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“Managing Risk and Dealing with Uncertainty. An Evaluation of Nuclear Energy Policy for the Case of Germany.”

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Contents

Key to Abbreviations

AtDeckV	*Atomrechtliche Deckungsvorsorge-Verordnung*
AtG	*Atomgesetz*
BfS	*Bundesamt für Strahlenschutz*
CAPM	*capital asset pricing model*
CASTOR	*cask for storage and transport of radioactive material*
CHPP	*catastrophic harm precautionary principle*
COMEST	World Commission on the Ethics of Scientific Knowledge and Technology
EnBW	Energie Baden-Württemberg AG
EU	European Union
IAEA	International Atomic Energy Agency
IE	*irreversible effect*
IHPP	*irreversible harm precautionary principle*
kWh	*kilowatt hour*
MP	*maximin principle*
MW	*megawatt*
NCB	*nuclear catastrophe bond*
NIMBY	*not-in-my-backyard*
NRM	*nuclear risk management*
NRSP	*nuclear risk-sharing pool*

OV *option value*

PAA Price Anderson Act

PD *permanent disposal*

PDS *permanent disposal site*

PE *precautionary effect*

PP *precautionary principle*

PPP *polluter-pays-principle*

SA Solidarity Agreement (”Solidarvereinbarung”)

SDR *special drawing rights*

SRM *social risk management*

TTE *tail thickening effect*

UNESCO United Nations Educational, Scientific and Cultural Organization

WE *wealth effect*

WNA World Nuclear Association

WTO World Trade Organisation

1. Introduction

Motivation

In order to meet the increasing demand for energy, many industrialised countries, to a substantial extent, still rely on nuclear energy sources. Proponents of atomic technology promote its efficiency and potential to guarantee an autonomous nationwide energy supply. Furthermore, since the process of generating nuclear energy avoids the release of carbon emission into the atmosphere, they assume the technology's ecological footprint to be environmentally sound in contrast to the generation of energy by means of fossil resources.

Nevertheless, the utilisation of nuclear forms of energy involves various sources of risk that confront societies with a variety of problems to be dealt with. Prominent sources of risk are the construction, the operation and the maintenance of nuclear power plants. Human error, technical malfunction, terrorist attacks or natural catastrophes like earthquakes or tsunamis, for example, can trigger off a sequence of events that could result in a meltdown of the reactor core. As a consequence, radioactive material released into the environmental system would involve serious problems for human health, substantial environmental damage as well as extensive losses within the economic system. Another important source of atomic risk is the increasing stock of nuclear waste. Scientists all over the world are busily engaged in finding an adequate solution for ultimate and final disposal. The long-term isolation of harmful substances contained in nuclear waste by means of a natural rock barrier constitutes the most encouraging option according to current scientific standards. So far, however, nuclear waste producing economies have not been able to install a well-performing permanent disposal site and, therefore, have to resort to interim storage facilities thereby exposing societies to the uncertain hazards emanating from radioactive waste.

On the one hand, societies are well aware of the potentially adverse consequences of the generation of nuclear energy and the corresponding worst-case scenarios. Therefore, the atomic energy industry is a sector, which has to comply with a wide range of obligations and statutory requirements imposed by regulatory authorities. On the other hand, severe nuclear accidents are assumed to be rather low-frequency events. The probability of a core melt accident to occur for an average nuclear power plant is estimated to range between one in ten thousand years and one in a million years, respectively. Consequently, citizens in western economies relying on nuclear energy like the United States, Japan or France seem to be accustomed living with the corresponding social risk. Within this context, the predominant general refusal of nuclear technology within the German society is rather an exception.

Eventually, it is the sudden appearance of catastrophic events that cause the social risk implied by the generation of nuclear energy to gain centre stage of political and public debates. The occurrence of a partial core meltdown at 'Three Mile Island' (USA) in 1979, the 'maximum credible accident' in Chernobyl (Ukraine) in 1986 and, of course, recent alarming events at nuclear installations in Fukushima (Japan) serve as vivid examples. Within this respect, furthermore, it is important to point out the regular cross-border transport of nuclear waste from specific installations to reprocess radioactive fuels in France to the interim storage facility in Gorleben (Germany). These so-called 'CASTOR transports' routinely cause substantial responses on the part of Germany's civil society and arouse intense debates about consequences and sustainability of nuclear technology. In fact, it was the strong presence of the latter debate in German and Austrian media that stirred the interest in the topic and initiated the economic examination of nuclear risk within the present thesis.

Nuclear energy, at the moment, is still a pillar of economic growth and prosperity in many industrialised countries. In this respect and despite all security concerns, it is a matter of priority to be dealt with in a most efficient way. Correspondingly, the adequate management of nuclear risk in a socio-economic context is an essential question that should be addressed separately to the question of principle concerning the general justification of the use of nuclear technology. From the perspective of the German legislator, the utilisation of nuclear energy forms is still an important technology to bridge the gap between the increasing demand for energy and the rather slow technological development of renewable energy sources. Besides general theoretical aspects, the further analysis pays special attention to the institutional arrangements in Germany made in order to control and to minimise nuclear risk for society.

It is beyond question that nuclear risk can be referred to as one of the most hazardous forms of economically driven industrial risk and, not least, it is the extraordinary time dimension associated with all forms of nuclear risk that urges societies and policy makers to accept, analyse and overcome enormous challenges. For example, due to the strongly limited assimilative capacity of the environmental system, atomic waste will occupy the resources of a large number of future generations until the material's nuclear radiation will reach a level that is uncritical for human health.

Importantly, however, the present thesis proceeds from the basic idea that there is no genuine connection *a priori* between a certain type of risk and expected losses for society. It is argued that the final impact of the generation of nuclear energy on social well-being depends on society's capability to adapt to the specific circumstances of nuclear technology and the associated social hazard. The adaptive capacity, in turn, is shaped by various policy measures and the institutional framework installed by legal authorities. Thus, the thesis tries to answer the following research questions.

Research Questions

- Based on results of economic theory, what is the adequate institutional and commercial attitude towards nuclear risk?

A main concern of the present thesis is, therefore, to collect and to systematise the contributions of economic theory within the domain of nuclear risk and, subsequently, to evaluate the institutional framework provided by the German policy maker as well as the strategies chosen by German nuclear plant operators and potential victims of atomic hazard in response to these statutory requirements. To this end, the thesis introduces the concept of *nuclear risk management* and examines the relationship between nuclear hazard and policy measures aiming at a socially efficient distribution of nuclear risk. Furthermore, it addresses the potential adaptation strategies on both the supply and the demand side of nuclear energy in response to the institutional framework provided by the policy maker.

In order to answer this first research question, the thesis aims to accomplish the following objectives: *firstly*, to arrange different policies, which are currently applied within the scope of *nuclear risk management* into a coherent system; *secondly*, to identify the optimal policy measures from an economic viewpoint; *thirdly*, to present the current legal and economic adjustments to the generation of nuclear energy in Germany and to evaluate them according to the acquired results of economic theory.

The last part of the thesis, on the basis of economic theory, tries to shed light on the current political and public debate in Germany regarding the legal extension of a nuclear installation's operational lifespan. To this end, it focuses on the relationship between atomic generation of energy, the prevalence of scientific uncertainty and nuclear policy and analyses the economic arguments in respect of a *precautionary principle* – a principle, stating that certain hazardous actions should not be undertaken until scientific uncertainty has been unravelled, even if the commitment to the principle would entail substantial socio-economic costs. The research question, therefore, reads as follows:

- From an economic viewpoint, is a *precautionary principle* generally justified within the regulation process of atomic energy generation? In particular, which economic motives could serve as a rationale of a *precautionary principle* in the specific context?

In order to answer the second research question, the approach of the present thesis is, *firstly*, to analyse various existing economic models of 'decision-making under uncertainty' and, *secondly*, to identify the adequacy of the models within the nuclear context.

The thesis, in this regard, refers to the discussion on the concept of the 'option value' in the fields of environmental economics, which was raised *inter alia* by Arrow & Fisher (1974). Specifically, articles by Fisher (2000) and Gollier & Treich (2000) and (2003) are addressed. The thesis, furthermore, briefly presents a paper by Weitzman (2007), which constitutes an alternative approach to model the problem of decision-making under uncertainty. The overall discussion on the precautionary principle is structured according to a conceptual contribution by Sunstein (2005).

1.1. Outline

Chapter 2 introduces the concept of *social risk management* (SRM), illustrates the realisation process of social risk and provides an insight into SRM related strategies, namely, risk prevention, risk exposure reduction, risk mitigation and risk coping, respectively. Furthermore, it states the objectives of *nuclear risk management* (NRM) and discusses the different instruments for policy makers within an NRM context, namely, regulation and economic incentives.

Chapter 3 addresses potential policy measures aiming at nuclear *risk prevention*. Based on established results of economic literature, it outlines an economic efficiency criterion and proceeds with the associated discussion on optimal civil liability rules in the context of the generation of nuclear energy. The basic principles and the organisational structure of the main international nuclear liability regimes are introduced. The chapter concludes with a discussion on nuclear liability in Germany and its incentive effect for risk prevention.

Chapter 4 focuses on different strategies aiming at an optimal level of *victim compensation*, namely, liability insurance, the building of financial reserves, risk-sharing pools, government provided compensation and financial market solutions, respectively. Both efficiency and applicability of each strategy are analysed in the context of atomic energy in Germany.

Chapter 5 turns to the question about the adequacy of precautionary measures within the nuclear context. It explicitly takes account of the prevalence of scientific uncertainty and analyses the arguments against, and in favour of a *precautionary principle* as a potential guideline for political landmark decisions in the field of nuclear energy.

Chapter 6 concludes and provides an executive summary of the main results.

2. Nuclear Risk Management

The previous Chapter 1 gave an overview over the different sources of atomic risk and its characteristics pointed the significance of the nuclear industry in Germany.

The following discussion analyses nuclear risk from an economic point of view. It does not challenge nuclear generation of energy in general. Instead, it outlines the question of the adequate institutional and commercial attitude towards risk. Therefore, taking as given both the employment of nuclear energy sources and society's exposure to specific forms of nuclear hazard, the objective of the following Chapters 2, 3 and 4 is to address the scope and the various challenges of *nuclear risk management* (NRM). To this end, the relation is analysed between atomic hazard, policy measures aiming at an efficient distribution of social risk and adaptation strategies on both the supply and the demand side of nuclear energy.

2.1. Social Risk Management

A first challenge of the analysis is to find an adequate framework in order to arrange both a variety of problems associated with nuclear hazard and corresponding possible solutions in a coherent way. It is useful at this stage to borrow from theoretical concepts of *social risk management* (SRM).[1] One of the basic ideas of SRM is that there is no genuine connection between a certain type of risk and expected

[1] *Social risk management* is a conceptional framework that analyses possible strategies for households, governments and other institutions to deal with various sorts of risk, such as natural

losses for society. For example, societal and economic implications of a catastrophic event need not inevitably be disastrous; on the other hand, even modest changes in the environmental system may cause irreversibilities that raise serious problems for society: "It all depends on the effectiveness of societies' adaptive capacity, which is shaped by policies and institutions" (Heltberg *et al.* 2009: 89).

Therefore, technological, industrial or natural risks do not *directly* influence expected social welfare. In fact, it is the impact of various adaptation mechanisms – e. g., insurance arrangements, technological safety measures or precautionary schemes – that plays an important role in determining the social loss due to hazardous activities finally realised. Furthermore, the decision by any agent within a risk generating process whether or not to implement a certain adaptation strategy crucially depends on the underlying institutional framework, which has to be provided and designed by governments and other decisive authorities.

To capture these aspects, Figure 2.1 follows the notion of a 'risk vulnerability chain' (*cf.* Heltberg *et al.* 2009) and conceptualises the relation between risk, risk management arrangements and expected losses for society, respectively, realised social welfare.[2] The framework is presented in order to show the capabilities of SRM within the realisation process of social risk and to enable the reader to gain insight into the logical succession of social risk management related issues.

Policy makers can impose compulsory regulative standards or create adequate economic incentives in order to maximise the expected rate of return of a specific

disasters or global climate change caused by human activity. The main concerns of SRM are welfare improvement and equity, economic development and growth, as well as poverty alleviation. For a more detailed discussion on the diverse strategies of SRM and its possible objectives see *inter alia* Holzmann & Jørgensen (2001) and Heltberg, Siegel & Jørgensen (2009).

[2]The figure is based on Heltberg *et al.* (2009: 92); the illustration is slightly altered for the specific purposes of the present thesis.

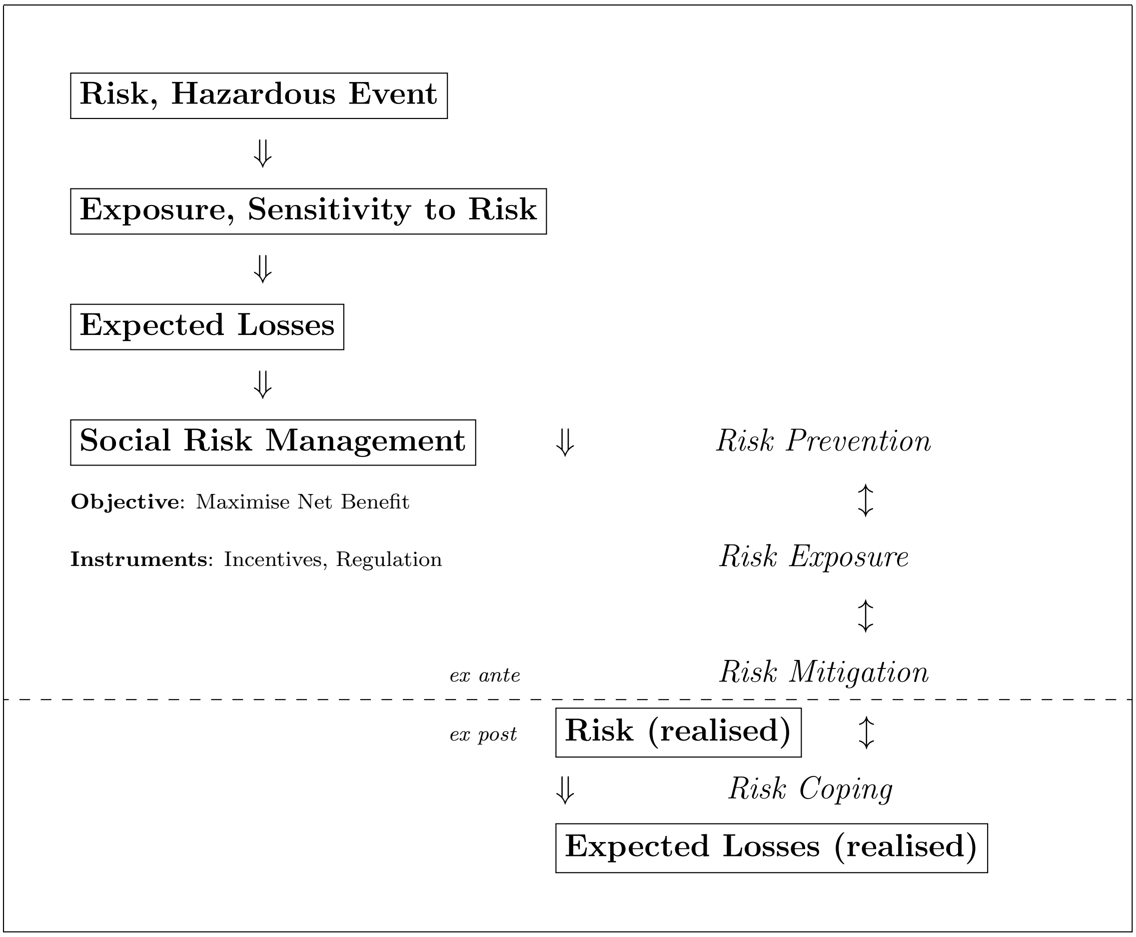

Figure 2.1.: *Social Risk Management and the Risk-Impact Chain*

hazardous (economic) activity, respectively, minimise the expected net damage of a certain risk for society. Four risk management strategies can be identified.

Risk Prevention: The aim of prevention strategies is to reduce the probability of a catastrophic event to happen. In the context of nuclear energy generation, these strategies among other things entail setting mandatory safety standards and defining adequate liability rules for nuclear operators.

Risk Exposure Reduction: Risk exposure reduction is a measure to alleviate the sensitivity of households or society to specific types of risk. Depending on the characteristics of a certain risk, there are numerous ways to reach such an immunisation against hazardous events. In the specific context, both the supply and the demand side of atomic energy can, in principle, make provisions against the negative impacts of risk. Regulators can create legal rules in order to establish such provisions. Furthermore, they can invest in, or accelerate research on alternative energy sources, which would reduce society's currently claimed necessity to expose itself to nuclear risk.

Risk Mitigation: The target of risk mitigation strategies is to reduce the potential adverse impacts of a future *realised* hazard. In the case of nuclear risk, mitigation measures imply the regulation of compensation standards or the design of a suitable legal framework that guarantees various compensation mechanisms to be established in an efficient way. (Liability) insurance or risk-sharing agreements serve as examples for such compensation instruments.

Prevention, mitigation and sensitivity reduction can be referred to as *ex ante* strategies of SRM, since actions are undertaken before a shock occurs. They are accompanied by an *ex post* instrument of SRM, which comes into use after an adverse event takes place.

Risk Coping: The aim of coping strategies is to relieve the impact of the risk once it has occurred. Public compensation funds or catastrophic relief programmes serve as examples.

It is important to emphasise the interconnection between the different measures of SRM, since it shows that the potential success of a certain policy cannot be identified independently from the application of other instruments. For example, *mitigation* strategies can outperform the effect of measures that directly aim at *prevention*, while the specific design of *coping* arrangements has significant repercussions on all other strategic levels of SRM.[3]

Heltberg *et al.* importantly point out that all strategies of risk management entail *real* as well as *opportunity costs* and should ideally result in the "ability to avoid the negative impacts of risky events and recover from them" (*ibid.* 2009: 92). Obtaining an intuition for those (opportunity) costs and presenting concepts to estimate them is one of the major challenges of the thesis.

2.2. Objectives of Nuclear Risk Management

The following discussion on *nuclear risk management* (NRM) will focus on the levels of risk prevention, risk mitigation and risk coping. However, it has transpired to be methodologically convenient to refer to a slightly different classification of risk management measures.

The following analysis, therefore, is arranged in the following way. On the one hand, Chapter 3 focuses on the NRM measure of risk *prevention*. It analyses the instruments aiming at the *direct* reduction of the risk of nuclear accidents. On the other hand, Chapter 4 provides the main arguments in respect of several risk *compensation* strategies. That is, it combines the concerns of both risk mitigation and risk coping mechanisms, respectively. It is important to bear in mind that all regulations in respect of *compensation* – being anticipated by the parties involved in the risk generating process – have a strong effect on the realised level of risk *prevention*. Thus, instruments aiming at the adequate remuneration of victims potentially entail an *indirect* reduction of the risk of nuclear accidents.

To further unravel the complexity of NRM, besides the differentiation between economic incentives and regulation, the dichotomy of supply and demand is ac-

[3]Section 2.2 discusses this complexity in more detail.

centuated throughout the analysis. Both sides react to, and are affected by the institutional framework provided by governmental authorities.[4] It is helpful to give attention separately to both the impact of, and the response to nuclear policy by the nuclear plant operators on the supply side and by potential victims of nuclear energy, which may also represent the demand side of atomic energy. This conceptualisation of NRM, which serves as a guidline for the following chapters, is illustrated in *Figure* 2.2.

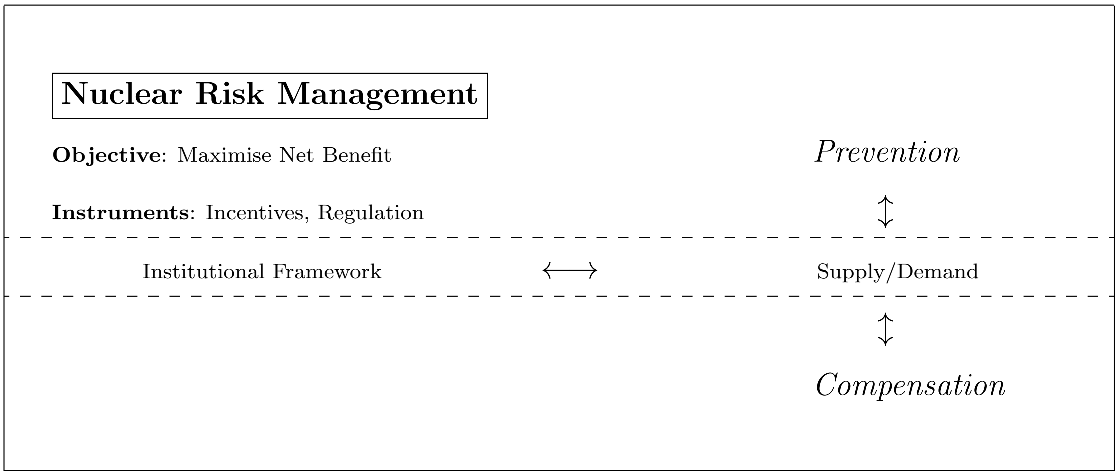

Figure 2.2.: *Nuclear Risk Management*

Therefore, the main task of NRM is twofold, namely, to reach an optimal level of prevention and to guarantee an adequate amount of compensation (Faure & Fiore 2009: 103): *Firstly*, policies must be designed in order to minimise the risk *ex ante* of the generation of nuclear energy. Risk prevention can be achieved

- through economic incentives, by installing an adequate legal framework so that nuclear plant operators will internalise the total cost of their hazardous activities, or

[4]The emphasis throughout the following Chapters 3 and 4 lies on the adaptation strategies implemented by the supply side. However, the role of the demand side is explicitly addressed in Sections 3.1.1 and 4.4.1.

