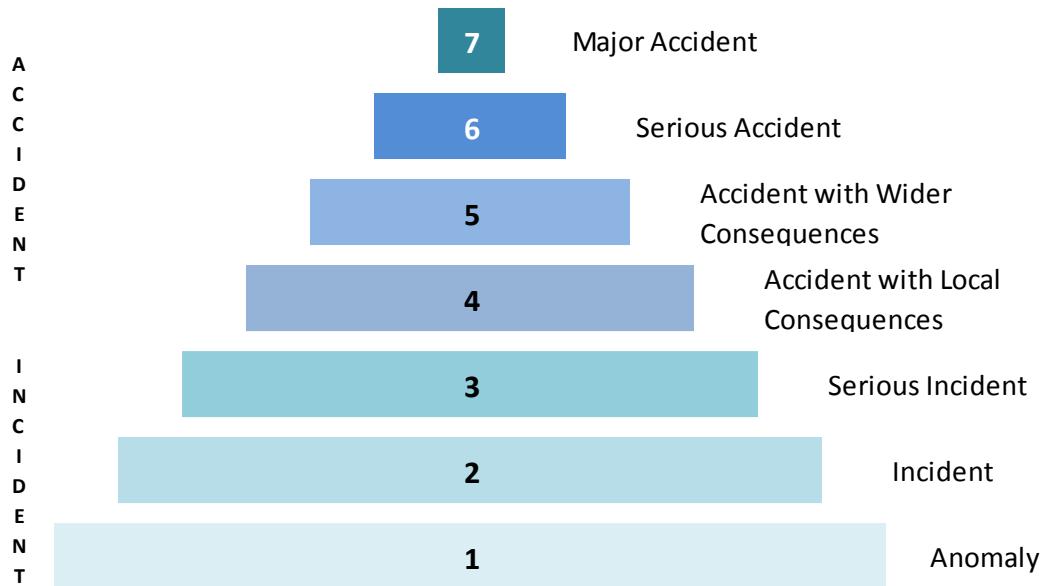
International Nuclear Event Scale. Compiled by the authors using (IAEA, 2012c).

Appendix 4. Cost Elements of a Nuclear Accident (NEA, 2000)

1) The application of countermeasures to reduce doses:
a) Population movement
• Transport away from the affected area
• Temporary accommodation and food
• Supervision of the evacuated area and monitoring of people
• Loss of income (GDP contribution)
• Lost capital value and investment on land and property.
• Psychological effects of worry and upheaval.
b) Agricultural restrictions and countermeasures
• Already produced goods which happen to be in the surrounding area when the explosion takes place
• Potential production which is
c) Decontamination
• Cost of cleaning process, including the necessary equipment and materials, as well as the disposal and transportation of the generated waste.
• Cost of labour.
• Cost of health effects induced in the work force foregone due to the explosion
2) Radiation-induced health effects in the exposed population.
a) Direct health care costs
b) Indirect costs, due to the loss of earnings during treatment and convalescence or of the total expected future earnings in the case of death
c) Non-monetary costs, such as pain, grief and suffering associated with each effect
3) Psychological effects.
4) Impact on the activity with which the installation is associated, for example the power programme
5) Impact on economic factors: employment, revenues, losses of capital, etc.
6) Long-term social and political impact.
7) Environmental and ecological impact.

The list of possible nuclear damages based on the NEA (2000) study. Compiled by the authors using (NEA, 2000).

Appendix 5. Calculations: Costs of Countermeasures to Reduce Doses

TRANSPORTATION COST (EUR)	
ASSUMPTIONS	
Number of evacuated people	46,000
Distance to Turku (km)	110
Distance to Tampere (km)	150
Rate to rent a bus (EUR per day)	500
Number of buses needed to be rented, capacity of 50 people	920
Price of diesel (EUR per litre)	1.40
Litres of diesel required per 100 km for a bas	25
Average monthly salary in Finland	3,040
Number of supervisors	200
CALCULATIONS (EUR)	
Bus rental	460,000
Total diesel cost for buses going to Tampere 2 return trips	96,986
Total diesel cost for buses going to Turku 2 return trips	71,123
Supervision of evacuated area(200 people, daily rate)(EUR)	20,267
TOTAL COST (EUR)	**648,376**

Table 1. Calculations of transportation costs (EUR).
Compiled by the authors using (STUK, 2009) (Mennaanbussilla, 2012) (Polttoaine, 2012) **(Statistics Finland, 2012d)**.