- through regulation, by identifying compulsory safety standards.

Secondly, NRM has to implement policies that aim at minimising the social loss *ex post* from nuclear risk. In general, governments may employ three types of policies that enable the compensation of victims of nuclear accidents:

- They may create liability rules so that nuclear plant operators themselves will search for efficient solutions to meet potential compensation requirements. (These solutions include contracting liability insurance, accumulating reserves, participating in mutual risk-sharing pools or relying on the financial market through specific nuclear catastrophe bonds.)

- They may create a suitable legal and economic environment, respectively, ensure the necessary conditions for the insurance industry to cover nuclear risk.

- Finally, policy makers may establish rules for tax-based victim compensation.

The complexity of theses dimensions has already been mentioned. By way of example, three possible cases illustrate the problem of interconnection. The design of the legal and economic framework for victim compensation mechanisms has a strong impact on the precautionary measures nuclear plant operators are willing to undertake voluntarily. Clearly, this effect is not constrained to prevention within the production processes; the threat of potential future compensation requirements urges nuclear plant operators to choose a location that minimises society's sensitivity to nuclear risk in the first place. Furthermore, the way nuclear reactor operators deal with both prevention and compensation requirements changes substantially whether governments *ex ante* determine rules for public compensation funds or whether they prefer to decide on public catastrophe alleviation on an *ad hoc* basis once an adverse event has occurred. Consequently, conceptual overlapping is somewhat inevitable but explicitly identified throughout the thesis.

Importantly, the use of the term 'nuclear risk' within Chapters 3 and 4 has to be determined. In order for expected value analysis to be applicable in the case of a certain form of risk, it is necessary to be able to assign objective risk probabilities. Hence, 'nuclear risk' solely refers to the possibility of a reactor core melt accident, which is accompanied by scientific certainty. Off-site or transportation related accidents are explicitly excluded from the analysis. Furthermore, other sources of nuclear hazard like the final storage and disposal of nuclear waste are neglected, since due to the lack of scientific certainty the methods of NRM do not apply.[5]

Thus, the objective of the further analysis is:

- *firstly*, to arrange the policy measures currently applied into a coherent system;
- *secondly*, to identify the policies that are, based on economic reasoning, favourable to the concern of NRM;
- *finally*, both to present and to evaluate current legal and economic adjustments to the generation of nuclear energy in Germany.

[5] A methodological approach to nuclear hazard and uncertainty will be presented in Chapter 5.

3. Nuclear Risk Management and Prevention

In a first step, it is necessary to define an optimality criterion that guarantees the *efficient* level of prevention. Within this context, policies based on economic incentives show that they outperform those approaches resorting to regulation.

Nuclear risk prevention, i. e. taking precautionary measures in order to avoid a core meltdown, is a complex engineering process:

> The engineering of safety into nuclear plants is based on the 'defense in depth' principle: a sequence of safety mechanisms is built into the plant, any one of which is capable of halting a developing accident. For an accident to occur at a commercial nuclear reactor there must be an 'initiating event' followed by a sequence of failures by safety components.[6] (Heyes 1995: 1029)

Probabilistic Risk Analysis, a method used to quantify the probability of low-frequency events, distinguishes between two possible sources of 'initiating events', namely, *external hazards* and *human error* (*cf.* Heyes 1995: 1030).[7]

[6] For example, an initiating event such as the loss of offsite power will only lead to a reactor meltdown under the following scenario (*cf. ibid.*): firstly, it is failed to deactivate the turbine generator; secondly, emergency power is not available; thirdly, secondary heat is not removed.

[7] A more detailed catalogue including the sources of nuclear accident risk is presented in

Of course, it is a crucial question, whether a certain 'initiating event' can be referred to as *exogenous* or *endogenous* to a nuclear plant operator. One the one hand, human error or technical failure clearly are in the range of influence of the operator and, therefore, *endogenous*. On the other hand, natural events like earthquakes or tsunamis, or terrorist attacks seem *exogenous* at a first glance. This perception, however, could be challenged bearing in mind the nuclear plant operator's general possibility to take precautionary steps even against those extreme events.

Within the context of the criterion for optimal prevention, it is important to highlight the crucial role *human error* plays within the process of nuclear energy generation. The risk stemming from human action, be it accidental or malicious, is a factor that has not been satisfactorily incorporated in nuclear PRA (Heyes 1995: 1028). From this point of view, it seems extremely difficult to formulate an optimality criterion for the efficient level of prevention that provides a clear guideline for a command-and-control approach. A policy maker cannot observe every detail within the chain of safety mechanisms. In particular, s/he cannot monitor and control error-prone human operation. Nuclear policy based on *regulation* can, therefore, not rely on conceptual criteria but has to resort to current scientific findings.

In contrast, economic theory provides a distinct efficiency measure that enables a nuclear policy approach relying on *economic incentives*. Therefore, with respect to policy instruments that aim at an optimal level of risk prevention, the discussion starts with addressing the optimal design of civil liability. Bearing in mind the conceptual framework developed in the previous sections, it should be highlighted

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Trebilcock *et al.* (1997: 218): "[D]esign errors, errors in construction, human errors in operation, errors or failure in computer systems or in monitoring or detection systems, failures from the running of aging equipment, and risks created by externally initiated events such as natural disasters or malicious interventions."

that the policy measures to be discussed primarily entail responsiveness on the supply side.

The economic efficiency criterion can be derived from a simple social objective function, which aims at minimising the sum of both prevention costs $c(x)$ born by nuclear plant operators and total expected damage $d(x)$ born by potential victims, where x denotes the level of prevention (Schäfer and Müller-Langer 2005: 3).[8] For simplicity, we act on the assumptions of risk neutrality, the absence of administration costs and a constant level of production. Furthermore, the analysis refers to the case of unilateral accidents. Hence, the policy maker's objective function and the corresponding first order condition read as follows:

$$\min \quad c(x) + d(x) \tag{3.1}$$

$$c'(x) = -d(x) \tag{3.2}$$

This suggests that nuclear plant operators have to extend their precautionary effort up to the point where the marginal cost of prevention is equal to the victims' marginal benefit.

A necessary condition for this criterion to be met is the full internalisation of total costs on the supply side, which includes the entire costs of externalities caused by the hazardous activity:

> [S]ince they generate risks for the environment and for human health, from an economic perspective, nuclear operators have to be exposed to the full risk costs that they generate. This means that efficient internalization [...] mechanisms have to be designed to cover these risks. (Faure & Fiore 2009: 103)

A small economic model, presented below, illustrates that in the specific context *full strict liability* is the adequate liability rule to assure full cost internalisation

[8]Clearly, $c'(x) > 0$ and $d'(x) < 0$.

and hence to reach the efficient level of prevention. However, it is valuable to provide for terminological clarity beforehand.[9]

Terminology

Civil Liability: Civil liability is defined as a legal regime, which, from an economic perspective, aims at exposing potential tort-feasors to total damage costs, in order to provide them with the necessary incentives for prevention.

Strict Liability: According to the principle of strict liability tort-feasors are held liable irrespective of their actual behaviour. Specifically, in the case of a nuclear accident, there is no need for victims to prove the negligence of the plant operator.

Full Strict Liability: Corresponding to this principle tort-feasors are held liable without limit.

Negligence: The negligence rule guarantees that tort-feasors will be held liable only if their precautionary effort falls short of a certain prevention level of due care defined by the policy maker.

Channelled Liability: Under the principle of channelled liability, the downstream supplier, i. e., the plant operator, is held liable *exclusively*, regardless of any upstream supplier's negligent bahaviour.

Unilateral Accident: A unilateral accident is characterised by the potential victims' inability to influence the magnitude of expected damage. Accident risk

[9]For a more detailed discussion on civil, strict and channelled liability see e. g. Faure & Fiore (2009: 108 *et seq.*) and (2008a: 229 *et seq.*), and World Nuclear Association (2010: 2). The difference between strict liability and negligence is discussed *inter alia* in Shavell (1980) and (1986), and Schäfer & Müller-Langer (2008).

is solely determined by the plant operator's behaviour.

Judgement-Proofness: A tortfeasor is called 'judgement-proof' if expected compensation requirements by far exceed the net worth of the tortfeasor's assets, once an accident has occurred.

3.1. Civil Liability

The following discussion, which summarises the main results of a model by Shavell (1980), has mainly two objectives. Firstly, to contrast *strict liability* to the liability rule of *negligence*; secondly, to highlight that in the specific context, full cost internalisation is a necessary and sufficient condition to reach the optimal level of prevention.

The Model

Good y (nuclear power), denoted in income equivalents, is sold on a competitive market. Nuclear plant operators are assumed to act as profit-maximising price takers and, therefore, gain zero profit. Production technology exhibits constant returns to scale and entails an external, unilateral accident risk, which is, in the absence of any civil liability, entirely born by victims. Furthermore, it is assumed that parties are risk-neutral and that victims are strangers in the sense that neither operators nor the representative consumer are affected by accident risk themselves. Finally, operators are supposed not to be judgement-proof, i. e., they either have unlimited net worth or can purchase liability insurance on a perfectly competitive insurance market.[10]

Denoting unit prevention costs by $c(x)$ and expected unit liability payments by

[10] The latter assumption is explicitly formulated in Trebilcock & Winter (1997: 222).

L, the operator's cost minimisation problem is defined by:[11]

$$\min_x \quad c(x) + L \tag{3.3}$$

Let p be the market price; then the zero-profit condition is given by:

$$p = c(x) + L \tag{3.4}$$

Customers maximise utility, which is composed of the consumer's gross benefit of y, $b(y)$, his expenses on y and expected accident damage he has to face, D:[12]

$$\max_y \quad b(y) - py - D \tag{3.5}$$

Equations (3.3), (3.4) and (3.5) jointly determine the equilibrium for p, y and x.

The social planner's solution serves as the benchmark for an efficient outcome. Taking into account the (consumption) benefits of good y, as well as both the operator's cost of prevention and the victim's unit damage cost, $d(x)$, the policy maker aims at maximising social welfare:[13]

$$\max_{x,y} \quad b(y) - yc(x) - yd(x) \tag{3.6}$$

The efficient level of prevention, $x*$, is the solution to the following cost minimisation problem, which coincides with the optimality criterion of equation (3.2):

$$\min_x \quad c(x) + d(x) \tag{3.7}$$

The efficient level of activity, $y*$, is then determined by:

$$\max_y \quad b(y) - y\left(c(x*) + d(x*)\right) \tag{3.8}$$

[11] It is assumed that $c'(x) > 0$ and $c''(x) > 0$.

[12] It is assumed that $b'(y) > 0$ and $b''(y) < 0$. For the moment, is is further assumed that consumers and potential victims are two diverse groups of individuals, i.e. $D = 0$.

[13] It is assumed that $d'(x) < 0$ and $d''(x) > 0$.

Since under the absence of any civil liability the operator is not held responsible, s/he does not internalise any risk costs s/he generates and refrains from any precautionary effort. Clearly, the level of prevention is socially inefficient. As a consequence, a low market price induces the consumers to demand an amount of nuclear energy, which is also inefficient from a social perspective.[14]

Under *strict liability* the nuclear operator has to minimise both expenditures on prevention and entire expected damage costs. This liability rule, therefore, guarantees *full cost internalisation* in the specific context. As a result, the operator's decision problem resembles the social planner's solution. Due to the adequate legal and economic incentive, the efficient level of prevention is chosen and the market equilibrium price sends the right signal for consumers to demand the socially desirable amount.[15]

In contrast, the *negligence rule* implicates an inefficient outcome in two different ways. Firstly, supposing the due care level of prevention is small enough, such that the operator has an incentive to act non-negligently[16], the market price does *not* reflect total risk costs, which results in a socially inefficient consumption level of nuclear energy.[17] In other words, the operator is able to "escape" cost internalisation by acting non-negligently. Secondly, under fairly weak assumptions, it can be

[14] If $L = 0$, the operator's optimal decision according to equation (3.3) is $x = 0$. $x < x*$, since in general $x* > 0$. In equilibrium the market price equals therefore to $p = c(0)$. To examine the consequences for equilibrium activity level, we have to compare the first order conditions of equations (3.5) and (3.8), i. e. $b'(y) = c(0)$ and $b'(y*) = c(x*) + d(x*)$, respectively. (Note, that is was assumed that victims are strangers, i. e. $D = 0$.) Since $c(0) < c(x*) + d(x*)$ and $b'' < 0$ it follows that $y > y*$.

[15] Strict liability implies that $L = d(x)$. Therefore, equation (3.3) equals equation (3.7) and $x = x*$. Furthermore, $p = c(x*) + d(x*)$ and from equation (3.5) it follows that $y = y*$.

[16] I. e. the enacted level of prevention, $\bar{x}$, is small enough such that $c(\bar{x}) \leq \min c(x) + d(x)$.

[17] The operator chooses $x = \bar{x}$; therefore $p = c(\bar{x})$ and for analogues arguments as in footnote 14 it follows that $y > \bar{y}$, where $\bar{y}$ denotes the socially optimal level of activity, given $\bar{x}$.

shown that the policy maker defines a safety standard, which exceeds the socially preferable level of prevention, since "it is socially desirable to compensate for [the] inability to control the activity level by forcing injurers to exercise special care" (Shavell 1980: 12).

It is still possible to challenge the assumption according to which consumers do not have to bear any consequences of accident risk themselves.

Strict liability remains to yield efficient results. Again, the operator has to internalise total risk costs, which is reflected in the market price, and chooses an optimal prevention level. Consumers – due to full financial compensation – do not have to bear any losses caused by a nuclear accident and will demand the socially efficient level of nuclear energy.

Under the absence of civil liability, in general, prevention and activity levels are inefficient, except when consumers are perfectly informed and perceive the risk correctly. The latter case is highly implausible and can be ruled out based on results of empirical economics, which suppose that individuals tend to treat the probability of low-frequency events as essentially zero.[18] Furthermore, even if individuals would not exhibit this kind of irrational behaviour, the assumption of symmetric information between plant operators and victims can be rejected on theoretical grounds.

It is, therefore, reasonable to assume that the consumers misperceive, i. e., underestimate, nuclear accident risk.[19] Under a negligence-regime, again, the operators can escape liability, complying with the enacted safety standard. Since, therefore, accident costs are external to the operator, the market price is too low and consumers, underestimating the risk of a nuclear accident, purchase an amount of

[18] For a detailed discussion and experimental results see *inter alia* Sunstein (2005) and McClelland, Schulze & Coursey (1993).

[19] Expected accident damage D, therefore, equals to $y(1+\lambda)d(x)$, where $\lambda < 1$.

nuclear energy, which is socially inefficient.[20] (On the contrary, if consumers were perfectly informed and the policy maker was able to define the socially optimal due care level of prevention, a *negligence rule* could lead to an efficient outcome. For the reasons mentioned above and due to problems of controlling and monitoring discussed at the beginning of Chapter 3, this can be rejected in the specific case.)

The aim of the preceding analysis was to highlight the *theoretical* convenience of holding the nuclear industry strictly liable, which can be summarised as follows:

> Strict liability *internalizes* the costs of the accident to the transaction that is generating the risk. Care decisions are efficient under strict liability because the producer bears the full social costs and benefits of increased care. The activity level, or quantity of the commodity purchased, is efficient because the market price for the commodity reflects the full marginal social cost of production, including the costs of accidents. The product is consumed up to the point where the marginal social value of consumption equals the marginal social cost. (Trebilcock & Winter 1997: 222)

Additionally, strict liability entails further *practical* advantages. *Firstly*, strict liability is a cost-effective strategy in relation to negligence in the sense that it entails less administrative expenses (Schäfer & Müller-Langer 2008: 6 *et seq.*). Defining a prevention level of due care is a costly process. Given the adequate economic incentive, plant operators are better informed to choose the efficient level of prevention at minimum cost. Furthermore, monitoring the operator's behaviour and proving negligence is also involved and expensive. In addition to

[20] If $x = \bar{x}$ it follows that $L = 0$ and $p = c(\bar{x})$. The first order condition of the consumers' maximisation problem reads as $b'(y) = c(\bar{x}) + (1 + \lambda)d(\bar{x})$. In comparison with the social planner's problem $b'(\bar{y}) = c(\bar{x}) + d(\bar{x})$, and since $\lambda < 0$, respectively $b'' < 0$, it follows that $y > \bar{y}$.

these cost saving potentials on the side of policy makers and courts, strict liability financially alleviates civil action by potential victims. This increases the pressure for operators to engage in precautionary activity. *Secondly*, strict liability might be preferable from a distributive point of view. In the case of a nuclear accident, it is assured that victims are fully compensated under all circumstances, since plant operators cannot escape liability by acting non-negligently.[21]

3.1.1. Magnitude of Liability

The benchmark case presented above is conditioned on restrictive assumptions and although strict liability has an established juridical tradition, disagreement about the extent of the nuclear sector's liability still remains. The following discussion, based on Trebilcock & Winter (1997: 221 *et seq.*), shows that the specific characteristics of nuclear risk are by no means an argument against *unlimited* liability as the socially preferred rule.

A first point of critique refers to both the nature of atomic externality and the role of the consumer as a potential victim: It can be argued that since consumers of nuclear energy are potentially affected by nuclear hazards, an efficient outcome could be achieved through bilateral negotiation.[22] In this case, incentives for prevention do *not* depend on civil liability rules ('Coasian irrelevance'). An individual consumer does indeed take into account the personal risk s/he faces due to an extra unit of nuclear energy purchased, but s/he does not account for the potential losses born by third parties. 'Coasian irrelevance', therefore, only takes place under the unrealistic assumption that *all* consumers and victims as well as

[21]Clearly, the latter argument does only hold under the assumption that the corresponding *standard of justice* is the so-called *polluter-pays-principle* (PPP), a principle which is widely accepted in environmental law but still divergently appreciated in different legal regimes.

[22]A concept first to be discussed in a famous article by Coase (1960).

the operator reach a mutual agreement. Consequently, the argument is not strong enough to reject *full* strict liability.

Secondly, it can be questioned to what extent nuclear risk can be referred to as *unilateral*. Bearing in mind the possibility of reducing sensitivity to risk[23], it can be argued that nuclear operators as well as potential victims should bear responsibility. The latter can essentially reduce expected accident damage, since they are free to choose a residence far away from nuclear plants. Under that point of view, a legal regime holding operators exclusively liable fails to create the right incentives on the side of potential victims. Nevertheless, victims would have to invest in information about nuclear risk and technology – expenses that operators will incur anyway to reduce on-site damage costs. Furthermore, the opportunity costs of an uninhabited risk zone and the consequent loss of economic activity would be enormous. Based on the principle of 'least-cost avoidance', this argument can consequently be rejected.

Thirdly, critics of an *unlimited* liability rule refer to the inefficiencies of the tort system. Identifying and compensating victims, indeed, involves substantial transaction costs. But this is true for *any* compensation mechanism. Furthermore, only tort law and its liability mechanism can guarantee total cost internalisation and create efficient safety incentives.

Finally, Trebilcock and Winter address the issue of second-best considerations. In contrast to alternative methods, the low carbon footprint of atomic energy recovery is used as an argument in favour of subsidising the nuclear industry by reducing liability. Nevertheless, they argue, such comparison of externalities is awkward, since a subsidisation rather creates perverse incentives against prevention. Policy makers are well advised to treat different externalities – such as pollution or nuclear risk – autonomously. Accordingly, second-best considerations

[23] *Cf.* section 2.1 on *social risk management*.

do not challenge the principle of full strict liability in the specific context.

3.1.2. Liability and Regulation

The nuclear industry is a highly regulated sector. Based on an elaborate economic model, Trebilcock & Winter (1997) try to examine whether the presence of compulsory safety standards can make a case for a limitation of liability at the social optimum. The analysis emanates from the fact that the regulator is confronted with a plurality of different safety dimensions. Some of them, which can be officially monitored – such as the nuclear plant's initial design features or modifications of its equipment –, and some of them, which cannot be controlled – such as various human decisions and (hidden) actions within the operator's risk preventing activity.

In the case of preventive measures that can be monitored on a 'zero-one' basis – e. g., the quality of plant material – *full* liability is efficient on all accounts, irrespective of the level of regulation. The underlying intuition is that an expansion of liability will further minimise social costs, while it cannot create perverse incentives for the operators to further engage in inefficiently high prevention levels in over-regulated safety dimensions. In the presence of regulative measures that can only be monitored with an observation error – e. g., the accuracy of plant employees – *unlimited* liability remains optimal, as long as the policy maker does not impose a safety standard that exceeds the socially efficient level. In that particular case, the operator would have an incentive to misleadingly extend preventive efforts.[24] The authors' results can be summarised as follows:

> [F]ull strict liability dominates limited liability in providing efficient incentives for safety even if the existing regulatory standards are ex-

[24] It seems rather improbable though that policy makers would over-regulate dimensions, which cannot be monitored adequately.

> cessive in dimensions, such as the physical design requirements of the plant, that are monitored without error. In this sense the most basic principle in the economics of torts – that the assignment of a higher share of accident costs to a single tort-feasor will improve the tort-feasor's incentives to avoid the accident – extends to the case of a mixed tort-regulation incentive system. (*ibid.*: 227)

3.1.3. Liability and the 'Insolvency Problem'

So far, the desirable impact of full strict liability on prevention levels has been shown, supposing plant operators to be perfectly solvent in the case of an accident. Importantly, economic theory provides evidence that this result is not robust, once the latter assumption is rejected. In the case of anticipated insolvency, the policy maker is confronted with a moral hazard problem of serious consequence, since a tort-feasor has no incentive to internalise costs s/he presumable cannot be held liable for. It has been shown that strict liability leads potentially judgement-proof tort-feasors to engage in inefficiently low levels of precaution (Landes & Posner 1984: 420).

This can be illustrated using the model by Shavell (1980), presented above. If an operator's assets do not suffice to meet total compensation requirements, once a severe nuclear incident has occurred, the operator will only partly internalise damage costs, i. e., compensation payments that assumingly exceed the operator's net worth are external to the firm's cost minimisation problem. Assuming that both marginal prevention costs and expected marginal expenses on liability are increasing in the level of prevention, a *de facto* limit on liability due to the operator's judgement-proofness will lead to under-deterrence. Again, the market mechanism will transfer the price signal into socially undesirable levels of activity.[25] (This

[25] $L = \mu d(x)$, where $\mu < 1$, and equation (3.3) cannot yield the efficient outcome of equation

effect is still dominant under the alternative assumption that prevention reduces expected accident damage at a *decreasing* rate.[26])

Insolvency is a highly probable scenario in the case of nuclear incidents. Relating to the possible off-site consequences of a severe accident, Heyes *et al.* (2000: 94) note that a comparison of various expert studies suggests a "reasonable" estimate to be anything between $1 and $100 billion. Faure & Fiore (2009: 117) refer to expert estimates of worst-case damages that range between €10 billion and €100 billion. This potential catastrophic impact is a strong economic argument for policy makers to commit operators to purchase financial coverage (Faure 2007: 343).

Making liability insurance compulsory is especially important in the case of strict liability, since it has been shown *inter alia* by Shavell (1986) that tortfeasors do not have any incentives to purchase financial coverage voluntarily. Given liability insurance were obtained, Shavell furthermore illustrates that – except when insurance companies were perfectly able to monitor the operator's preventive behaviour – care levels were too low from a social perspective.

The notion to completely solve the 'insolvency problem' through an obligation to purchase liability insurance is based on two rather unrealistic assumptions. First, the insurance market has the capacity to provide sufficient funds to cover entire expected damage costs; secondly, the insurance market does not exhibit informational asymmetries. Accordingly, it has to be analysed whether relaxing

(3.7). Assuming that $c'' > 0$ and $d'' > 0$, comparative statics imply that $x < x*$, since in the optimum $dx/d\mu > 0$. Furthermore, price equation (3.4) and consumer's utility maximisation (3.5) suggest that $y > y*$.

[26]Here, $d'' < 0$: A necessary though plausible condition for the result to hold is that marginal prevention costs increase more rapidly than marginal costs of liability decrease, proportionately to the expected cap on liability. If $L = \mu d(x)$, comparative statics from equation (3.3) show that $\frac{dx}{d\mu} = -\frac{d'}{c''+\mu d''}$. It follows that $dx/d\mu > 0$ if $-\mu d'' < c''$ and $dx/d\mu < 0$ otherwise, respectively. This condition is not considered by Schäfer *et al.* (2008: 9) who wrongly conclude that under strict liability under-compensation *in general* leads to under-deterrence.

these assumptions provides an argument *against* holding nuclear operators *fully* liable.

Trebilcock & Winter (1997: 228 *et seq.*) argue that the first point of critique – according to which the insurance market cannot entirely cover nuclear risk – is inappropriate to oppose unlimited liability, in general: Firstly, extended liability always creates positive incentives for prevention. Secondly, the private insurance market can be completed by government provided liability insurance and even if premiums were set too low, unlimited liability is preferred, since a cap on liability actually corresponds to a public liability insurance at zero-cost, preventing full internalisation of accident costs.

The prevalence of asymmetric and imperfect information between operator and insurance company is an inadequate argument, too. The authors are able to show mathematically that, again, *full* liability ensures the social optimum. Even the slightest possibility to monitor the operator's behaviour will create incentives to raise the prevention levels beyond official safety standards, given liability is extended. The following statement concludes the discussion on the 'insolvency problem' and the optimal level of liability:

> To argue for unlimited liability, it is enough to point out that [a] limit [. . .] is equivalent in its incentive effects to the provision to of liability insurance at a *zero* price. (*ibid.*: 231 *et seq.*)

Results

So far, the two main insights provided by the analysis can be summarised as follows:

- Since strict liability – from a point of view of prevention – creates optimal economic incentives on the supply side, it should be preferred to a negligence rule.

- For similar reasons liability should be unlimited. This result does not change, no matter whether basic assumptions of the benchmark case are weakened, regulation is included into the analysis, or the 'judgement-proof' problem is considered, respectively.

3.1.4. 'Channelling' of Liability

To complete the discussion on the optimal civil liability regime for nuclear plant operators, the issue is addressed whether responsibility of upstream suppliers of components and services should be 'channelled' to the operator.[27]

Indeed, given both the absence of administration costs and unlimited net wealth as well as ignoring distributive effects, the Coase theorem implies that the downstream producer of nuclear energy and upstream suppliers will reach a mutual agreement, which guarantees both efficient levels of prevention and activity, irrespective of the initial allocation of liability. Furthermore, since the contracting parties' objective is to minimise total costs, the mutual agreement ends up in transferring liability to the party, which is best informed in order to avoid risk costs, i. e., the plant operator. The rule of 'channelled' liability, therefore, seems efficient from a social perspective referring to the 'best-placed decider' argument. Nevertheless, this result changes in the presence of the 'insolvency problem'. 'Channelling' amplifies the negative consequences of a *de facto* limit on responsibility:

> The channeling of liability to the operator magnifies the effect of the limit by forcing the limit to apply to the *total* liability of the operator plus all input suppliers. The negative incentive effects on both care and activity are magnified correspondingly. (Trebilcock *et al.* 1997: 233)

[27] The presented arguments resort to Trebilcock & Winter (1997: 232 *et seq.*).

The authors advise against mandated 'channelling' of liability and conclude that in addition to a strict liability rule for plant operators, upstream suppliers should optimally be held liable for nuclear accidents on a negligence basis.

3.2. Liability Regimes

The aim of the following section is firstly to provide a short overview of the different liability regimes, presenting the international conventions on nuclear energy currently in force[28] and secondly, to evaluate the liability rules based on the theoretical results that have been achieved so far.

According to the World Nuclear Association (WNA), an international organisation to promote the concerns of currently 85 percent of the world's nuclear energy producing operators, most international conventions and national laws regarding nuclear third party liability are based on 5 basic principles:

- Operators are held strictly liable: On the side of the victims, the obstacle to proof negligence is suspended in order to unburden the litigation process. On the side of operators, this policy creates the adequate incentives for prevention. Economic theory advocates this approach.

- Operators are exclusively liable: It has been shown in the previous section that 'channelling' of responsibility leads to perverse incentives for prevention in the presence of limited liability or presumed insolvency. Nevertheless, this policy measure does not only influence behaviour on the supply side. In defence of this principle, one has to highlight its objective to alleviate litigation, i. e., to encourage potential victims to insist on their right for compensation. Since under 'channelled' liability operators are confronted

[28] The overview is based on World Nuclear Association (2010) and Faure *et al.* (2008a), (2008b) and (2009), respectively.

with a higher quantity of expected civil lawsuits, this particular nuclear policy might in fact create positive incentives for prevention. However, the dominant effect cannot be identified *a priori*.

- The operators liability is limited in amount and in time: Undoubtedly, these limits represent a socialisation of nuclear risk. Following the arguments of WNA, this is just the fair price society has to pay in order to profit from nuclear energy, since the state has to take risk for *any* major infrastructure facility to materialise. Needless to say, such reasoning is not supported by economic theory. Wrong incentives and market distortions outweigh the value of nuclear energy for society. Taking account of the potential catastrophic harm due to atomic hazards, any form of subsidisation should be avoided from an economic perspective.

- Operators are mandated to purchase financial coverage: According to economic theory, this is necessary to avoid that operators become insolvent in the case of an accident. Nevertheless, the following sections will illustrate that current international arrangements are not suitable to guarantee both an efficient level of prevention and an adequate amount of compensation.

- Finally, the principle of 'exclusive jurisdiction' states that only the legal entity in which an accident takes place is legally responsible: On the one hand, this provides the operators with a degree of certainty. On the other hand, it further alleviates the litigation process, which especially is advantageous in the case of transport related off-site accidents.

There exist two *international* regimes regulating nuclear liability; furthermore, several states refer to individual arrangements.

3.2.1. OECD Regime

Nuclear liability of most OECD member states is governed by the *Paris Convention* (1960), which came into force in 1968 and is currently ratified by 14 states including *inter alia* France, Sweden, the United Kingdom and Germany. It was supplemented by the *Brussels Convention* (1963) and was amended in the years 1964, 1982 and 2004, respectively.

The *Paris/Brussels Conventions* incorporate the principles illustrated above and distribute liability among three levels – the first tier being privately funded, the remaining two being financed on a public basis: the operator, the individual state of a potential accident, and the community of the conventions' member states.

Currently, most nuclear operators in the OECD area profit from a cap on liability, which is defined by the individual member state and does not exceed the amount of €210 million. For example, French operators are individually liable for third party claims up to €91 million (Faure & Fiore 2008a: 231); the remaining risk of damage up to €360 million is allocated to French taxpayers and to the community of all contracting parties to the *Paris/Brussels Conventions*, respectively. The liability caps before and after the last amendment of the *Paris Convention* in 2004 are presented in Table 3.1.[29] Importantly, the 2004 amendment has yet not been ratified by enough countries to pass into force. Five concerns though attract attention:

Firstly, a future ratification involves a remarkable increase in both total and especially in operators' liability. Nevertheless, €1.5 billion is a negligible amount compared to actual estimates of worst case scenarios between €10 and €100 billion. This tension is even more remarkable since, *secondly*, the definition of 'nuclear damage' will be extended to the concepts of environmental harm and economic

[29] Data stem from Word Nuclear Association (2010); caps according to the *Paris Convention*'s 1982 amendment are converted from *special drawing rights* (SDR) into € by a factor of 1.2.

	Paris/Brussels Conventions 2. Amendment (1982)	*Paris/Brussels Conventions* 3. Amendment (2004)
Operator's Liability Cap	*cap*	700
State's Intervention	210 − *cap*	500
Contracting Parties Coverage	150	300
Total	360	1,500

Table 3.1.: *Liability Caps according to* Paris/Brussels Conventions *(in million €)*

loss. From a viewpoint of efficient prevention, although substantially increased, the 2004 protocol's liability caps, therefore, cannot be supported by economic reasoning. *Thirdly*, the amendment extends the limitation on liability in time. In the case of death or individual harm, the prescription delay for a lawsuit against operators is specified to 30 years, while other types of damage must be sued for debt within a period of 10 years. *Finally*, the 2004 protocol explicitly allows member states to pursue a policy of *unrestricted* liability. However, it has to be highlighted that, in contrast to all other countries in the OECD area, German nuclear legislation was already able to establish a policy of unlimited liability.

3.2.2. Alternative Regimes

The second *international* regime to regulate nuclear liability joins the member states of the IAEA under the *Vienna Convention* (1963), which came into force in 1977 and is currently ratified by 10 states. Its 1997 amendment became effective in 2003 and is characterised *inter alia* by an operators' liability cap of approximately €360 million and a definition of 'nuclear damage' that includes ecological harm. A joint convention in 1988 regulates liability between the parties of the *Paris/Brussels Conventions* and the *Vienna Convention*, respectively.

Countries like China, India, Japan or the United States, which bear significant nuclear capacity, rely on their own liability arrangements. US American nuclear law serves as an important benchmark. Liability in the United States is governed by the Price Anderson Act (PAA) (1957), which was amended last in 2005. Most notably and in contrast to the OECD regime, under the PAA the government does *not* bear any financial burden in the case of a nuclear accident. The individual operator is held liable up to $300 million. Additional capital, summing up to approximately $10.5 billion, is provided through a mutual fund by all nuclear operators. Emanating from modest estimates of accident scenarios, financial provisions are sufficient to cover entire damages. Consequently, US American nuclear law guarantees *full* cost internalisation – the necessary condition to reach efficient levels of risk prevention. Of course, if one factors in possible scenarios entailing nuclear damage that far exceed $10 billion, the nuclear policy regime in the United States loses part of its merits.

3.2.3. Implicit Nuclear Liability Subsidy

On the grounds of economic theory, it has been already argued that a liability cap on the side of plant operators prevents the risk of nuclear energy generation from being considered within the production process in a socially efficient way.

It has been shown in the literature that such restrictions on liability, therefore, constitute an indirect subsidy to the nuclear industry (Faure & Fiore 2009; Heyes & Heyes 2000; Dubin & Rothwell 1990). Evaluations of the annual nuclear subsidy for operators in France, Canada and the United States, respectively, suggest that the negative consequences of a liability cap on prevention levels are by no means negligible.[30] Faure & Fiore (2009: 118 *et seq.*) estimate the implicit nuclear subsidy of an average nuclear operator in France to range between €140,000 and €3.3 million.[31] This corresponds to the additional costs per reactor-year a nuclear operator would have to come up for without restrictions on liability – though under the (unrealistic) assumption that private liability insurance would be available without limit, at the *actuarial* price. The results translate into a subsidisation of the French nuclear industry in the amount of €8.12 million, respectively €191.4 million per year. The authors underline that the average subsidy would decrease at a rate of 44.2 percent under the arrangements of the 2004 protocol. Nevertheless, they conclude, the non-internalised risk costs would still cause socially inefficient prevention levels.

Besides concerns regarding an insufficient level of prevention, the indirect subsidisation is subject to further criticism. *Firstly*, it causes competitive disturbances; full cost internalisation would alter the competitiveness of the nuclear sector within the whole energy industry. Faure & Fiore (2009: 123), nevertheless, are able to show that an internalisation of total risk costs would be financially sustainable in the case of the French nuclear industry, since the implicit subsidy currently at most accounts for 11.26 percent of the industry's average annual benefit. Furthermore, the industry could transfer the burden of cost internalisation

[30] The estimations are based on a technique developed by Dubin & Rothwell (1990), which was supplemented by Heyes & Liston-Heyes (1998). The method is particularly convenient, since it specifies the density function of nuclear damage using only two pieces of information; data on private liability insurance arrangements and data on expert estimates regarding the probability and the dimension of nuclear worst-case scenarios. The subsidy is defined as the expected value of the non-internalised damage, i. e., the expected value of loss above the liability cap.

[31] The wide range results from the different estimates of accident probabilities, worst-case scenarios and the risk aversion of the insurance industry.

entirely to consumers of energy without any substantial loss in competitiveness. *Secondly*, implicit subsidisation prevents potential victims from being fully compensated. It is argued that victim compensation is *not* merely a distributional issue. Considering the potential catastrophic consequences of a nuclear accident the question of adequate victim compensation appears to be a matter of economic efficiency.[32]

Currently, German legislation does not offer any explicit liability cap to the nuclear industry. *Prima facie*, the concept of a nuclear liability subsidy does not, therefore, seem to be applicable. Nevertheless, if one takes into account the strongly debated issue of the 'insolvency problem', and if one factors in the poor arrangements currently made for victim compensation *ex ante*, the question about an implicit subsidy for German operators is still predominant.

3.3. Nuclear Liability in Germany

Germany is a member country to the *Paris/Brussels* protocols. Therefore, nuclear operators are strictly liable, which is uncontroversial from an economic point of view. According to German nuclear law, operators additionally have to come up for *entire* accident damage.[33] This policy of unlimited liability is unique in current international liability regimes. As has been shown in the previous sections, economic theory encourages this approach.

German nuclear operators are individually obliged to provide financial coverage up to €2.5 billion. The amount of coverage is defined in relation to the risk

[32] The issue of Compensation is discussed in detail in the following Chapter 4.

[33] Nuclear legal regulation in Germany is formulated in *Gesetz über die friedliche Verwendung der Kernenergie und den Schutz gegen ihre Gefahren (Atomgesetz – AtG)* and *Verordnung über die Deckungsvorsorge nach dem Atomgesetz (Atomrechtliche Deckungsvorsorge-Verordnung – AtDeckV)*, respectively. For a brief summary see *e.g.* Deutsches Atomforum (2010).

of an individual plant.[34] The plant's productive capacity, denoted in *megawatt* (MW), serves as proximity. It shows that the marginal burden for operating plants above a capacity of 1004 MW is zero. Thirteen out of 17 German nuclear plants capitalise on this legal cap on compulsory provision. For example, the operator of the largest nuclear installation in Germany (Isar-2) did not have to internalise risk costs correlating to 418 MW in the year 2010. This can be equivalently interpreted as an indirect subsidisation, since the operator does not have to provide for additional compensation funds in the amount of €1.2 billion. Clearly, this cap undermines the incentive effect of the policy.

Since the insurance market is not able to supply sufficient funds, the duty to provide for financial security is furthermore accomplished *via* a risk-sharing pool including all nuclear operators.[35] Producers of nuclear energy in Germany are individually insured against third party accident damage up to €256 million, while the mutual fund is supposed to cover the remaining amount of €2.244 billion. German compulsory liability provisions, although comparatively extensive, are not sufficient to cover expected financial requirements in the case of an accident. In respect of *direct* financial precaution, nuclear law in Germany does not, therefore, assure the economic condition for efficient risk prevention. Although it outperforms regulation standards according to the *Paris/Brussels* protocols, it cannot create the strong incentives entailed in US American law.

In Germany there are currently six different *operating companies* managing the operation of up to six nuclear power stations, which are mainly organised as limited liability companies.[36] *Operating companies* are subordinate to one of four major

[34] *Cf.* §9 AtDeckV.

[35] A detailed discussion on both nuclear insurance and mutual risk-sharing pools is presented in the following Chapter 4.

[36] German *operating companies* (numbers of nuclear power stations are indicated in brackets): *E.ON Kernkraft GmbH* (6), *EnBW Kernkraft GmbH* (4), *KKW Grundremmingen GmbH*

German *energy groups*, which are organised as joint-stock companies.[37]

To compensate for insufficient *direct* financial precaution, *operating companies* in Germany are liable for damages that exceed the €2.5 billion level with their entire assets. This policy is in line with economic theory.

Nevertheless, its expected effect crucially depends on the extent an individual operator can be assumed to be 'judgement-proof'. If the operator's net worth in the case of an accident is presumed to be lower than expected total losses, it can consequently be argued that the operator's *ex post* asset value constitutes an *indirect cap on liability*, which would prevent entire cost internalisation.[38] Hence, efficient prevention levels may not be reached within the German liability regime. Table 3.2 summarises the results achieved so far.

Tier of Guarantee	*Coverage*	*Incentives for Prevention*
Operator's individual *liability insurance*	€256 million	High incentives relative to common liability regimes in OECD area.
Risk-sharing pool	up to €2,244 million	Strong incentive relative to average OECD countries; weaker effect in comparison to US PAA.
Operator's assets	theoretical: unlimited coverage *de facto*: net worth *ex post*	In theory, policy creates efficient incentives; *de facto* the operator's expected net worth *ex post* constitutes an implicit liability cap; efficient prevention level are not guaranteed.

Table 3.2.: *Nuclear Liability in Germany – Incentives for Preveniton*

To provide a final evaluation of German nuclear policy from the standpoint of

(2), *RWE Power AG* (2), *KKW Brunsbüttel GmbH* (2) and *KKW Lippe-Ems GmbH* (1).

[37] German *energy groups*: E.ON, RWE, EnBW and Vattenfall.

[38] *Cf.* previous Section 3.2.3 on the implicit nuclear subsidy.

prevention, it is necessary to clarify whether unlimited liability is a credible threat to avoid insolvency related issues of moral hazard. Two driving forces behind the occurrence of the 'insolvency problem' can be identified:

One argument for nuclear operators to consider themselves as 'judgement-proof' has already been mentioned: Operators have no incentives to internalise entire risk costs if a firm's anticipated net asset value *ex post*, i. e., once an accident has occurred, is lower than expected third party liabilities. It is reasonable to assume an operator's stock exchange value to suffer from substantial losses in the case of an accident. In particular, it will presumably draw near zero, since it is the nuclear installation itself which constitutes the main net worth. The 2009 financial reports of German energy groups reveal that subordinate limited companies operating up to four nuclear power plants do not exhibit an adequate capital base in respect of future liability claims. Values on equity capital range from €10 million to €166 million.[39] According to this scenario, four operating firms running 9 out of 17 nuclear plants in Germany *de facto* would face an implicit cap on liability in the amount of €2.5 billion – the sum, which obligatorily has to be made available *ex ante*. *RWE power AG*, showing a capital base of approximately €2 billion, is an exception. As far as the level of *operators* is concerned, a policy of full strict liability does not entirely solve insolvency related issues.