SHORT-TERM ACCOMMODATION COST (EUR)	
ASSUMPTIONS	
Number of accommodated people	46,000
Length of accommodation period (days)	30
Cost of accommodation (EUR per day)	90
TOTAL COST (EUR)	**124,200,000**

Table 2. Calculations of short-term accommodation costs (EUR). Compiled by the authors using (STUK, 2009) **(Statistics Finland, 2012a)**.

FOOD COST (EUR)	
ASSUMPTIONS	
Number of people provided with food	46,000
Length of food provision period (days)	14
Food allowance (EUR per day)	6.85
TOTAL COST (EUR)	**4,411,615**

Table 3. Calculations of food costs (EUR). Compiled by the authors using (STUK, 2009) (Numbeo, 2012).

MONITORING OF PEOPLE'S HEALTH (EUR)	
ASSUMPTIONS	
Number of people requiring a health check	46,000
Cost of one health check	27
TOTAL COST (EUR)	**1,242,000**

Table 4. Calculations of monitoring of people's health costs (EUR). Compiled by the authors using (STUK, 2009) (Kela, 2012).

LOSS OF INCOME (EUR)	
ASSUMPTIONS	
GDP of Finland (EUR)	195,723,000,000
Total population	5,410,233
Number of people leaving within the 20 km radius	46,000
Total area of Finland (squared km)	338,424
Area of Finnish territory within the 20 km radius	1,256
CALCULATIONS	
GDP per capita (EUR)	36,176
GDP loss within the 20 km radius *	1,664,116,499
GDP per one squared km of Finland	578,337
GDP loss within the 20 km radius *	726,390,823
TOTAL COST (EUR) - maximum of * is considered	**1,664,116,499**

Table 5. Calculations of loss of income (EUR).
Compiled by the authors using (STUK, 2009) **(Statistics Finland, 2012e) (Statistics Finland, 2012f)** (Finland, 2012).

COST OF RESIDENTIAL SPACE REPLACEMENT (EUR)	
ASSUMPTIONS	
Number of relocated people	46,000
Percentage of population living in household	75%
Number of people in a household	2.79
Percentage of population living alone	25%
Average residential space per person (square meters)	39
Average floor flat area (square meters)	79
Construction cost of 1 square meter of residential space (EUR)	2,500
Average price for 1 square meter of residential space (EUR)	1,703
Consumer durable goods allowance per household (EUR)	10,000
Personal expenditures allowance (EUR)	5,000
CALCULATIONS	
Number of required additional flats	23,866
Total cost of additional flats (EUR) *	3,210,805,070
Total consumer durable goods allowance cost	238,655,914
Total personal expenditures allowance cost	230,000,000
Number of required new residential area (square meters)	1,794,000
Construction cost of new residential space (EUR) *	4,485,000,000
TOTAL COST (EUR) - maximum of * is considered	**4,953,655,914**

Table 6. Calculations of cost of residential space replacement (EUR).
Compiled by the authors using (STUK, 2009) **(Statistics Finland, 2012b) (Statistics Finland, 2012c)**
(Statistics Finland, 2009) (Gardiner, 2011).

COST OF OFFICE SPACE REPLACEMENT (EUR)	
ASSUMPTIONS	
Number of relocated people	46,000
Average office space per person (square meters)	0.62
Construction cost of 1 square meter of office space (EUR)	1,947
TOTAL COST (EUR)	**55,907,728**
COST OF RETAIL SPACE REPLACEMENT (EUR)	
ASSUMPTIONS	
Number of relocated people	46,000
Average office space per person (square meters)	0.73
Construction cost of 1 square meter of office space (EUR)	1,764
TOTAL COST (EUR)	**59,095,072**
COST OF INDUSTRIAL SPACE REPLACEMENT (EUR)	
ASSUMPTIONS	
Number of relocated people	46,000
Average office space per person (square meters)	1.56
Construction cost of 1 square meter of office space (EUR)	1,068
TOTAL COST (EUR)	**76,668,533**
TOTAL COST OF OFFICE/RETAI/INDUSTRIAL SPACE (EUR)	**191,671,333**

Table 7. **Calculations of cost of office/retail/industrial space replacement (EUR).**
Compiled by the authors using (STUK, 2009) (KTI, 2012) (Gardiner, 2011).