Nevertheless, individual operators are subordinate to large parent companies and German energy groups like *RWE*, *E.ON* or *EnBW* might exhibit significant equity capital to cover future third party claims. Table 3.3 lists German *energy groups'* capital resources and relates them to the individual group's share of nuclear risk in Germany.[40] It appears that three parent companies, which jointly account

[39] *Cf.* RWE (2010), Vattenfall Europe (2010) and EnBW (2010); data in respect of *E.ON Kernkraft GmbH* are not included in the reports.

[40] Data on equity capital are drawn from firms' 2009 business reports RWE (2010), E.ON (2010), Vattenfall Europe (2010) and EnBW (2010), respectively. Firms' share on nuclear risk is

Energy Group	Risk Share in %	Equity Capital in bn. €
E.ON AG	45	44
RWE AG	27	13.7
Vattenfall Europe AG	7	9.8
EnBW AG	22	6.4

Table 3.3.: *German Nuclear Energy Groups: Risk Share and Equity Capital*

for 78 percent of nuclear risk in Germany, individually hold sufficient capital to cover expected damage costs, employing low-level estimates of nuclear catastrophes. Consequently, NRM in Germany, to some extent, is able to create correct economic incentives for prevention. It is necessary, however, to abstract from worst case scenarios above the €10 billion level and to assume that the disposable equity capital of the *parent company* constitutes the *de facto* limit on liability.

Four points of critique remain: *Firstly*, the system does not provide an efficient incentive effect for EnBW, an energy group owning an operating company managing four nuclear power stations and accounting for 22 percent of atomic energy in Germany. Under full strict liability, an equity base of €6.4 billion is not sufficient to rule out the possibility of the energy group's 'judgement-proofness'. *Secondly*, the social outcome of German nuclear regulation has to be adjusted in virtue of the *uncertainty* correlating with *ex post* asset values. *Thirdly*, the results above are based on the assumption of a specific low-level estimate of nuclear damage costs. If one considers the possibility of worst case scenarios in an amount of up to €100 billion, the nuclear liability regime in Germany loses part of its incentive effect for efficient prevention. *Fourthly* and most importantly, operating firms and parent companies are two distinct legal entities. It is a crucial question whether

calculated as fraction of total production of nuclear energy (in MW). Data on operators' productive capacity are provided by *Bundesamt für Strahlenschutz* (2010).

the unlimited liability of the individual operator can be exhaustively transferred to the superior corporate level.[41]

A second argument for the 'insolvency problem' to occur refers to the role of the government and its specific concerns in the case of a severe nuclear incident. It can be argued that companies of this size are too important to fail from a national economic perspective. Once an accident has occurred, policy makers have an incentive to act in a way, such that losses in employment are minimised. Furthermore, a mandated insolvency presumably causes the energy market to become even more monopolistic. In total, the social planner, therefore, has a strong incentive to deviate from a predefined behaviour and to bail out nuclear operators. Not least, this argument draws upon WNA's statement on *Liability for Nuclear Damage*.[42] It is argued that above various provisions for victim compensation guaranteed *ex ante* "there is at least a tacit acceptance that the installation state will make available funds to cover anything in excess of these provisions, just as is the case with any major disaster – natural or other" (WNA 2010: 5). This would, of course, reduce the credibility of the threat to become insolvent and full strict liability could not guarantee an efficient level of prevention. As seen from this perspective, German nuclear regulation seems to be deficient in comparison to, for example, the US American PAA, since in the latter case, sufficient compensation funds have to be assured *ex ante* and policy makers prevent being on the horns of a dilemma.

[41] This is a delicate judicial concern, which is beyond the scope of the present analysis. The lack of legal precedence further exacerbates accurate predictions.

[42] Note that all nuclear energy groups involved in the German energy market currently are members of WNA.

Evaluation

- German legislation in reference to the tier of *direct* financial provision does not create optimal incentives for nuclear risk prevention.

- If recourse claims of potential victims can only resort to capital funds of the *operating companies*, the policy of unlimited liability does not solve the 'insolvency problem'.

- Efficient prevention levels are guaranteed by the German liability regime if it is the case that *parent companies* can be held liable with their entire assets. Nevertheless, the argument is invalid if expert estimates of worst-case scenarios beyond the level of €40 billion are to be believed.

- Regardless of the policy of unlimited liability, it can be argued conclusively that *nuclear risk management* in Germany does not guarantee the optimal level of risk prevention as long as the 'insolvency problem' is not solved satisfactorily. To this end, the policy maker would have to ensure adequate arrangements for victim compensation *ex ante*, respectively, to substantially extend compulsory financial provisions in order to cover the entire needs of potential victims.

3.4. Nuclear Safety Regulation

At the beginning of Chapter 3, it already has been stated that nuclear safety regulation constitutes an inferior approach in relation to policies of economic incentives. Referring to the principle of 'least-cost avoidance', it has been argued that, given the adequate economic incentive, nuclear plant operators are assumed to reach the socially desirably level of risk prevention in a cost-effective way.[43]

Nevertheless, it has transpired that both (implicit) caps on liability and the predominance of the 'insolvency problem' lead to an insufficient preventive effort on the side of power plant operators. Hence, an incentive policy might *de facto* fail to develop its desired effect. Therefore, the question arises whether prudent safety regulation is able to fill this gap in a satisfactory way.

Faure & Fiore (2009: 126 *et seq.*) point to the role of international institutions like IAEA and EURATOM, which – in the form of standards and recommendations – exercise a "draconian control" on the member countries' nuclear installations. Safety rules appear to be "much stricter than in any other industrial risky activity". In Germany, nuclear safety standards are enforced *via* a continual supervisory review, which assesses the "actual status of existing installations [...] according to the latest scientific and technological developments" (Vorwerk 2002: 11). In addition, German operators are individually obliged to perform safety reviews according to specific guidelines. Results of the reviews have to be submitted to nuclear authorities after a timespan of ten years.

Within this respect, it is possible to point at a *first* disadvantage of the command-and-control approach in relation to policies of economic incentives. The regulation process appears to be static and inflexible. The sequence of command, in order to enforce new safety standards, consists of the Federal Ministry for the Environment, the 'Länder', the Reactor Safety Commission and the operators of nuclear plants, respectively (Vorwerk 2002). In regard to flexible and efficient risk prevention, therefore, nuclear safety regulation is clearly not an instrument favoured by economic theory (Faure & Vanden Borre 2008). A *second* disadvantage has already been mentioned in previous sections. The authority's capability to monitor plant

[43] *Cf.* Section 3.1.1. A more detailed discussion can be found *inter alia* in Faure & Fiore (2009), Faure & Vanden Borre (2008) and Shavell (1984), respectively.

operators is substantially limited *a priori*, which impedes an efficient regulation process. Thus, one has to object to the notion of nuclear safety regulation as a perfect substitute for the instrument of civil liability.

4. Nuclear Risk Management and Compensation

At this point of the thesis, the reader should be able to understand the role of *ex ante* policy measures of nuclear risk prevention. Three insights should be kept in mind: *Firstly*, creating economic incentives is a strong tool, which can avoid the shortcomings of a command-and-control approach. *Secondly*, economic theory is able to formulate a distinct efficiency criterion. Although an abstract argument, it can be applied to tort law – holding plant operators strictly liable without limit guarantees an efficient outcome. *Thirdly*, from an economic point of view, various objections, which question the criterion's applicability in the context of atomic energy generation, are not convincing. Furthermore, the capability of Germany's nuclear policy to incorporate results of economic theory has been analysed, relating its performance to both alternative regulatory approaches and their outcomes, respectively.

The following section, in contrast, focuses on *ex post* policy instruments aiming at an efficient level of compensation. In order to avoid textual overlapping, the following analysis abstracts from the influence of compensation rules on the outcome of policy instruments aiming at risk prevention. Instead, it concentrates on the policy maker's challenge to guarantee compensation payments both at a highest possible amount and at adoptable costs, respectively. The discussion reviews the main methods of compensation currently in use: insurance, reserves and risk-sharing pools. Furthermore, alternative compensation mechanisms – like compensation or financial market solutions – and the potential role of the government as (re)insurer of nuclear risk are critically assessed.

Referring to the conceptual framework presented in Sections 2.1 and 2.2, three important questions have to be kept in mind throughout the subsequent discussion:

- What are the nuclear plant operator's costs of implementing different measures for compensation? Which mechanism can be considered as cost-effective and sustainable on the supply side? In what follows, a compensation mechanism is defined as *cost-effective* if it guarantees a given level of remuneration at lowest possible costs for the plant operators.
- Which methods are suitable from a demand side point of view? That is, which compensation instruments are able to satisfy the claims of potential victims in an extensive way? The level of compensation least required to meet the demand side criterion is set to €10 billion per accident.
- What are the necessary economic and legal conditions for the different compensation mechanisms? What role should the government play in respect of these requirements?

Accordingly, the objective of the section is to identify the economically favourable compensation instruments in order to evaluate the provisions made by plant operators in response to current nuclear policy in Germany.

4.1. Liability Insurance

Insurance companies conventionally set their premiums according to the expected value of loss, i. e., the probability of an adverse event multiplied by the amount of damage resulting from it. There exists a wide range of estimates regarding the probability of a nuclear accident.[44] The values employed in the further analysis are $p_1 = 10^{-4}$, $p_2 = 10^{-5}$ and $p_3 = 10^{-6}$ per reactor, per year. The corresponding 'worst case' scenarios entail losses in the amount of $l_1 = 10$, $l_2 = 40$, $l_3 = 70$ and $l_4 = 100$ billion €, respectively.

Here, it is assumed that a core melt down is solely the result of malfunction; 'initiating events' like human error or terrorist attacks, which are highly uncertain and, therefore, cannot be associated with a certain probability, are not taken into account (*cf.* Faure *et al.* 2009: 117).

The literature assigns conditional probabilities to the magnitude of an accident, once a core meltdown has occurred (Faure & Fiore 2008a: 234 *et seq.*). The conditional probability of an accident to involve losses below €1 billion is set to 81 percent; conditional on a meltdown, there is a remaining chance of 19 percent that the quantity of radioactive releases emitted is high enough to cause damage between €1 billion and €100 billion . Since these 'minor' and 'major' accidents are assumed to be uncorrelated, and since in Germany the mandated sum insured is such that the insurance companies' expected losses are not effected by the magnitude of the accident, conditional probabilities can be ignored hereafter.

Consequently, the *actuarial* premium – in order to insure against losses up to €256 million – ranges from €256 to €25,600 per reactor per year. Nevertheless, nuclear plant operators in Germany have to come up for premiums in the amount of €13 million per reactor-year (Scheer 2010: 358), which – even if the most catastrophic scenario is considered – exceeds the 'fair' value by a factor of 500.

In respect of the requirements mentioned above, private liability insurance does not seem to be an adequate solution from an operator's point of view. It shows

[44] *Cf.* Faure *et al.* (2009), Heyes *et al.* (2000), Dubin and Rothwell (1990), and the citations therein.

that this is not a specific problem to be solved by decent policy; instead, structural explanations highlight the extraordinary and abnormal role nuclear risk is playing within the insurance industry.[45]

First of all, the generation of nuclear energy – as one of the most hazardous industrial activities – does in fact constitute a *non-actuarial* risk: Neither the insurer can build his expectations on empirical evidence suggesting a reliable estimate of risk probability, nor the number of risks is high enough such that actual total damage statistically approaches the insurer's expectations; nuclear risk, therefore, cannot be diversified. Moreover, uncertainty emanating from a long time horizon of nuclear hazard exacerbates entering into conventional insurance contracts, since insurers may be confronted with indemnity claims a long time after an insurance contract has expired. It is consequently reasonable to assume that insurance companies will charge an extra premium, reflecting their aversion against uncertainty, associated with nuclear risk. In addition to this ambiguity-markup, the actuarial premium can be extended by three additional cost factors: insurance companies' administration or loading costs, VAT taxes on insurance contracts and finally, the insurance industry's monopolistic structure, which allows companies to charge profit premiums.

Faure & Fiore (2008a; 2008b) find that all factors potentially contribute to the excessively high premiums for nuclear operators all over the world. The private insurance market for nuclear liability is highly monopolistic and organised on a national basis. Different insurers (and re-insurers) join forces in mutual insurance

[45] A short but very instructing critical summary on both the assumptions and the basic results of classical insurance models is presented in Gollier (2005). The benchmark case predicts competitive markets to guarantee a Pareto-efficient allocation of social risk and a socially efficient level of risk prevention; public intervention translates into market distortion. It is, however, obvious that the model's restrictive assumptions are *not* applicable to the special case of nuclear risk.

pools in order to guarantee sufficient capacity. On the one hand, this alleviates the engagement of the private market in an ultra-hazardous segment; besides the financial incentive, a monopolistic and regionally differentiated market structure facilitates the monitoring process. On the other hand, this system inevitably entails the potential for substantial profit markups. Furthermore, missing pressure of competition allows for loading costs that could far exceed the conventional estimated 30 percent markup on the 'fair' insurance premium. Hogarth and Kunreuther (1985) are able to show empirically that ambiguity aversion is especially remarkable for low probability events of risk, where opportunities for learning over time are limited. Still, current premiums in Germany could only be rationalised if the insurers' ambiguity aversion would account for an additional markup of more than 200 percent. This huge divergence between actuarial values and commercial premiums suggests the following thesis:

> Since the nuclear risk is exceptional and non-diversifiable, the insurer might prefer to determine his premium as a percentage of the estimated damages, rather than relying on the objective value of the risk. (Faure & Fiore 2008a: 238)

Therefore, the non-actuarial characteristic of nuclear risk cannot entirely explain the insurance industry's behaviour. Radetzki *et al.* (2000) identify two additional problems regarding all sorts of industrial risk, potentially resulting in losses of catastrophic dimension:

Firstly, the consequences of a nuclear accident exceeds the insurance companies financial capabilities. Although the latter may exhibit an equity capital base to cover potential catastrophic losses, nuclear risk is not consistent with a standard insurance principle, according to which expected losses of each individual risk should be covered by premium income from the same insurance class, at any point of time. Clearly, if premiums were set to their *actuarial* values, under the specific circumstances it would take an insurance company several centuries to build adequate reserves. On the contrary, actual insurance contributions of all nuclear plant operators enable the insurance industry to meet the criterion within a timespan of one year.

Secondly, of all non-actuarial risks industrial hazards seem to exhibit a special status within the insurance community. The industry notably shows diverging attitudes towards industrial risks on the one side and natural hazards on the other side. This appears to be odd, since latter events themselves entail catastrophic harm; the private insurance market was able, for example, to cover insured damages in the amount of $17 billion when *Hurricane Andrew* devastated the state of Florida in 1992 (Rabin *et al.* 2005: 45). Yet, the insurance industry's cautious approach towards industrial risk can be explained: On the one hand, risk consequences of natural events are precisely defined and insurers do not have to deal with uncertainty with reference to compensation entitlements. On the other hand, constant occurrence of catastrophic events facilitates both a rapid building of reserves and an *actuarial* approach.

Evaluation

From a *nuclear risk management* point of view, two main results should conclusively be underlined:

- For various conceptual reasons, Germany's nuclear policy regime is inefficient from a supply side point of view. Resorting to private liability insurance to cover parts of potential compensation requirements entails excessive costs for nuclear operators if the *actuarial* insurance premium is employed as the adequate reference value.

- Under the aspect of adequate victim compensation, private liability insurance is an inappropriate instrument, too.

- The insurance industry would not be able to provide coverage in the amount of €10 billion, which would at least be necessary to satisfy the needs of potential victims.[46]
- A mandated increase in direct provisions for compensation would clearly not be sustainable for operators; extrapolation suggests annual premiums in the amount of €0.5 billion per reactor.

4.2. Reserves

An alternative method to provide for third party liability is the building of financial reserves on the operator's balance sheet. The literature points to the instrument's considerable cost saving potential, since financial reserves do not constitute 'sunk cost'. Annual expenses on insurance premiums in the amount of €13 million are 'sunk' to the operator under all circumstances. A reserve set aside for victim compensation – although temporarily immobilised – will still be available to the company if no accident occurs during the plant's operational lifetime.[47]

Despite this apparent advantage, the compensation mechanism at hand gives rise to four critical considerations. The first points to the protection of potential victims and the role of regulatory authorities. A necessary condition to qualify the employment of reserves as an adequate instrument for self-insurance is a statutory framework, which prevents the amount set aside from being invested or used for alternative purposes. In the case of an operator's insolvency induced by a nuclear incident, the policy maker has consequently to give priority to victim compensation

[46] Kunreuther *et al.* (1993) point to the potential limit on insurability of risks entailing strong ambiguity aversion.

[47] A detailed discussion on operating firms' *opportunity costs* of the building of financial reserves is presented below.

on a legal basis. German nuclear policy takes provision in respect thereof to some extent; recourse claims of other operators, for example, are subordinate to potential victims' charges (Pelzer 2007: 45).

The second point of critique refers to the instrument's disposability on the supply side. Pelzer (2007) hints at the limited potential for individual plant operators in order to build reserves. Of course, operators in Germany are subsidiaries of huge parent companies, the latter being able to supply the requisite capacity. Nevertheless, such cooperation is a delicate issue, since operator and parent company are distinct legal entities. (The further analysis acts on the assumption that parent companies support individual nuclear plant operators.)

Thirdly, the issue of economic incentives to build reserves has to be addressed. Faure & Fiore (2008a: 239) allude to current international accounting standards, according to which reserves set aside for *uncertain* types of risk are part of firms' capital funds and, therefore, not tax-deductible. This clearly does not create incentives to build reserves to comply with mandated liability provision. In a related matter, the German policy maker did accommodate nuclear plant operators; reserves set aside for atomic waste disposal are tax-exempt. It could be argued, therefore, that the political intent in Germany would, in principle, support the instrument of reserve building. Critics nevertheless argue that such a tax policy primarily creates a distorting competitive advantage on the side of nuclear energy generation (*cf.* Scheer 2010: 358).

Fourthly and most importantly, reserves are *idle* resources to the operating firms. Therefore, although assets will eventually be fully disposable once accidents have successfully been prevented for an entire operating period, the building of reserves entails *opportunity costs* on the side of the operator in the form of forgone returns. In order to estimate those expenses Faure & Fiore (2008a; 2008b) resort to the *capital asset pricing model* (CAPM). They are able to show that – in the case of nuclear energy generation in France – replacing insurance coverage by financial reserves entails a cost saving potential of 75 percent.

4.2.1. Capital Asset Pricing Model

The CAPM was the first theoretical framework to relate the risk of an investment with its expected return.[48]

k_i ... Expected rate of return of capital fund i

r_f ... Risk-free interest rate

r_m ... Market interest rate

$(r_m - r_f)$ ... Risk premium

β_i ... 'Financial beta'[49]

In equilibrium, i. e., in a state where investors cannot outperform the market, the expected return of a certain capital fund has to be equal to the risk-free interest rate plus a risk premium, corresponding to the market premium multiplied by a measure of the fund's relative risk towards entire market risk:

$$k_i = r_f + \beta_i(r_m - r_f) \tag{4.1}$$

The model appears to be appealing for the purposes of NRM, since – under several restrictive assumptions – a moderate degree of information is sufficient to evaluate the implicit costs of building reserves. The risk-free interest rate compares with the long-run return of state bonds and the market premium is the stock market's long-run excess return above the yields of government loans. All key figures, together with the risk coefficient, can easily be inferred from the companies' annual business reports.

[48] The concept was developed *inter alia* by Sharpe (1964) and Lintner (1965). For a critical discussion *cf.* e.g. Perold (2004) or Fama & French (2004). The further analysis adopts part of the notation used in Faure & Fiore (2008a).

[49] $\beta_i > 1$ implies the risk of company i to be *higher* than average market risk, and *vice versa*.

Faure *et al.* (2008a; 2008b) refer to a specific application of the CAPM, according to which the expected return, k_i, can be interpreted as direct costs of the capital fund. This is possible under CAPM's assumption that investors aim at maximising profitability while trying to minimise risk. Therefore – from an investor's standpoint – k_i constitutes the rate of profitability required from the company's resources. Consequently, it represents the operator's opportunity cost of building reserves (Faure *et al.* 2008a: 241).

Table 4.1 captures the conditions of making financial provision for German energy groups in terms of CAPM's criteria. It presents both the upper and lower limits found in the firms' 2009 financial reports[50] and the corresponding values for the capital funds' costs. Following the arguments above, data imply that investors

	High evaluation	Low evaluation
r_f	4.5%	4%
$(r_m - r_f)$	5%	4%
β_i	1.1	0.78
k_i	10%	7.12%

Table 4.1.: *Cost of Capital Funds for German Energy Groups*

demand a yield between 7.12 and 10 percent in order to give consent to the building of reserves. Given this information, it is possible to estimate the average annual expenses on reserves per reactor, evaluated at the time of plant commissioning:[51]

$$A_R = \left[\left(R - \frac{R(1-p)^T}{(1+k_i)^T}\right) + \left(\sum_{t=1}^{T} \frac{R \cdot p}{(1+k_i)^t}\right)\right] \cdot 1/T \tag{4.2}$$

[50] *Cf.* RWE (2010), E.ON (2010) and EnBW (2010). The reports include the numbers for the years 2008 and 2009, respectively.

[51] According to the approach by Faure *et al.* (2008a; 2008b), it is for simplicity assumed that within a nuclear plant's operational lifetime there can only occure one accident.

Estimated costs are composed of two parts. The first captures the notion of reserves, R, being immobilised in the first period, but returning to company's available funds once accidents have been avoided for the entire operational lifespan, T; since k_i constitutes the firm's opportunity cost of building reserves, it is used as the adequate time discount factor. The second cost element takes account of the fact that reserved capital will be mobilised for victim compensation, once an accident has occurred; the expected value of total loss over the entire operational period, again, is properly discounted.

The reference point to evaluate average reserve costs is the average annual insurance premium, evaluated at the first period of plant operation:[52]

$$A_I = 1/T \cdot \sum_{t=1}^{T} \frac{P}{(1+\delta)^t} \tag{4.3}$$

Equations (4.2) and (4.3) enable the evaluation of nuclear policy in Germany – which obliges operators to cover accident damage up to €256 million by means of liability insurance – from a supply side point of view: On the one hand, average insurance costs, A_I, amount to €7.26 million, respectively, €8.28 million per reactor-year, depending on the average operator's time preference rate.[53] On the other hand, the annual costs of reserves, A_R, would account for €7.12 million, respectively, €7.62 million. Table 4.2 illustrates the situation.[54] German data im-

[52]Faure *et al.* (2008a) mistakenly reference to the actual annual insurance premium, P.

[53]The insurance premium, P, is equal to €13 million. An average operating period of a nuclear plant, T, is assumed to be 32 years (Vorwerk 2002: 10). The upper boundary of the time preference rate, δ_h, is set according to the risk-free interest rate indicated in the financial reports of German large energy groups and, therefore, assumed to be 4 percent (*cf.* EnBW 2010). The lower boundary of the time discount factor, δ_l, is set to 3 percent (*cf.* Faure & Fiore 2008b: 307).

[54]Reserves, R, equal to €256 million, and accident probability is assumed to be $p = 10^{-5}$. High-end calculations resort to $k_h = 10\%$ and $\delta_l = 3\%$. Low-end calculations use $k_l = 7.12\%$ and $\delta_h = 4\%$.

Coverage: € 256 million	A_I $(P = 13)$	A_R $(R = 256)$
high evaluation	8.28	7.62
low evaluation	7.26	7.12

Table 4.2.: *Average Costs per Reactor-Year (in million €)*

ply that operators could reduce their average annual costs by 8 percent. It seems, therefore, that the compensation instrument of reserve building is more favourable to operators in order to meet current legal requirements.

One has to call attention to an important caveat. Fama & French (2004) suggest the empirical relationship between the β-factor and expected returns to be flatter than CAPM predicts[55], and claim applications of the model to be interpreted with special attention. They are able to show that up to a β-factor of 1.3 costs of equity capital, k_i, tend to be undervalued systematically. Potential savings of 8 percent inferred from the results above, therefore, need not be a final argument in favour of financial reserves. Nevertheless, sensitivity analysis shows that – suggesting the opportunity costs of equity capital to be 15 percent – the building of reserves still bears potential cost savings in the amount of 4.5 percent.

Having stated the supply side's financial advantage of building reserves as opposed to contracting liability insurance, the question remains whether the compensation mechanism, in general, is suitable to cover the entire needs of potential victims. (To be accurate, conditional probabilities in order to differentiate between minor and major accidents should be included in the analysis for reserves that exceed the level of €1 billion.[56] Consequently, equation (4.2) would have to be extended, which would slightly reduce average annual reserve costs. Since results do not change substantially, conditional probabilities are ignored in the

[55] *Cf.* equation (4.1)

[56] *See* Section 4.1.

further analysis.) It shows that a provision of €10 billion would entail annual expenses ranging between €278 million and €298 million per reactor, an amount which cannot be born by an individual operator.

Furthermore, setting aside €10 billion for *each* reactor would even be unsustainable for *parent companies*. The following formula is used to calculate annual costs to cover the risk of several nuclear installations, where n_i denotes the number of nuclear plants according to the company's interest in nuclear installations:[57]

$$A_{R,i} = \left[R_i - \frac{R_i(1 - p \cdot n_i)^T}{(1 + k_i)^T} + \sum_{t=1}^{T} \frac{R_i \cdot p \cdot n_i}{(1 + k_i)^t} \right] \cdot 1/T \tag{4.4}$$

For example, *E.ON*, the largest energy group in Germany currently operating five nuclear plants and holding shares of six other installations, would have to build reserves in amount of €72.6 billion, which would entail annual expenses of approximately €2.1 billion.[58] Clearly, this approach would not be sustainable for the supply side of nuclear energy.

If German nuclear policy would be designed such that each company would be obliged to build a single reserve of €10 billion to cover the risk of all their nuclear installations, the costs of adequate victim compensation could, of course, be decreased substantially.

Table 4.3 presents the high and low-end scenarios according to equation (4.4), summarising the corresponding annual costs of reserves for German energy groups.[59] Results suggest that, given that compulsory financial provision is legally sufficient to cover the risk of *all* installations, even large energy groups in Germany could not easily bear the annual costs of reserves. Estimates of average costs range between

[57] For example, *RWE* runs two nuclear plants and participates in the operation of three further installations with a share of 87.5%, 75% and 75%, respectively; therefore, $n_{RWE} = 4.38$; correspondingly, $n_{E.ON} = 7.26$, $n_{EnBW} = 4$ and $n_{Vattenfall} = 1.37$.

[58] Here, $n_{E.ON} = 7.26$, $R_{E.ON} = R \cdot n_{E.ON} = 72.6$, and $k_{E.ON} = 0.0802$.

[59] High evaluation: $k_h = 10\%, n_h = 7.26$; low evaluation: $k_l = 7.12\%, n_l = 1.37$.

Coverage: 10,000	$A_{R,i}$ ($R_i = 10n_i$)	$A_{R,i}$ ($R_i = 10$)
High evaluation	2,163	298
Low evaluation	381	278

Table 4.3.: *Average Reserve Costs for Parent Companies (in € million)*

€278 million and €298 million per year. Furthermore, even multinational companies like *Vattenfall* or *RWE* cannot easily set aside €10 billion for self-insurance against third party liability; for example, necessary funds would correspond to nearly one half of *E.ON*'s total reserves in 2009.

Evaluation

Conclusively, three findings should be kept in mind from a nuclear policy perspective:

- To qualify financial reserves as an adequate instrument for future victim compensation, nuclear law has to restrict the use of the funds entirely to third party liability requirements.

- In contrast to liability insurance the building of financial reserves constitutes a more favourable instrument on the supply side. Economic theory suggests that German operators should be free to choose reserves instead of liability insurance in order to provide for the first tier of third party liability provision.

- Given that parent companies can be obliged to take over responsibility and supposing that legal provision binds reserves to liability claims, financial reserves still do *not* seem to constitute a sustainable compensation mechanism in order to provide for victim compensation in an extensive way.

4.3. Risk-sharing Pools

This section examines the functionality and the economic implications of a *nuclear risk-sharing pool* (NRSP) – an instrument which is implemented in current German nuclear policy. The concept is based on the notion of rational agents diversifying the risk of assets with identical but random returns, which was initially formulated by Rothschild and Stiglitz (1971). In its restated version, the 'diversification theorem' is applicable to the community of nuclear plant operators:

> [I]dentical risk-averse individuals facing the same distributions of losses gain by sharing losses equally. (Skogh & Wu 2005: 35)

A NRSP is a mutual agreement *ex ante* between operators in order to distribute the liability of each single operator to all members of the pool. The first successful application of this approach was undertaken by US American operators who mutually provide for compensation requirements in amount of $10.5 billion under the Price Anderson Act. In Germany, to fulfil the obligation to provide financial coverage in the amount of €2.5 billion per incident, in 2001 the four parent companies currently operating 17 nuclear power plants joined in a national risk pool, declared in the Solidarity Agreement ("Solidarvereinbarung") (SA);[60] additional to individual liability insurance, the pool guarantees a second tier of compensation in the amount of €2.244 billion per accident, "provided neither the operator nor the respective parent company are in a position to provide the money necessary for the compensation" (Pelzer 2007: 44).

A NRSP has to overcome theoretical challenges, since nuclear installations appear not to exhibit the same distribution of expected losses bearing in mind various differences in age, size or technique. The responsibility of an individual pool member can be specified according to two differentiation criteria: the level of care and

[60]This approach is explicitly encouraged by German nuclear law (*cf.* §13 AtG and §1 AtDeckV).

the level of activity, respectively (Faure *et al.* 2008b). Within this respect, a major advantage is the instrument's independence of governmental regulation, since operators themselves are best informed to identify adequate differentiation attributes. The level of care, on the one hand, includes the individual operator's compliance of existing safety standards, the location of the plant and its construction type; nevertheless, nuclear installations in Germany are quite similar within this context and the measure of differentiation is, therefore, negligible. The second criterion, on the other hand, is applied by the NRSP of German energy groups. The share each company has to contribute to the pool is specified according to its proportion in the generation of total thermal reactor power (Pelzer 2007: 44).

In contrast to conventional liability insurance, the pooling of risk has three conceptual advantages (Faure & Fiore 2008b, Skogh & Wu 2005): First, a risk pool circumvents the *actuarial* problem. In contrast to insurance companies, members of a pool do not have to be certain about both actual probabilities of an accident and the amount of damage. As long as the participants are subject to the same (uncertain) risk, it is sufficient to have moderate information about minimal criteria that measure the *relative* difference between the member's contribution to total risk.

Secondly, pool members are in a favourable position to control other participants; by comparison, insurers often lack information and technical knowledge for an efficient monitoring process. Clearly, pool participants have furthermore strong *economic incentives* to develop efficient control criteria, which, in turn, reduces the pool members' possibility of free riding. Therefore, the institution of a NRSP is a valuable instrument to contribute to the process of risk prevention, discussed in Section 3.

Thirdly, the approach entails huge cost saving potentials. Analogously to the argument in Section 4.2, a risk-sharing pool does avoid 'sunk costs' on the side of the operators. Furthermore, since the instrument does not require a pricing of risk *ex ante*, which only results in an actuarial price in the presence of sufficient empirical evidence, it avoids costs due to the ambiguity of nuclear risk.

Based on an economic model by Skogh & Wu (2005), it is possible to argue that, given the opportunity, operators led by self-interest will *voluntarily* reach a mutual agreement in order to build a risk pool under most circumstances. In the presence of varying expected losses, information about *relative* differences between the pool members is sufficient to reach a Nash-equilibrium, as is currently the case in respect of the German NRSP. Such an equilibrium might not be reached if differences exist within the probability of risk; nevertheless, this eventuality was excluded for nuclear generation of energy in Germany. The authors are furthermore able to show that equilibria even arise if risk aversion differs among pool members. Consequently, the approach of nuclear risk management in Germany to enable operators to organise liability requirements *via* a mutual risk pool seems to be a promising and sustainable policy.

Faure & Fiore (2008b) provide a method to evaluate the operators' (opportunity) costs of participating in a NRSP.[61] There exist three different possible arrangements in order to provide for the risk pool's funds: Firstly, pool members set aside funds *ex ante* reserved for future contributions ; secondly, operators pay contributions *ex ante*; thirdly, contributions are allocated *ex post*.

As previously mentioned, each pool member's contribution payment is set conforming to its share on total nuclear risk generation; Table 4.4 summarises current arrangements made by German energy groups.[62] Importantly, the amount of each member's contribution does not vary along with the method of payment; nevertheless, corresponding costs change substantially (Faure & Fiore 2008b: 309).

[61] The notation used by the authors is changed in parts within the further analysis.
[62] Data are drawn from companies' 2009 financial reports.

Energy group i	*E.ON*	*RWE*	*EnBW*	*Vattenfall*
Share v_i	42%	25.9%	24.9%	7.2%

Table 4.4.: *Companies' Shares on German Nuclear Risk Pool*

If contributions to the pool are guaranteed through the building of *reserves ex ante* (*RSP1*), a pool member's average costs per year are defined as follows:[63]

$$A_{RSP1,i} = \left[C_i - \frac{C_i(1 - p \cdot n)^T}{(1 + k_i)^T} + \sum_{t=1}^{T} \frac{C_i \cdot p \cdot n}{(1 + k_i)^t} \right] \cdot 1/T \tag{4.5}$$

(Again, the formula takes into account the pool members' opportunity costs of the building of financial reserves, since the idle use of temporarily immobilised resources involves forgone profits in substantial amount.)

Clearly, the method entails two advantages: Firstly, in comparison to liability insurance, contributions C_i are not 'sunk'; if no accident occurs in one of the pool members' nuclear installations, they can be carried over to the next period and will ideally return to the companies' property once the agreement has expired. Secondly, in contrast to the building of *individual* reserves, the distribution of total costs distinctly alleviates the provision process on the supply side. The approach, nevertheless, requires legal effort on the side of the policy maker; trustees in bankruptcy must in general be refused to have access to the funds.

[63] For a derivation and an interpretation of the formula, compare the remarks on equations (4.2) and (4.4) in the previous section. Opportunity costs of building reserves, k_i, are assumed to range between 7.12 and 10 percent. For simplicity, conditional probabilities are ignored, therefore $p = 10^{-5}$. The average lifespan of nuclear plants $T = 32$. Each pool member's payment $C_i = C \cdot v_i$, where C denotes the total financial capacity of the risk-sharing pool, and values of the risk share v_i range from 7.2% to 42% (*cf.* Table 4.4). The total number of nuclear installations within the risk-sharing pool, n, is equal to 17.

In the case of contributions to be *paid ex ante* (*RSP2*), the average annual expenses for a company running n_i nuclear plants can be calculated in the following way:[64]

$$A_{RSP2,i} = \left[C_i - \frac{C_i(1-p\cdot n)^T}{(1+\delta)^T} + \sum_{t=1}^{T} \frac{C_i \cdot p \cdot n}{(1+\delta)^t} \right] \cdot 1/T \tag{4.6}$$

In contrast to the latter, this approach guarantees compensation funds to be immediately available in the case of an accident, regardless of any government intervention. Assuming this organisational form of an NRSP is made compulsory, a further convenience is that members of the risk pool are not confronted with high opportunity costs of holding reserves.

The third possibility to organise a mutual risk pool is to collect contributions retrospectively (*RSP3*), which is applied by current nuclear risk management in Germany. In this case the regulator obligates pool members to subject themselves to a regular certification process confirming the funds availability in case of an accident.[65] This process may entail costs in amount of G. Average annual costs to the members of the risk pool, evaluated at the time of plant commissioning, are defined as follows:

$$A_{RSP3,i} = \left[\sum_{t=1}^{T} \frac{C_i \cdot p \cdot n}{(1+\delta)^t} + G \right] \cdot 1/T \tag{4.7}$$

In Germany, the certification process, which identifies the solvency of sufficient means, is included in the annual year-end accounting of the company (Pelzer 2007: 45). Therefore, costs of the guarantee, G, play a rather insignificant role in the case of the generation of nuclear energy.

This approach is characterised by enormous saving potentials for the companies, since assets reserved for potential victim compensation are not immobilised, as long as accidents are avoided. Faure & Fiore (2008b: 308) claim insolvency not to be a major issue within this respect; in the specific case of insolvency of an individual

[64] Again, the time discount rate, δ, is assumed to range between three and four percent.

[65] *See* §13 and §14, AtG.

operator, funds for victim compensation are not reduced, since the remaining pool members have to cover for the respective amount. Consequently, this type of nuclear policy creates strong incentives for an efficient monitoring process among the risk pool members, which entails positive effects on the level of risk *prevention*. Nevertheless, the argument refers to the situation of US American nuclear policy, where the mutual agreement is made between 103 nuclear operators, each of them taking responsibility for a small part of total risk. In the case of Germany, however, insolvency issues might arise, since liability is only diversified between four large energy groups.

It shows that a *nuclear risk-sharing pool* constitutes a *cost effective* instrument on the supply side of atomic energy generation in Germany. As already mentioned, in addition to the first tier of liability insurance in the amount of €256 million per reactor, the four members of the NRSP in Germany guarantee for a second tier accounting for €2.244 billion per year. Table 4.5 contrasts the corresponding average costs per reactor-year, highlighting the enormous cost advantages of mutual risk pooling systems.[66] Each of the three approaches to finance the risk pool by

Coverage: €2,244	A_I	A_R	A_{RSP1}	A_{RSP2}	A_{RSP3}
High evaluation	72.61	66.81	3.94	2.97	0.014
Low evaluation	63.65	62.37	3.68	2.55	0.013

Table 4.5.: *Average Annual Costs per Reactor (in € million)*

far outperforms the other two instruments, i. e., liability insurance and individual reserve building, respectively. Average expenses between €13,000 and €3.94 million per year imply that financial provision currently mandated by German policy

[66]Average reactor: $R_{AR} = 2,244$, $C_{AR} = 2,244/17$, $P_{AR} = (13/256) \cdot 2,244$; $p = 10^{-5}$; $k_h = 10\%$, $k_l = 7.12\%$, $\delta_h = 4\%$, $\delta_l = 3\%$ and $T = 32$. According to arguments mentioned above it is assumed that $G = 0$.

is sustainable even on an operator basis.

Data in respect of the German nuclear industry furthermore point to the capability of an NRSP to provide for capital funds in the amount of €10 billion, which are defined as necessary in order to meet potential victims' entire claims. Estimations of average annual costs range from €56,000 to €17.55 million for an average nuclear installation, respectively from €68,000 to €125.28 million on the level of German energy groups. Results are summarised in Table 4.6.[67]

Coverage: €10,000	A_{RSP1}	A_{RSP2}	A_{RSP3}
Plant Level			
High evaluation	17.55	13.23	0.064
Low evaluation	16.40	11.35	0.056
Energy Group Level			
High evaluation	125.28	94.44	0.455
Low evaluation	20.07	13.89	0.068

Table 4.6.: *Average Annual Costs – Plant and Energy Group Level (in € million)*

A *nuclear risk-sharing pool* based on *ex post* contributions (*RSP3*) obviously constitutes a sustainable method on the supply side. Nevertheless, supposing that annual audits are sufficient to resolve any insolvency related moral hazard problems, this approach does still raise the question of the victims' access to the compensation funds, once an accident has occurred. This critical consideration is based on two arguments – the first referring to the legal status of the NRSP in Germany, the second pointing to tort law and economic incentives.

[67] High evaluation: $C_h = C \cdot v_h$, where $v_h = 42\%$; $k_h = 10\%$ and $\delta_h = 4\%$. Low evaluation: $C_l = C \cdot v_l$, where $v_l = 7.2\%$; $k_l = 7.12\%$ and $\delta_l = 3\%$. $n = 17$, $T = 32$ and $C_{ar} = 10,000/17$. G is again assumed to be zero.

Firstly, Pelzer (2007: 49) underlines that the German risk pooling system – in contrast to US American nuclear risk management – is not based on a statutory framework. Instead the Solidarity Agreement ("Solidarvereinbarung") constitutes a voluntary contract, which includes the options of amendment and annulment. Accordingly, Faure & Vanden Borre (2008: 283) point to the negative consequences on the side of potential victims. If due to its voluntary nature a private pooling arrangement would be modified subsequently "there would be little guarantee that money would effectively be available to compensate victims after an accident". Legal authorities could circumvent the problem by changing the legal status of the risk pool; nevertheless, this turns out to be a non-trivial problem:

> Legislators that impose an obligation on operators to use their private means to cover or contribute to covering the legal liability of another operator might conflict with guaranteed property rights. (Pelzer 2007: *ibid.*)

In contrast, Faure *et al.* (2008: *ibid.*) are "not convinced that these legal problems cannot be overcome if the legislature can at least justify why in this specific case the pooling through retrospective premiums must be introduced".

Secondly – independent of the voluntary characteristic – if funds are not mobilised *ex ante*, potential tort-feasors have strong incentives to impede the process of tort law to the detriment of potential victims. Evidence of this presumed behaviour of members to the risk pool can be found in the mutual agreement on risk sharing (SA):

> The partners furthermore undertake to support the operator liable in claims handling. In doing so, they in particular deploy infrastructure and specialised manpower. They will use their influence to achieve additional assistance from their respective group of companies [Section 2 of the Agreement]. (Pelzer 2007: 45)

Bearing in mind potential victims' excess expenses to sue for damages, it can consequently be argued that a risk pool financed on an *ex post* basis is an *inadequate* compensation instrument on the demand side.[68]

Another point of critique refers to the presumed negative effect on *risk prevention*, discussed in Section (3). If funds are not set aside *ex ante*, and if the community of nuclear energy producers provides for mutual legal assistance, the expected value of loss due to third party liability claims will be reduced substantially. Consequently, individual nuclear plant operators do not have to internalise full damage costs, which finally reduces the operators incentives for efficient precautionary measures.

The first approach (*RSP1*) does not entail these inconvenient features but appears to be disadvantageous in respect of the social planner's necessity to make special legal provision; furthermore, pool members have to bear the burden of high annual reserve building costs. Therefore, it is argued in this thesis that a risk-sharing pool based on *ex ante* contributions (*RSP2*) should be preferred from the point of view of victim compensation. Of course, this financing method has to be embedded into a statutory framework, which appears to be a crucial issue; but arguments have already been brought forward that mitigate such critical considerations.

Nevertheless, it is still not clear whether such an approach – entailing average costs between of €11.35 million and €13.323 million per reactor-year, respectively ranging from €13.89 million to €94.44 million per year on the level of German energy groups – is sustainable on the side of energy supply.

[68] In respect of the potential victims' economic *incentives* to engage in a litigation process, it has to be highlighted that, within continental law regimes, the winner of a tort lawsuit goes free and does not have to bear any process costs.