Appendix 6. Calculations: Costs of Radiation-Induced Health Effects

DIRECT HEALTH COSTS (EUR)	
ASSUMPTIONS	
Person-sieverts radiation dose	2,400,000
Risk of getting cancer	10%
Factor to account for population density	0.8
Average cost of a cancer treatment (EUR) in 2006	30,000
CALCULATIONS	
Number of additional cancers	192,000
TOTAL COST (EUR)	**5,760,000,000**

Table 1. Calculations of direct health costs (EUR).
Compiled by the authors using (Hohmeyer, 1988) (Cancer Society of Finland, 2012) (Finland, 2012).

INDIRECT HEALTH COSTS: REPLICATION OF HOHMEYER'S ANALYSIS, 1988 (EUR)	
ASSUMPTIONS	
Person-sieverts radiation dose	2,400,000
Risk of getting cancer	10%
Factor to account for population density	0.8
Years of employment foregone in case of fatal cancer	20
Years of employment foregone in case of non-fatal cancer	10
Mortality rate	50%
Annual salary (EUR)	36,480
Long-term inflation rate in Finland	1.6%
Discount factor (risk-free rate in Finland)	2.0%
CALCULATIONS	
Number of additional cancers	192,000
Net present value of fatal cancer (EUR)	689,263
Net present value of non-fatal cancer (EUR)	351,401
TOTAL COST (EUR)	**99,903,724,113**

Table 2. Calculations of indirect health costs based on the replication of Hohmeyer's analysis (1988) (EUR).
Compiled by the authors using (Hohmeyer, 1988) (Worldwide Inflation Data, 2012) (Bloomberg, 2012)
 (Statistics Finland, 2012d).

HEALTH COSTS: REPLICATION OF OTTINGER'S ANALYSIS, 1990 (EUR)	
ASSUMPTIONS	
Person-sieverts radiation dose	2,400,000
Risk of getting cancer	7.7%
Factor to account for population density	0.8
Mortality rate	75%
CALCULATIONS	
Number of additional cancers	147,840
Net present value of fatal cancer (EUR)	4,975,256
Net present value of non-fatal cancer (EUR)	497,526
TOTAL COST (EUR)	**570,044,890,375**

Table 3. Calculations of health costs based on the replication of Ottinder's analysis (1990) (EUR).
Compiled by the authors using (Ottinger & al., 1990).

Appendix 7. Sensitivity Analysis

DIRECT HEALTH COSTS (EUR)	
ASSUMPTIONS	
Person-sieverts radiation dose	291,200
Risk of getting cancer	3%
Factor to account for population density	0.8
Average cost of a cancer treatment (EUR) in 2006	30,000
CALCULATIONS	
Number of additional cancers	6,989
TOTAL COST (EUR)	**209,664,000**

Table 1. **Sensitivity analysis results of direct health costs (EUR).**
Compiled by the authors using (Hohmeyer, 1988) (Cancer Society of Finland, 2012) (Finland, 2012).

INDIRECT HEALTH COSTS: REPLICATION OF HOHMEYER'S ANALYSIS, 1989 (EUR)	
ASSUMPTIONS	
Person-sieverts radiation dose	291,200
Risk of getting cancer	3%
Factor to account for population density	0.8
Years of employment foregone in case of fatal cancer	20
Years of employment foregone in case of non-fatal cancer	10
Mortality rate	50%
Annual salary (EUR)	36,480
Long-term inflation rate in Finland	1.6%
Discount factor (risk-free rate in Finland)	2.0%
CALCULATIONS	
Number of additional cancers	6,989
Net present value of fatal cancer (EUR)	689,263
Net present value of non-fatal cancer (EUR)	351,401
TOTAL COST (EUR)	**3,636,495,558**

Table 2 **Sensitivity analysis results of indirect health costs (EUR).**
Compiled by the authors using (Hohmeyer, 1988) (Worldwide Inflation Data, 2012) (Bloomberg, 2012) **(Statistics Finland, 2012d)**.