To answer this question, it is examined whether the nuclear industry in Germany, in the presence of additional costs due to extensive financial third party provision, is still competitive in relation to other energy producing sources. The production costs per *kilowatt hour* (kWh) of various energy sources are summarised in Table 4.7, which shows that currently the production of atomic energy is one of the most cost-effective methods in Germany.[69] Nuclear operators bear production

Energy Source	Production Costs
Brown coal	2.9
Coal	3.3
Nuclear power	*3.5*
Natural gas	4.2
Wind power (on-shore)	9.6–14.4
Biomass	9.6
Hydropower	10.2
Wind power (off-shore)	12.1–18
Photovoltaics	52–62

Table 4.7.: *German Energy Sector – Production Costs (in Cent/kWh)*

costs of 3.5 cent per kWh, while energy producers employing ecological energy sources like biomass, hydropower or wind power have to account approximately for the triple amount. Energy sources actually competing with nuclear power are brown coal, pit coal and natural gas, which entail corresponding production costs between 2.9 and 4.2 cent per kWh, respectively.

To calculate the additional production costs per kWh of pool member i in order to provide for potential third party liability, the present analysis applies the

[69] Data are based on calculations by *Universität Stuttgart, Institut für Energiewirtschaft und Rationelle Energieanwendung* (Wissel *et al.* 2008: 13 *et seq.*).

following formulae:

$$K_{RSPj,i} = \frac{A_{RSPj,i}}{kWh_i} \tag{4.8}$$

$$kWh_i = MW_i \cdot H \cdot \phi_i \tag{4.9}$$

kWh_i indicates total annual energy supply of pool member i, MW_i denotes the total capacity of the pool member's nuclear installations, H is the maximum annual operating time, and ϕ_i stands for average power plant utilisation.[70]

Table 4.8 presents the high and low-end estimates of the additional costs per kWh a risk pool member has to bear in order to provide for third party liability in the amount of €10 billion.[71] The analysis above implied the approach of an NRSP

Coverage: €10 bn.	K_{RSP1}	K_{RSP2}	K_{RSP3}
Plant Level			
high evaluation	0.18	0.14	0.00066
low evaluation	0.17	0.12	0.00058
Energy Group Level			
high evaluation	0.17	0.13	0.00061
low evaluation	0.17	0.12	0.00059

Table 4.8.: *Additional Costs (in Cent per kWh)*

financed on the basis of *ex ante* contributions (*RSP2*) to be preferable from the viewpoint of potential victims. Accordingly, operators would have to face excess

[70] Trivially, $H = 8760$ hours. Data on MW_i are drawn from *Bundesamt für Strahlenschutz* (2010). Operators' websites provide information on the plants' occupancy rates ϕ_i and (partially) on total energy supply kWh_i.

[71] Average reactor: $C_{ar} = 10/17$, $MW_{ar} \approx 1265.7$, $\phi_{ar} \approx 87.1\%$ and therefore $kWh_{ar} \approx 9.7 \cdot 10^9$. High evaluation: $C_h = C \cdot v_h$, where $v_h = 42\%$; $kWh_h = kWh_{E.ON} \approx 75 \cdot 10^9$; $k_h = 10\%$ and $\delta_h = 4\%$. Low evaluation: $C_l = C \cdot v_l$, where $v_l = 7.2\%$; $kWh_l = kWh_{Vattenfall} = 11.6 \cdot 10^9$ $k_l = 7.12\%$ and $\delta_l = 3\%$. Again, $n = 17$ and $T = 32$.

production costs accounting for 0.12 cents, respectively 0.14 cents per *kilowatt hour*. This amount is negligible in respect of the relative performance of nuclear power within the German energy sector.[72] On the one hand, generation of nuclear power is still much cheaper than the production of energy by means of natural gas or renewable sources. On the other hand, increased production cost in the amount of 3.64 cents per kWh does not substantially change its competitiveness in relation to the most cost-effective energy sources in Germany, i. e., brown coal and pit coal. It can consequently be argued that operators are, in principle, able to pass additional costs on to the consumers of energy.

Having demonstrated both the merits of a risk pooling system based on *ex ante* contributions from a victims' perspective and its financial sustainability on the side of energy supply, the latter compensation mechanism can finally be identified as efficient from a viewpoint of *nuclear risk management*.

Evluation

Theoretic arguments, applied aspects and policy related results, respectively, can be summarised as follows:

- Economic theory strongly supports the installation of a *nuclear risk-sharing pool* as a *cost-effective* instrument to provide for third party liability.
  - Given the opportunity, potential risk pool members will efficiently reach a mutual agreement. Both the identification of optimal differentiation criteria and an effective monitoring process are guaranteed through economic incentives. The presumed loss of efficiency in context of an alternative command-and-control approach can be avoided.
- Three different ways exist to organise a risk pool. Pool members prefer

[72] *Cf.* Table 4.7.

to contribute on an *ex post* basis, which constitutes the most cost-effective approach from a supply-side point of view. From a victims' perspective, nevertheless, pool members should be obliged to pay the contributions *ex ante*, in order to secure the access to the funds and to avoid perverse incentives within the process of risk prevention.

- Nuclear policy in Germany successfully employs the compensation mechanism. Results of the latter analysis indicate three suggested improvements:
  - To guarantee the availability of compensation funds the risk-sharing pool should be legally based on statutory obligation.
  - To avoid moral hazard issues and to protect the demands of potential victims, the risk pool should be financed *via* contribution payments *ex ante*. Suppliers of atomic energy can bear the additional costs.
  - From a standpoint of victim compensation, direct financial provision by German energy groups should be substantially extended. According to various estimates, this policy would be sustainable for the supply side of nuclear energy. Production costs would only increase marginally, leaving the industry's competitiveness rather unaffected.

4.4. Alternatives

The analysis so far discusses compensation mechanisms to be applied on the supply-side. This section, in contrast, addresses the potential role of both the demand-side and the government within the process of victim remuneration.

4.4.1. First Party Insurance

Based on the principle of 'least-cost avoidance', it is, in principle, possible to ask the question whether potential victims should purchase *first party insurance* in order to individually cover losses caused by nuclear accidents. Empirically, *first party insurance* proves to be a sound instrument to cover various sorts of (natural) risk entailing catastrophic harm. Its theoretical advantage in contrast to third party liability insurance is that it allows "a much better adaptation of the premium and policy condition to the risk and thus a better risk differentiation" (Faure 2007: 345). Since premiums are set according to individual exposure to loss, the selective pressure of the insurance industry on potential victims would guarantee an efficient exposure to risk on a social level;[73] for example, individuals would optimally avoid locating in flood-prone areas. Of course, the argument does not necessarily translate into the case of industrial risk.

In Section 3.1.1, arguments have been presented that oppose the notion of potential victims of nuclear accidents being involved in the process of risk *prevention*. It has been argued that nuclear plant operators are better informed in order to reduce risk in a cost-effective way (the principle of 'least-cost avoidance'). Nuclear risk, it has been intended, constitutes a 'unilateral' hazard. However, the question still remains whether, from the viewpoint of NRM, first party insurance should be considered as an auxiliary instrument to provide for sufficient victim *compensation* – a notion based on the inefficiency of both tort law and third party liability in the presence of 'judgement-proof' tort-feasors. It shows, nevertheless, that the approach can be qualified as inadequate within this respect. Two main arguments have to be highlighted.

Firstly, there are no reasons to believe that potential victims would resort to first party insurance voluntarily (Faure 2007: 346 *et seq.*). They do not have any

[73] *See* Section 2.1 on *social risk management* (SRM).

incentives to insure against personal damage, since social security systems will automatically cover parts of the risk, once an accident has occurred. Furthermore, 'moral hazard' problems arise, since potential victims can expect at least some kind of *ad hoc* government support. Finally, psychological arguments refer to reduced incentives to contract first party insurance due to a distorted risk assessment on the individual level (especially of low-frequency events), and due to a so-called 'status quo' bias, according to which individuals prefer a highly uncertain loss to the purchase of insurance coverage at certain costs.

It could be argued that in the specific case, the policy maker should mandate potential victims, i. e., individuals who are located in the direct environment of a nuclear installation, to purchase adequate first party insurance coverage. This could, in principle, affect the choice of residence of potential victims and therefore reduce the expected societal losses due to nuclear accidents. Nevertheless, one can object this reasoning, since *secondly*, arguments presented in Section 4.1 on liability insurance remain. The structure of the private insurance market as well as the special characteristics of nuclear risk impede an efficient use of this approach. Furthermore, the latter would entail negative distributional effects, since it clearly violates the 'polluter-pays-principle', which is commonly accepted in environmental policy.

Conclusively, it can be argued that unlike natural catastrophes such as hurricanes or earthquakes, where first party insurance is a feasible option preferred by economic theory, nuclear catastrophes, in principle, do not allow for the adoption of this demand-side compensation mechanism. Therefore, if it transpires that measures of remuneration on the supply-side are insufficient to cover all expected third-party losses, policy makers have to resort to government provided compensation.

4.4.2. Government Provided Compensation

Experience with major nuclear accidents shows that the dimension of public disaster relief should by no means be underestimated. For example, government spending in order to alleviate the aftermath of the Chernobyl accident accounted for 22.3 percent of the Belarusian national budget in 1991; at the beginning of the century, between five and seven percent of public expenses in Ukraine still had to be devoted to Chernobyl-related relief programmes (IAEA 2006).

Public intervention within the process of victim compensation is arranged through two different institutional channels.

A *first* part of victim remuneration is based on the *social security system.* This tier of compensation is an automatic process guaranteed mainly through the public health care system. Furthermore, unemployment insurance or public pension systems have to be mentioned within this respect. These institutions – securing a basic protection for all potential victims "in order to enable everybody a dignified and self-organised existence" (Magnus 2006: 130) – alleviate the aftermath of a severe nuclear incident; policy makers do not have to intervene actively. Importantly, however, social security does not aim at full compensation of occurred damage.

To provide a *second* tier of public relief, governments may implement specific catastrophe funds. The question of the optimal design of such a fund is not trivial. Firstly, it can be organised structurally; i. e., specific terms and conditions regarding the legal validity of, and the entitlements to the fund are defined by the policy maker *ex ante.* Secondly, governments can prefer to decide on specific funds *ad hoc*, once an accident has occurred. Pros and cons of both approaches have been broadly discussed in the literature (*cf.* Faure 2007).

On the one hand, *economic theory* distinctly advocates the *ad hoc* solution, since – unlike a public compensation fund defined *ex ante* – it does not cause substantial 'moral hazard' problems:[74] If potential victims of any catastrophic event anticipate to be compensated for losses in the future, they will not purchase insurance coverage; *ex post*, governments might be forced to intervene. Furthermore, they could even be encouraged to develop a risk-loving behaviour; a phenomenon labelled "bet for resurrection" (Gollier 2005: 10). It has so far been underlined that potential victims of atomic risk should entirely be excluded from taking responsibility. Therefore, objections against structural funds seem invalid in the case of nuclear threat. Nevertheless, it can be argued that 'moral hazard' issues correspondingly apply to the supply-side of nuclear risk generation. In the presence of *ex ante* arrangements for catastrophe funds, nuclear operators have less incentives to provide for third party remuneration. And clearly, a *structural* disaster fund would undermine the threat of unlimited liability and, therefore, diminish the incentives for efficient risk prevention.

On the other hand, from a *legal perspective*, statutory rules in respect of public victim compensation are preferred to *ad hoc* decisions. First of all, the approach creates legal certainty – rules that determine whether a victim is entitled to compensation or not are established by the policy maker. Faure (2007) accepts this argument in respect of compensation *via* social security in order to guarantee victims' basic needs, i. e., provide compensation for lost income and health expenses; beyond that, it can be challenged whether public intervention for property damage can be justified in this context.[75] Secondly, a statutory approach does not raise equity issues, since potential victims of a specific catastrophic event are not discriminated against groups of victims being affected by other disasters at another point of time. In contrast, the implementation of funds case-by-case crucially depends on both media and political attention; consequently, amount and procedures

[74] Within this respect, Faure (2007) *inter alia* resorts to theoretical results of Gollier (2005) and Epstein (1996). A more applied analysis can be found in Gron and Sykes (2002).

[75] *Cf.* Faure (2007: 353 *et seq.*) and footnote 33 therein.

of, respectively entitlements to compensation may change substantially.

Faure (2007: 354 *et seq.*) suggests that – if necessary at all – a public compensation fund should be organised *ex post* according to three criteria. *Firstly*, reimbursement payments should be determined after the 'principle of subsidiarity', i. e., victims should be obliged to primarily make use of any third party compensation claim, respectively any existing first party insurance coverage. This should mainly avoid 'free rider' issues on the side of victims. According to the arguments above, this criterion seems to be inadequate in the case of nuclear accidents. It might, on the contrary, be indicated to support victims publicly in the first place, since tort law is a long and costly process; this is in line with the following criterion. *Secondly*, if in the case of a catastrophe, it is politically preferred to deviate from the 'subsidiarity principle', the public compensation fund should be assigned the victim's right to sue the tort-feasor for damage. This type of policy guarantees a maximum support of victims, while it sustains the incentives for nuclear operators to take efficient precautionary measures. *Thirdly*, Faure suggests that catastrophe funds should, whenever possible, be financed by those who actually contribute to the risk.

Public Victim Compensation in Germany

In the case of a catastrophic event, social security in Germany covers the categories of personal illness and injury; furthermore, victims are reimbursed for property damage "where persons lack a sufficient economic basis for life" (Magnus 2006: 122). Non-pecuniary losses like pain or suffering are not covered by the social system. In order to avoid negative incentives, social insurers are theoretically entitled to use tort law against the tort-feasors (*ibid.*: 138). Nevertheless, Faure (2007: 343) criticises that "given the high costs of these recourse actions there is a tendency by (social) insurers in some countries not to use these rights".

There does not exist any statutory instrument dealing exclusively with public compensation of catastrophic damage. Nevertheless, experience regarding recent events of disastrous magnitude shows that German policy makers tend to employ *ad hoc* compensation funds. The Act on Flood Victim Solidarity (*Flutoperhilfesolidaritätsgesetz*) following the flood disaster in August 2002 – which provided extensive means in the amount of €8.1 billion – serves as an example. It can be regarded "as a model of how Germany reacts in cases of catastrophes of national importance" (Magnus 2006: 123). Legislation meets the first two criteria stated above. Firstly, the Act allocates financial means according to the 'principle of subsidiarity'. Secondly, the principle is suspended if the process of tort law turns out to be unacceptable for the victims' short term needs; in this case, the compensation fund acquires the victims' right to sue tort-feasors. Finally, the compensation fund is financed on a public tax base. To uniformly distribute the burden of industrial risk over society clearly contradicts the 'polluter-pays-principle'. Nevertheless, in respect of nuclear accidents, this financing method is inevitable since a public catastrophe fund will theoretically only come into force after the financial means of both the tort-feasor and the risk-sharing community are exhausted.

- Conclusively, it can be summarised that nuclear risk management in Germany incorporates the results of economic analysis in respect of state-aided victim compensation, since it tries to support potential victims at the maximum amount while adequate incentives on the side of nuclear energy generation are maintained as far as possible.

4.5. Financial Market Solutions

It has been shown that a recourse to state-funded victim compensation is a rather questionable approach from the viewpoint of economic theory. Therefore, an important task of *nuclear risk management* is to search for alternative sources if both the insurance industry and the community of nuclear operators lack sufficient financial capacity within this respect. Relying on the financial markets to cover potential compensation requirements in a context of nuclear energy generation has so far not been considered as an option within NRM. Nevertheless, to complete the discussion, it is appropriate to briefly outline the concept of specific *nuclear catastrophe bond* (NCB).[76]

So far, financial markets have gained some experience regarding risk diversification of *natural* hazards. Since 1996, various *catastrophe bonds* (cat-bonds) have been issued in order to provide insurance against disastrous events like hurricanes or earthquakes. Although an emerging market, its global volume currently accounting for $15 billion is relatively small (*cf.* Triebe 2010).

A cat-bond is a floating-rate loan issued by (re)insurers or banks, carrying a special option on catastrophic events. Investors have to pay a nominal value at the beginning of the contract period, which is in general invested in state loans. Should a predefined event occur, the cat-bond falls in value, respectively loses its entire worth and the corresponding amount is transferred to the emitters in order to cover their losses. To compensate investors for the possibility of the asset's complete failure, the cat-bond's interest rate usually exceeds the market rate by up to six percent (*cf.* Stein 2005).

Similarly, the idea of a nuclear cat-bond is to transfer the consequences of nuclear risk to large-scale players on the financial markets like pension funds, hedge funds or other portfolio managing entities. Radetzki *et al.* (2000: 189) conjecture that "these institutions would be more willing and better able than insurers to handle the very large size of potential damage liabilities represented by industrial [...]

[76]The section mainly refers to results of Radetzki & Radetzki (2000), which are discussed critically.

catastrophes". In respect of the present thesis, nuclear cat-bonds could be an instrument of special interest in order to cover nuclear damage amounting to €100 billion in the most pessimistic worst-case scenario.

Nuclear cat-bonds could be issued by specific groups of insurers of nuclear operation or by a pool of operators, respectively. The collected funds of the NCBs would be released for victim remuneration in occurrence of losses that exceeded the harm insured on the private market or on the base of a mutual risk-sharing fund. For instance, investors in German nuclear cat-bonds would lose (part of) their capital if a nuclear accident would involve damage accounting for at least €2.5 billion.

The challenge of the policy maker would be to create adequate legal and economic preconditions: Firstly, sources of nuclear risk must be explicitly held liable *without limit*. It has again to be highlighted, however, that it is a non-trivial issue to effectively enforce this policy, i. e., to solve any insolvency related problems. Secondly, efforts have to be made in order to establish markets in which nuclear cat-bonds can be traded.

A supply-side argument supports the approach. Economic literature on 'time-diversification' identifies the financial market as a perfect substitute to conventional insurance under the assumptions of both the economic agent's infinite lifetime and the absence of any borrowing constraints (Gollier 2005 and 1994). These assumptions seem to apply to large energy groups rather than to individuals. It can, therefore, be argued that generators of nuclear risk would have efficient incentives to employ financial market solutions in order to provide for future liability requirements.

According to economic analysis, four advantages of NCB can be identified:[77] Firstly, in contrast to the insurance industry's restricted capacity to meet potential

[77] *Cf.* Radetzki & Radetzki (2000).

payment requests, the capacity of the financial market does not seem to have any binding limits as to this respect. On the one hand, this conjecture can be objected to insofar as it has been shown empirically that – in respect of the diversification of *catastrophic* risk – financial markets are nationally segmented. "A possible explanation for the home bias of individual portfolios comes from various tax incentives for retirement funds to invest within the country" (Gollier 2005: 7 *et seq.*). For example, US American investors hold 94 percent of their assets in domestic securities.[78] Clearly, this would entail a certain limitation on the demand-side of the instrument, reducing the available financial means. On the other hand, Radetzki *et al.* (2000: 189) highlight that the amount required from a nuclear cat-bond, which they assume to account for $100 billion, would only represent 0.3 percent of the financial market's total capacity in the United States.

Secondly, funds could be provided at substantially low costs. Considering the extremely low probabilities of a nuclear catastrophe, the authors suggest that holders of nuclear cat-bonds would just require a risk premium exceeding the risk-free interest rate by a small fraction of 1 percent (*ibid.*). To issue a NCB in the amount of $100 billion, according to their estimations, expenses for an average nuclear reactor in the OECD area would range between 0.017 and 0.17 US cents per kWh (Radetzki & Radetzki 1997). Bearing in mind the results of the previous sections, costs seem to be sustainable from the perspective of nuclear energy supply.[79]

Nevertheless, it can be challenged whether the market solution would, in fact, ensure the socially efficient solution. Gollier (2005) identifies two problems, which cause an 'insurability problem' due to inefficiently large risk premiums regarding

[78] Gollier refers to results by Baxter & Jermann (1997) and French & Porteba (1991).

[79] In contrast, according to the analysis in Section 4.3, estimated costs of a risk-sharing pool to cover third party liability up to €10 billion account for 0.12 cent per kWh, per average reactor in Germany.

the securitisation of catastrophic risk. The first one has already been mentioned, namely, the 'home bias' effect reduces the number of investors that are willing to bear part of the risk. The second problem refers to the structure of the investors' community observed on financial markets:

> Given that many people do not hold any stock portfolio, they do not hold shares of (re)insurance companies that are considering covering catastrophic risks. The remaining shareholders will require a larger risk premium to participate, because of the larger size of the risk. (*ibid.*: 7)

The latter objection might be of less importance if large pension funds would participate in the coverage of nuclear hazard. Nevertheless, a third point of critique refers to the results presented in Section 4.1 regarding the insurance industry's attitude to nuclear risk. There is no reason to believe that private investors would act in a more *actuarial* way. Their investment behaviour might as well be characterised by a strong aversion against uncertainty and ambiguity.

A third merit of nuclear cat-bonds constitutes their independence of the business cycle; cat-bonds potentially stabilise the value of portfolios. This desirable feature would make nuclear cat-bonds an interesting option for large-scale portfolio managers and would consequently mitigate some of the objections mentioned above.

Finally, Radetzki *et al.* argue that the implementation of nuclear cat-bonds bears the potential to gain substantial scientific insight into the field of nuclear risk generation. According to their thesis, unlimited liability together with the transfer of nuclear risk to private financial markets would ideally accentuate an *objective price* of nuclear hazard.

> If the transfer of the top risk to a particular risky industry through the suggested arrangements were to involve costs making the industry

> non-viable, then that would be an important signal that the markets do not find the activity worthwhile. (Radetzki & Radetzki 2000: 192)

Nuclear Catastrophe Bonds in Germany

The financial market, in principle, is able to provide capital for victim compensation that far exceeds the capacity of both German energy groups and the insurance industry, respectively. From this point of view, the instrument of a nuclear catastrophe bond appears to be an interesting alternative in addition to compensation arrangements presented in the previous sections. Various advantages of the approach have been opposed to points of criticism – some of them being theoretical in nature, the others referring to empirical evidence.

- Conclusively, it can be argued that the outcome of a policy resorting to private solutions *via* the financial markets cannot be identified *a priori*.
- It has to be underlined that the success of this approach crucially depends on the policy maker's effort to avoid the 'insolvency problem'.
- The instrument of an NCB has to be tested empirically before it is possible to suitably evaluate this strategy.

5. Nuclear Risk and Precaution

The previous Chapters 3 and 4 gave an overview over the different policy options to handle the specific characteristics of atomic *risk*. The aim of the following sections, instead, is to focus on the relationship between atomic generation of energy, nuclear policy and the prevalence of (scientific) *uncertainty*.

It is examined whether including *uncertainty* into the analysis gives rise to arguments in favour of a *precautionary principle* (PP). A principle, stating that certain hazardous actions should not be undertaken until uncertainty has substantially unravelled – even if the commitment to this principle would entail substantial (socio-economic) costs. The latter would translate either into an immediate or into a dynamic strategy to back out of the exploitation of nuclear energy sources. Instead of identifying and evaluating different policy measures and adaptation strategies, the chapter addresses questions more general in nature:

- Can economic theory be applied to political landmark decisions in the field of nuclear energy?

- From an economic viewpoint, is a *precautionary principle* generally justified within the regulation process of atomic energy generation?

- If so, which particular economic motives can serve as a rationale of a *precautionary principle* in the specific context?

Current Debate

A (partial) answer to these questions would be valuable not least in respect of the political and public debate in Germany regarding the legal extension of a nuclear installation's operational lifespan. Arguments both in favour of, and against precautionary measures concerning the proper handling of nuclear hazard narrow down to ideological manifestations. Advocates and opponents basically differ in the reference on distinct expert opinions, respectively, vary in their confidence in a wide range of scientific results, which divergently assess the risk stemming from the generation of nuclear energy. So far, arguments considering the presence of *structural uncertainty* have not found their way into the discussion.

In 2002, the German government incorporated a precautionary claim into nuclear policy when an amendment of the Atomic Energy Act came into force, regulating the phase-out of the use of nuclear power. The German legislator came to the conclusion that despite high domestic safety standards in comparison to nuclear policy on an international level, the commercial use of nuclear energy should be restricted, since the possibility of major accidents cannot be fully ruled out.[80] Firstly, the German legislator decided not to allocate further licences to new nuclear installations. Secondly, rules had been determined regulating the expiration of operating licences. Each nuclear installation was assigned a particular residual amount of electricity to be produced, based on an average operational period of 32 years. To maintain flexibility, the operators were allowed to transfer permitted electricity volumes between their own installations. The resulting average residual operation period of a nuclear reactor, consequently, accounted for 11.5 years (*cf.* Vorwerk 2002: 9 *et seq.*).

In recent years, the German government departed from this strong precaution-

[80] *Cf.* OECD (2001: 58) and (2002: 76). The following remarks on the phase-out of nuclear energy in Germany draw on an article by Vorwerk (2002).

ary policy approach. The legislator decided to extend the lifetime of 17 nuclear reactors in Germany by an additional 12 years on average. In particular, the operational period of nuclear installations that were built prior to 1980 was increased on average by 8 years in comparison to the initial phase-out path. More modern reactors were allowed to be maintained in the power grid for an additional 14 years on average. The corresponding amendment to the Atomic Energy Act was passed by the German *Bundestag* at the end of 2010 (*cf.* OECD 2010: 76).

In response to recent alarming events in Japan and (supposedly) anticipating upcoming elections, the German government pronounced a moratorium in respect of the planned extension of operating lifespans holding in suspense both the decisions about the adequacy of a *precautionary principle* and the future of nuclear forms of energy generation in Germany, respectively.

5.1. General Issues: Stock Pollutants, Irreversibility and Uncertainty

Before the economic principle of precaution is discussed in detail, the following section addresses some basic theoretical concepts and introduces a few fundamental problems that jointly arise with the generation of nuclear energy. Gollier & Treich (2003: 79 *et seq.*) identify four common features of various forms of industrial, natural or environmental risk that magnify the complexity of the subject and further complicate the challenges of regulatory policy, namely, the long time horizon, the occurrence of irreversibilities, the prevalence of scientific uncertainty and the potential of scientific progress, respectively.

Crucially, the use of the term 'nuclear risk' is re-specified within the further analysis. 'Nuclear risk', from now on, additionally refers to various types of hazards emanating from (scientific) uncertainty regarding the ultimate storage and disposal of atomic waste. It shows that the above mentioned characteristics are applicable to 'nuclear risk' being understood in this sense.

Time Horizon and Stock Pollution

It is beyond question that the time horizon to be dealt with in respect of nuclear risk is tremendous. Nuclear waste is a highly accumulative stock pollutant, since in the specific case, the environmental system barely offers any assimilative capacity. In contrast to pure flow pollutants like traffic noise or other stock pollutants like carbon emission, where the ecosystem is partially able to absorb negative externalities, nuclear waste exhibits a persistence rate close to one hundred percent – at least in respect of a medium-term time horizon covering a significant number of present and future generations. For example, the half-life period of one of the possible fission products in nuclear reactors, the isotope Plutonium-239, accounts for more than 24,000 years. Accordingly, the decay process has to persist hundreds of thousands of years until the material's nuclear activity can be classified as safe for human health.

Irreversibility

Closely linked to the problem of pollutants accumulating over time is the idea of irreversibility emanating from various sorts of risk. Clearly, the generation of nuclear waste constitutes a physical irreversibility – at least within a reasonable policy time frame complying with the needs of both the present and several future generations. Furthermore, besides the material aspect, Gollier & Treich (2003: 79) point to another source of irreversibility, namely, the costs associated with the "time needed for adaptation of the socio-economic system". That is, the employment of hazardous production techniques may urge the policy maker to spend a considerable amount in order to compensate for possible catastrophic consequences.

These expenses constitute socio-economic irreversibilities in the sense that they cannot be used for more productive utilisations and, therefore, inevitably distort economic development.

For example, unexpected events during the process of the ultimate disposal of nuclear waste may force society to make available financial means in considerable amount within a short time period. The expenses for the ultimate disposal, respectively, the final storage of nuclear waste is estimated to account for €1.2 billion per nuclear reactor (*cf.* Fouquet *et al.* 2003: 312). Operators in Germany are, in principle, mandated to cover these costs themselves and, accordingly, to build adequate reserves. Nevertheless, it is still a controversial issue whether these obligations are substantially concretised (*ibid.*). For example, in 2009 the Federal Office for Radiation Protection had to take over the – initially privately organised – operation of the permanent disposal site 'Asse II' in the federal state Niedersachsen, when the intrusion of saline solution into the disposal site's shaft started to endanger the safe deposit of the radiative material.

Thus, nuclear risk can create irreversibilities in the sense that, once an adverse incident has occurred, society has to bear the costs of risk adaptation *ad hoc*, which in turn has an irreversible effect on both consumption patterns and social welfare.

Uncertainty and Scientific Progress

The scenario described above points to a third particularity of various forms of social hazards, which has to be considered by policy makers, namely, the prevalence of uncertainty or ignorance. Chapters 2, 3 and 4 referred to the problem of nuclear *risk* – outcomes and corresponding probabilities of occurrence could be identified. The scenario of a reactor core melt accident served as an example. A situation of scientific *uncertainty*, on the contrary, is characterised by the lack of information on outcome probabilities, while the case of *ignorance* is accompanied by the impossibility to identify both the consequences and the likelihood of potential catastrophic events (*cf.* Sunstein 2005: 33).

Within this respect, both the controversial question about the ultimate disposal of nuclear waste and the capability of scientific progress has to be addressed.[81] Several strategies to cope with the *permanent disposal* (PD) of radioactive material are, in fact, inadequate. Marine or space disposal as well as the transmutation of waste or long-term interim storage turn out to be either too dangerous, too complex or too costly, respectively (*cf.* Brasser *et al.* 2008: 6). Therefore, the PD in specific geological formations, i. e., the long-term isolation of harmful substances contained in nuclear waste by means of a natural rock barrier, constitutes the only feasible option according to current scientific standards.

Scientific results imply that it is, in principle, possible to resort to specific salt formations in order to install a PDS in Germany. Nevertheless, the scientific community still has to establish a commonly accepted procedure that allows to infer from both laboratory experiments and 'natural analoga', since no *direct* experience exists in respect of long-term behaviour of solid rock formations (*cf.* Brasser *et al.* 2008: 32, 38, 54 and 64). Therefore, it seems that scientific uncertainty has not entirely been unravelled. The incidents at the PDS 'Asse II' serve as an example. It has to be highlighted, however, that *scientific progress* is potentially able to resolve problems of uncertainty in the future.

In their article on the US American approach towards the construction of a PDS at Yukka Mountain, Winograd & Roseboom (2008) address another important issue in this respect, namely, political assertiveness. People tend to resist nuclear disposal sites to be established in their near neighborhood, a phenomenon which is

[81] Brasser *et al.* (2008) provide a comprehensive survey on the possibility of a *permanent disposal site* (PDS) in Germany. This survey was conducted by the German *Institute for Applied Ecology* together with the *Gesellschaft für Anlagen- und Reaktorsicherheit (GRS).*

labelled 'not-in-my-backyard' (NIMBY) within economic literature. This will be especially the case if site selection procedures are not communicated openly and in a comprehensible way as is currently the case, e. g., in the USA.[82] Short term political business cycles, therefore, can substantially delay inevitable long term solutions further increasing the risk of the generation of nuclear energy.[83] Thus, within the present thesis, it is argued that scientific uncertainty is accompanied by political ambiguity. As a consequence, both the final outcome of nuclear risk and corresponding probabilities of occurrence can be classified as highly uncertain as long as a *permanent disposal site* has not been successfully installed.

Importantly, a further source of uncertainty has to be highlighted. As already mentioned in Chapter 3 on risk prevention, the estimated probabilities of a core melt accident potentially followed by catastrophic consequences only take into consideration the possibility of technical malfunction. 'Initiating events' like human error, terrorist attacks or natural incidents like earthquakes are explicitly excluded from risk analysis and are, therefore, located in the domain of scientific uncertainty. Experience has shown that the error-prone nature of human action plays an important role in the genesis of nuclear accidents. The recent events in Japan vividly visualise that risk management and science still have to overcome many difficulties in order to adequately incorporate natural hazards into the analysis.

[82] The approach in Switzerland is an exception worthy of mentioning (*cf.* HSK 2005). The Swiss policy maker started to investigate in the late 1970s, identified clear rules for the selection process and managed to continuously inform the public on scientific progress. Potential sites have been identified, however, technical difficulties have still to be overcome.

[83] Clearly, this line of reasoning is built on the assumption that policy makers *solely* take decisions in order to maximise votes. Further investigation on this topic would be necessary to reinforce, respectively, to reject this hypothesis. However, this would go beyond the scope of the present thesis.

5.2. The Precautionary Principle

The *precautionary principle* (PP) is a concept closely linked to the idea of environmental 'sustainability', which has, so far, not been defined in a universal and precise way. Loosely speaking, its aim is to organise the (mainly economically driven) human intervention in the ecosystem in a less harmful and more sustainable way.[84] Various conceptualisations of the PP exist, each of them being "culturally framed" (O'Riordan & Cameron 1994: 12). That is, the formulation of the PP depends on a specific society's set of norms and values, respectively, on the way people within a society perceive the status of the environment. A society considering nature to be fragile and vulnerable in face of human intervention might exhibit a different attitude towards the PP than societies that assume the ecosystem to be robust within limits or that rely on a unlimited adaptability of the environment (*cf.* COMEST 2005: 28). The different approaches to genetically modified food both in the USA and in the EU serve as an example. However, from a comprehensive perspective, the core concern of the concept of precaution is to offer "a broad guide to policy makers to move to anticipate problems before they occur, which could involve acting before there is full scientific understanding of the circumstances" (Jordan & O'Riordan 1999: 18).

In spite of the vague status of the PP, it is possible to clearly identify the rationale behind the principle. The PP scrutinises the established interplay between (natural) science, economics, ethics, politics and law in the face of imminent

[84] An introduction to the genesis and the main characteristics of the PP is presented *inter alia* in O'Riordan & Cameron (1994) and Jordan & O'Riordan (1999). For a brief historical overview and a more applied discussion on the PP see, e.g., the UNESCO expert group report by the *World Commission on the Ethics of Scientific Knowledge and Technology* (COMEST 2005). A discussion on the PP in respect of the different economic approaches towards uncertainty is provided by Pearce (1994).

irreversibilities and catastrophic consequences or in the presence of scientific uncertainty. If potential environmental damage is accompanied by one or more of these circumstances, in principle, scientific risk assessment, subsequent results of economic (cost-benefit) analysis and the implication for the political decision process can be questioned.

5.2.1. Historical Background

The emergence of the PP, which can be interpreted as a shift from damage control *ex post* to a control of risk *ex ante*, is a logical consequence of scientific progress, technological innovation and economic growth, respectively (*cf.* COMEST 2005: 7). Economic prosperity accompanied by increasing pollution levels and progressive environmental destruction started to exhaust the ecosystem's assimilative capacity. As a consequence, policy makers tried to involve the economic sources of this deficiency by implementing the *polluter-pays-principle* (PPP). Where the PPP occurred to be insufficient, governments, under the assumption of manageable social hazard, started to emphasise the principle of risk *prevention* by installing adequate liability rules or by setting regulatory safety standards. The final stage of governmental action, namely, the rise of a *precautionary principle*, was reached when various forms of social risk emerged, which were accompanied by scientific uncertainty and entailed consequences of potential catastrophic extent. The threat of global climate change, the problem of acid rain and the risk of prevalent deforestation serve as examples.

Interestingly, the PP goes back to a precautionary concept within environmental policy implemented by the German government in the 1970s, namely, the 'Vorsorgeprinzip'. Initially, "*Vorsorge* implied fitting the best available abatement technology in order to minimize polluting emissions at the source" (Jordan & O'Riordan 1999: 19). The principle was established on the assumption that both economic growth and environmental protection can, in general, enforce each other rather than being in an antagonistic relation (*ibid.*: 20). The concept of 'Vorsorge', in succession, included various forms of pollution and social risk and was accompanied by four supplementing principles intended both to limit and to contextualise the PP, namely, the polluter-pays-principle, the principle of economic feasibility, the common burden principle and the idea of societal consensus (*cf.* Boehmer-Christiansen 1994). Subsequently, German policy makers tried to further establish the concept of precaution within the area of European countries, mainly in order to avoid competitive disadvantages. Within the EU, the PP currently constitutes a guiding principle in the fields of environmental policy (*cf.* Jordan & O'Riordan 1999: 21). On an international level, the breakthrough of the PP dates from the UN Rio Declaration on Environment and Development in 1992. Since then, the PP has become part of several international agreements, among others, the WTO's Agreement on Sanitary and Phytosanitary Measures in 1994 (*cf.* COMEST 2005: 8).

5.2.2. Concepts and Criticism of Precaution

As implied at the beginning of the section, a unique and formal version of the PP does not exist. For example, a communication of the EU commission from the year 2000 expresses the precautionary concern in the following, rather tentative, way:

> The precautionary principle applies where scientific evidence is insufficient, inconclusive or uncertain and preliminary scientific evaluation indicates that there are reasonable grounds for concern that potentially dangerous effects on the environment, human, animal or plant health may be inconsistent with the high level of protection chosen by the EU. (cited according to COMEST 2005: 13)

Importantly, this statement does not impose any restriction on EU institutions. The equivalent in German legislation dates from 1984. The PP in Germany develops its effect at the level of tort law and administrative jurisprudence (*cf.* COMEST 2005: 24). Its formulation has a more compulsive character. Importantly, it indicates its applicability to the context of nuclear risk:

> Responsibility towards future generations commands that the natural foundations of life are preserved and that irreversible types of damage [...] must be avoided. [...] The principle of precaution commands that the damages done to the natural world [...] should be avoided in advance and in accordance with opportunity and possibility. [...] Precaution means to develop [...] technological processes that significantly reduce environmental burdens, especially those brought about by the introduction of harmful substances. (cited according to COMEST 2005: 10)

The list of different versions of the PP could be prolonged. In spite of the absence of a universal formulation, Jordan & O'Riordan (1999: 24 *et seq.*) identify several topics, which seem to be central to the concept of precaution and which are of interest in respect of economic analysis.

Firstly, the PP is characterised by the political disposition to take *pro-active measures* even if the decision maker lacks a formal scientific proof of certain (catastrophic) scenarios to occur. This criterion clearly exceeds a policy of prevention. On the side of economic analysis, this has been severely critisised, since a PP, taken literally, has a strong paralysing effect and entails opportunity costs in substantial amount itself. It has to be mentioned, however, that the PP only comes into consideration if – due to scientific uncertainty – conventional risk analysis is impracticable, scientific results imply a certain plausibility and the extent of the potential damage caused by inactiveness is sufficient to trigger precautionary thinking.

Secondly, the PP, therefore, is accompanied by the criteria of *proportionality* and *cost-effectiveness*. A possibility to evaluate the social opportunity costs of implementing precautionary measures would be to take the difference between expenses on full precaution and the costs of reducing the potentially harmful activity down to the level suggested by traditional cost-benefit analysis. A decision rule whether or not to implement the PP in a strict sense would then require the presumed benefits to far exceed these opportunity costs. Economists still tend to favour a line of argument resorting to the instrument of cost-benefit analysis. However, some economists challenge the conventional decision rule of cost-benefit analysis within the environmental context; a precautionary perspective – even in a cost-benefit framework – could be realised insofar as the benefits of a potentially harmful activity should be *much* greater than corresponding costs (*cf.* Pearce 1994). This goes in line with the arguments presented in the economic literature on decision-making under uncertainty. The related concept of the 'option value' is discussed in the subsequent Section 5.3.

Thirdly, the PP stresses the importance of the well-being of future generations and widens the *time horizon* of political consideration. It, therefore, partially challenges the necessity of time discounting, the latter being widely accepted in the economic literature on environmental policy.[85] Nevertheless, common economic reasoning within a cost-benefit framework might be inadequate in the presence of highly toxic stock pollutants such as atomic waste. The following section 5.4 on worst-case analysis will discuss this topic in more detail.

Fourthly, the PP, in its strictest interpretation, implies a *shift* in respect of the *burden of proof*. Accordingly, the development of potentially hazardous technologies should only be undertaken if the possibility of substantial environmental

[85] As a starting point for the discussion *cf.* Stavins (2005).

harm can be excluded. Clearly, this criterion must partially be criticised from an economic standpoint, since it can impede scientific innovation and economic development.

Furthermore, the different formulations of the PP highlight both the importance of the ecosystem as a necessary precondition for human existence and its intrinsic value, respectively. Again, from an economic standpoint, the principle involves conceptual drawbacks, since it does not offer a clear guideline. In its crudest form, the principle would not allow to sacrifice any resources in order to achieve both economic growth and material wealth, respectively. Clearly, such a decision rule cannot be favoured from an economic perspective.

In a nutshell, theoretic results can be summarised as follows (*cf.* Sunstein 2005):

- On the one hand, it can be argued that the PP in its weakest form is a general assumption of human behaviour.

The unopposed obligation to use the seatbelt when driving a car or the tendency within wealthy societies to resort to balanced diet serve as examples.

- On the other hand, in its strongest conceptualisation, it can be shown that the principle consequently creates 'substitute risks', which would, in fact, contradict the idea of precaution. Thus, the principle is widely criticised to take a paralysing effect.

For example, a strongly regulated process of the final approval of new drugs protects patients from uncertain negative effects of medication but at the same time, it exposes them to a substitute risk in the sense that they may never receive the potential benefits of several promising compounds.

So far, it should have become clear that different approaches to, and corresponding problems associated with a PP are complex and occasionally located at the frontiers of economic analysis. To arrange the arguments and referring to results obtained by Sunstein (2005), the subsequent Sections 5.3 and 5.4 conceptually separate two possible sources of the *precautionary principle*, namely, *irreversibility* and *catastrophic harm*, respectively.

A presentation of the concept of the 'option value', a discussion of economic models spotlighting different economic motives behind precaution and a summary on the basic elements of worst case analysis addresses several problems concerning the PP that have been outlined so far. This could make it possible both to identify and to evaluate the potential *economic rationale* behind a PP in the case of nuclear energy generation.

5.3. Irreversible Harm and Decision-Making under Uncertainty

This part of the thesis addresses the notion of an *irreversible harm precautionary principle* (IHPP), according to which – under well-defined circumstances – it is economically efficient to pay a positive premium in order to avoid non-reversible damage and to preserve flexibility.

IHPP: "When regulators lack information about the likelihood and magnitude of a risk, it makes sense to spend extra resources to buy an 'option' to protect against irreversible harm until future knowledge emerges." (Sunstein 2005: 4)

For this approach of precaution, the concept of the 'option value' serves as an intelligible theoretical basis. The corresponding literature on decision-making under uncertainty is a valuable extension to the field of cost-benefit analysis.[86]

[86] The discussion was raised by articles of Weisbrod (1964) and Arrow & Fisher (1974). Weisbrod (1964) developed the idea of an 'option demand' for commodities with infrequent and uncertain purchase, which is, in general, not taken account of by private suppliers. Accordingly,

The concept can be outlined as follows: It is assumed, firstly, that *scientific uncertainty* prevails in respect of the potential consequences of certain alternatives. Secondly, it is supposed that at least one alternative can be referred to as a hazardous activity in the sense that its outcome is *irreversible*. It is, furthermore, assumed that *scientific progress* takes place. If these three presumptions hold, it is *rational* to adjust the expected return of the *reversible* alternative by an 'option value' (OV), which can be interpreted as the opportunity cost of maintaining flexibility in the future (*cf.* Sunstein 2005: 17).

The subsequent discussion presents both the significant assumptions and the main results of two economic models built on the notion of the OV. It is tried to answer the question whether the models' settings consort with circumstances of the generation of nuclear energy. Accordingly, it should be possible to make a point about *irreversibility* as a potential source of a *precautionary principle* in the nuclear context.

5.3.1. Option Value

Arrow & Fisher (1974) were among the first to examine the implications of including uncertainty into cost-benefit analysis. The latest version of the model including

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it was argued, that the private market solution may not guarantee the (potentially) socially efficient realisation of projects like national parks or urban transit. In the fields of environmental economics, Arrow & Fisher (1974) addressed the notion of a strictly positive (quasi) 'option value' associated with potentially reversible alternatives. The discussion on this OV, which explicitely does not depend on the assumption of risk aversion, was supplemented by contributions of Henry (1974) and Hanemann (1989). A similar concept is presented in Dixit & Pindyck (1994) who, in the domain of finance, discuss the characteristics of investment decisions under uncertainty. For a brief summary, see, e. g., Fisher (2000). A valuable attempt to further determine and evaluate the OV can be found *inter alia* in Fisher (2001) and Farrow (2004).

the results by Henry (1974) and Hanemann (1989) is presented in Fisher (2000).

The model's ingredients can be summarised as follows: It analyses the problem of a policy maker to decide between two alternative uses of a natural environment, namely, 'preservation' and 'development', within a two-period time frame. The alternative of 'preservation' can be referred to as a precautionary measure, while the 'development' option constitutes an irreversible transformation of the environment. In period one, certain knowledge about the alternatives' *future* benefits does not exist but it is supposed that uncertainty will unravel at the beginning of the second period allowing the decision maker to capitalise on prospective information. The decision maker's preferences are explicitly *not* assumed to contain any form of risk aversion. S/he maximises the net value of present and future profits.

It shows that the result of cost-benefit analysis changes in the presence of uncertainty. A risk-neutral decision maker has to extend the net benefit of the *reversible* alternative by a positive *option value*. The OV can be interpreted as "the value of information about future benefits *conditional* on retaining the option to preserve or develop in the future" (Fisher 2000: 201). Under the circumstances captured in the model, "the implications for an efficient control policy will generally involve *some* restrictions of the activity" (Arrow & Fisher 1974: 312 [emphasis added]).[87]

It is argued within the present thesis that the model, to a certain extent, resembles the problem of deciding whether or not to (further) resort to nuclear forms of energy production. The 'development' of a natural environment can be compared with the employment of specific natural resources to generate nuclear energy. Bearing in mind the irreversibilites associated with nuclear risk addressed in Section 5.1, the model is able to identify the existence of an OV within a nuclear context. *Firstly*, the physical irreversibility in form of nuclear waste, the lack of evidence in

[87]In the mathematically more elaborate version of the model (*cf.* Fisher 2000), however, the precautionary measure is restricted on a zero-one basis.

respect of a *permanent disposal site's* practicability and the consequential uncertainty regarding the actual costs and benefits of nuclear strategies, respectively, give rise to the applicability of the model in the specific context. *Secondly*, the model is able to capture the idea of 'irreversibilitiy' in a socio-economic sense. Unexpected expenses on the final waste disposal entirely born by society, which could substantially change the progress of consumption patterns, serve as an example. Thus, on the basis of the model, it is possible to plead in favour of the *irreversible harm precautionary principle*.

It has to be highlighted that, according to the version presented in Fisher (2000), the model implicitly incorporates the possibility of 'substitute risks' accompanied by precautionary measures, since it compares the results of cost-benefit analysis – both under risk and under uncertainty – based on *net* benefits. Benefits of 'development' are explicitly adjusted to possible environmental costs, which of course reduce the latter, but it seems conceptually unobjectionable to also refer to the revenues as net of 'substitute risks', which would consequently increase the net benefit of 'development'.

Nevertheless, the utilisation of nuclear resources could cause an additional form of irreversibility, which cannot be analysed applying this theoretical framework. 'Development', in a nuclear context, constitutes a technical commitment to a specific source of energy production. The decision in favour of atomic energy consequently diminishes investment opportunities in alternative energy sources. The resulting dependency on nuclear energy – at least in a medium-term time horizon – can be interpreted as non-reversible from a present viewpoint. Adopting the diction of the model, if at the beginning of the second decision period improved information would advise against the option of 'development', the commitment of the first period could still be binding in the sense that an insufficient technical development of alternatives may prevent an immediate exit of a strategy of further 'development'.

Two further drawbacks of the model can be identified, namely, the rather vague implication for policy makers and the ambiguity in respect of the direction of precautionary measures, respectively. *Firstly*, the model can, indeed, prove the existence of a positive OV under specific circumstances. However, it does not offer a clear decision rule for political authorities. OV theory implies that the net present value of an irreversible alternative should *significantly* exceed its costs in order to be able to profit on better future information. But it does not identify a specific threshold that would trigger a rational decision maker to pursue a precautionary strategy.

Secondly, the model assumes a situation, in which, so far, no 'development' has taken place. In a context of applied policy, this assumption usually is not fulfilled. Industries, in fact, constantly emit carbon dioxide and various industrialised countries, indeed, utilise nuclear forms of energy generation. Under these circumstances, irreversibilities exist that point in opposite directions. 'Environmentalists' would stress the irreversibilites manifested in the natural system, while 'industrialists' would highlight the importance of irreversibilities within the economic system, i. e., the forgone potential revenues due to restricted investment into current activities. Thus, it is *a priori* not clear whether the claim for precaution is on the side of 'environmentalists' – who insist on precautionary measures in favour of the ecosystem – or whether the status quo is determined by the concerns of 'industrialists' – who invoke precaution in the sense that their activities should *not* be curtailed as long as negative consequences of their actions have not been ultimately substantiated.

The economic literature provides models that try to overcome these conceptual difficulties.[88] For example, Fisher (2001) points to the opposing results of different

[88] A corresponding analysis in the context of nuclear risk has not, so far, been conducted. Both

approaches regarding an IHPP in the context of carbon emission reduction policies. Nevertheless, Farrow (2004) presents a theoretical framework to identify a threshold for the justification of an IHPP.[89] By means of a stochastic cost-benefit analysis and empirical parametrisation, the author is able to show that in the case of the US American approach to control emission levels (the 'Clean Air Act'), an IHPP – from an environmentalist's perspective – is a rational strategy under *all* circumstances. From the standpoint of environmentalists, the benefit-cost ratio exceeds the estimated threshold. Hence, a precautionary measure should be chosen, i. e., emissions should be reduced. Surprisingly, from the viewpoint of industrialists, the estimated threshold level is not reached, therefore, 'precaution' is rejected and emissions, again, are advised to be controlled.

Results can be summarised as follows:

- The theory of the *option value* within the context of environmental economics is a valuable extension of traditional cost-benefit analysis in the predominance of uncertainty.

- Economic models exist that also indicate the presence of an OV in a context of the generation of nuclear energy.

- OV theory faces conceptual problems in the case of irreversibilities (environmental or economical) pointing in opposite directions.

- Economic approaches exist that, in general, are able to overcome these difficulties. However, methods so far have not been applied to the context of nuclear energy generation.

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theoretical requirements and empirical methods are elaborate. It would, therefore, go far beyond the scope of the present thesis to conduct a project of this magnitude.

[89]Farrow resorts to an OV model by Dixit & Pindyck (1994).

5.3.2. 'Irreversibility Effect' and 'Precautionary Effect'

The following section sketches the main characteristics of a model by Gollier & Treich (2003), who present an elaborate framework for decision-making under uncertainty allowing for a more differentiated economic interpretation of the *precautionary principle*. They are able to identify two separate economic sources of the PP, namely, the 'irreversible effect' (IE) and the 'precautionary effect' (PE), respectively.

The outline of the model is similar to the approach presented in the previous section. At the respective beginning of two periods, a decision maker has to decide upon the 'development' of a resource in order to maximise expected lifetime utility. Initially, the model does not make any assumptions about the decision maker's attitude towards risk. Scientific knowledge at period one is insufficient to determine the actual future revenues of the alternatives but the option of 'development' is irreversible in the sense that it is supposed to limit the future radius of operation. Corresponding to the information available in period one, the decision maker has a belief about the probabilities of potential future outcomes to occur. Again, it is assumed that uncertainty will unravel at the beginning of the second period. Importantly, scientific progress is understood, therefore, as the confidence in the policy maker's ability to take the *efficient* decision in the future. Thus, again, the intuition behind the PP is to manage "the wait for better scientific information" (Gollier & Treich 2003: 86).

The authors are able to derive an *irreversible effect* (IE), which stands in the tradition of the OV. The optimal level of 'development' in period one decreases with the prospect of better scientific knowledge in the future. Again, this model does not offer a clear decision rule, respectively, it does not provide a *quantitative* criterion that determines when a precautionary measure is actually appropriate and when not.

Importantly, the model reveals that an IE can only be postulated under the assumption that second period utility does *not* depend on decisions made in the first period, i. e., the model, in its initial version, does *not* allow for the possibility of (negative or positive) externalities entailed by the 'development' alternative.[90] Clearly, this assumption does not hold in the context of nuclear risk, since the stock of nuclear waste will most likely affect consumption patterns and the welfare of many future generations. Therefore, the implication of scientific learning in a decision framework of uncertainty is examined supposing present consumption of a good with negative externalities, e. g., nuclear energy, to increase social risk in the future. To that end, it is supposed that first period consumption entails a negative externality (in the sense that it is accompanied by stock pollution), reducing second period utility proportionally to the level of initial 'development'. The persistence rate of the stock pollutant is known and assumed to be constant.

It shows that both uncertainty and the potential of scientific learning involve two opposing effects, depending on the preferences of the decision maker – the first surprisingly favouring the alternative of environmental 'development', the second advising for a strategy of precaution.

On the one hand, the prospect of more reliable future information suggests the decision maker to behave more efficiently in the future, which ,in turn, *increases* expected future consumption levels, i. e., future income. A *wealth effect* (WE), undermining the idea of precaution, can be identified: "[. . .] the increase in consumption generated by the better information structure tends to induce society to worry less about the future" (Gollier *et al.* 2000: 239). Hence, in order to smooth consumption patterns over time, the decision maker will *not* reduce consumption in the first period, despite the prevalence of negative externalities. The authors

[90] The following discussion on the impact of scientific learning in the case of stock pollutants and negative externalities is based on the analysis provided in Gollier, Jullien & Treich (2000).

highlight that the likelihood of the WE to occur increases the more the decision maker's preferences show signs of 'absolute risk aversion', a measure of the intensity of the decision maker's desire for insurance coverage.[91]

On the other hand, the prospect of more efficient future information increases uncertainty *ex ante* in the sense that future decisions will strongly vary according to the the actual scientific knowledge in period two. A *precautionary effect* (PE), supporting a policy of precaution, can be determined: higher uncertainty at the beginning of period one changes expected marginal utility of future consumption. Hence, the decision maker tends to *decrease* current consumption for a precautionary motive, i. e., efforts for 'development' are reduced in the sense of a *precautionary principle*. The PE is conditional on the social preferences in the sense that it depends on the decision maker's "willingness to save [in order to] to forearm oneself against future exogenous risks" (Gollier *et al.* 2000: 238). The authors underline that the likelihood of the PE to be the dominant effect increases the more the decision maker's preferences show signs of 'absolute prudence'.[92]

The authors conclude that the "way in which learning affects the current decision depends on the utility function" considered in the model (Gollier *et al.* 2000: 237). They are able to define a criterion guaranteeing the PE to outweigh the WE: uncertainty, the potential of scientific learning and the prevalence of negative stock externalities for future generations give rise to the justification of a *precautionary principle* if and only if the 'relative risk aversion' according to the decision maker's preferences is less than unity.[93] (For example, the condition is satisfied if the utility

[91]The level of 'absolute risk aversion' is defined by the Arrow-Pratt coefficient $A(\cdot) = -\frac{u''(\cdot)}{u'(\cdot)}$, where $u(\cdot)$ denotes the decision maker's utility function.

[92]The coefficient of 'absolute prudence', $P(\cdot) = -\frac{u'''(\cdot)}{u''(\cdot)}$, is a concept firstly introduced by Kimball (1990) to measure the strength of the precautionary saving motive (*cf.* Gollier *et al.* 2000: 238).

[93]This result holds for the class of 'hyperbolic absolute risk aversion' (HARA) utility functions.

function takes the form of the square-root. However, it can be shown that in the case of logarithmic utility, scientific uncertainty has *no* effect on the optimal level of precaution.)

Unfortunately, the criterion does not offer a clear guideline for a precautionary policy in the context of the use of nuclear energy sources. The economic literature, indeed, provides a variety of empirical approaches to estimate individual and societal risk aversion. However, there is no economic consensus on this topic (*cf.* Eisenhauer & Ventura 2003), since, e. g., evaluations of the 'relative risk aversion' range from less than unity – which would support a PP in the case of stock externalities – to well over 40 – which would clearly advise for a progressive policy in direction of the WE. Furthermore, the applications of these estimates to the context of nuclear risk seems to be limited. Empirical results are based *inter alia* on common consumption and saving decisions or on insurance purchases in the *actuarial* domain. However, it has already been underlined in previous chapters that nuclear risk takes a rather exceptional position within this context. People's preferences towards social hazards entailing potential *catastrophic* consequences could likely differ from those towards risks included in conventional investment decisions. The following Section 5.4 on worst case analysis will further discuss this topic.

However, the analysis reveals that arguments in favour of a PP cannot be excluded within a nuclear context *a priori*. Finally, the question arises whether and how far results of the analysis change if both the predominance of irreversibilities *and* the occurrence of stock externalities, respectively, are considered – as is the case in the context of the production of nuclear energy. Importantly, the authors are able to demonstrate that – once the decision maker's preferences satisfy

The analysis does not provide clear results for all non-HARA functions, i. e., the effect of uncertainty cannot be unambiguously identified (*cf.* Gollier *et al.* 2000: 238).

the criterion presented above – the *precautionary effect* (PE) and the *irreversible effect* (IE) work in the same directions, yielding an even stronger argument for precaution against irreversible harm (*cf.* Gollier *et al.* 2000: 242).

Results can be summarised in the following way:

- Economic analysis indicates that two driving forces behind a precautionary approach, namely the *precautionary effect* (PE) and the *irreversible effect* (IE) (the latter standing in the tradition of the OV concept) cannot be identified independently from the decision maker's preferences.

- Against the spirit of precaution, even under uncertainty, a decision maker may prefer to extend the potentially hazardous activity in order to avoid heterogeneity in consumption patterns. This behaviour can be referred to as the *wealth effect* (WE).

- Nevertheless, this result crucially depends on the specific way scientific progress is formulated within the model implying that the decision maker will *certainly* be able to take *efficient* decisions in the future.[94]

- Under well-defined circumstances, which cannot be excluded in the case of nuclear energy production *a priori*, both the IE and the PE imply that uncertainty and scientific learning affect rational decision-making in the sense of a *irreversible harm precautionary principle*.

- Further empirical research on the specific social preferences towards nuclear risk needs to be done in order to decide upon the accordance of the necessary criterion to justify precautionary policy actions. Thus, based on the theo-

[94] It will be shown in the subsequent Section 5.4.1 on the 'tail thickening effect' (TTE) that results substantially change once the concept of scientific progress is modelled in a different way.

retical analysis presented so far, it is not possible to make a final statement on the *precautionary principle* in the nuclear context.

5.3.3. Concluding Remarks

The discussion, so far, provided insight into the justification of a PP on the grounds of (environmental) irreversibilities, the prevalence of negative stock externalities and a specific concept of scientific progress, according to which uncertainty is supposed to resolve over time entirely. Two results should be kept in mind:

- Firstly, from a theoretical perspective, the context of nuclear hazard turned out to exhibit all premises that suggest the establishment of precautionary actions, which could either originate from the motive to capitalise on future knowledge (OV and IE) or from an initial precautionary concern (PE). However, it transpired that – from an economic point of view – it is inadequate to pass a *final* judgement on the IHPP's applicability as long as the decision maker's preferences, respectively, the social attitude towards nuclear risk has not been empirically analysed in detail.

- Secondly, from a policy-perspective, within the current political debate in Germany about the lifetime extension of nuclear power plants, respectively, about the immediate shutdown of the most precarious nuclear reactors, economic theory provides some *qualitative* arguments in favour of precautionary measures. Based on the economic models that have been presented so far, importantly, it is not possible to identify the optimal extent of precautionary strategies. However, in consideration of structural scientific uncertainty, theoretic results reject the application of traditional cost-benefit analysis within the nuclear context. Thus, the reference to particular 'substitute risks' in form of irreversibilities within the economic system does not constitute the strong argument against the PP, as would be the case in the presence of *manageable risk*.

In order to draw a complete picture, it is necessary to further address the role of governmental authorities in respect of the realisation of the IHPP and to discuss two diverging perceptions of the term 'irreversibility', which leads to the next section on *catastrophic harm* and worst case analysis.

Firstly, it has been shown in the economic literature that precautionary measures – i. e., in the specific context, the phase-out of nuclear energy and the investment in alternative sources – will not be established within a competitive environment (*cf.* Weeds 2002). As opposed to economic efficiency, agents in a framework of decentralised decision-making under uncertainty will not revert to the concept of the OV. This could serve as an incentive for the policy maker to actively promote precautionary policies (*cf.* Gollier & Treich 2003: 92 *et seq.*). Nevertheless, for the sake of economic efficiency, the policy maker is well advised not to develop 'present-biased preferences' (*cf.* O'Donoghue & Rabin 1999), according to which governments tend to rashly implement precautionary measures in order to gain special affirmation by their voters. This gives rise to a constraint for policy makers not to engage in precautionary matters in an inefficient way (*cf.* Gollier & Treich 2003: 94).

Secondly, it shows that the final justification of an IHPP crucially depends on the specific conceptualisation of 'irreversibility' (*cf.* Sunstein 2005: 20 *et seq.*). On the one hand, if it is strictly understood in terms of 'sunk cost', *every* regulatory action implies other non-reversible conditions and various forms of 'substitute risks'. For example, the investment in alternative energy sources is 'sunk'. Furthermore, the transition phase from nuclear to renewable technologies could involve distortions in the economic system. The corresponding costs, again, are 'sunk' and, therefore, 'irreversible'. An immediate phase-out of nuclear forms of energy production is likely to imply an augmented utilisation of carbon dioxide intense energy sources – at least in the short run – further increasing the risk of global warming. Hence, both the hazardous activity and the decision not to undertake it, in principle, entail 'sunk costs', which are 'irreversible' in their very nature. From this point of view, the IHPP can hardly be justified.[95] Nevertheless, whether the concept of the IHPP should be included into the analysis or not, primarily depends on (empirical) assumptions about the relative costs of these 'irreversibilities' pointing in opposite directions. Importantly, it has already been mentioned in Section 5.3.1 on OV theory that economic approaches exist trying to resolve these conceptual frictions.

On the other hand, the analysis changes if an action is defined as 'irreversible' "when restoration to the status quo is impossible or at best extremely difficult, at least on a relevant timescale" (Sunstein 2005: 18). According to this interpretation, the question of 'irreversibility' cannot be answered independently from the question of 'seriousness'. That is, 'irreversibility' is not an absolute term. It is a concept that has to be related to both a specific time horizon and certain criteria for the seriousness of a catastrophe. Thus, the IHPP is closely related to a *catastrophic harm precautionary principle*, which is discussed in detail throughout the subsequent section.

5.4. Catastrophic Harm and Worst Case Analysis

The following part of the thesis discusses the notion of a *catastrophic harm precautionary principle* (CHPP), according to which – under specific circumstances – it is a rational strategy to explicitly focus on hazards that are associated with

[95]Based on this reasoning, many economists have tended to argue *against* precautionary measures in the discussion on carbon emission and global warming (*cf.* Fisher 2001: 19 *et seq.*).

tremendous worst-case scenarios.

CHPP: "When risks have extremely bad worst-case scenarios, it makes sense to pay special attention to those risks, even if they are unlikely to come to fruition and even if existing information does not enable regulators to make a reliable judgment about the probability that they will occur." (Sunstein 2005: 4)

The CHPP can take different forms of intensity, denoted by CHPP1, CHPP2 and MP, respectively. The two weakest versions of the principle even apply in the context of *risk*.[96] Under the general assumptions of risk-neutrality or risk-aversion, they represent essential rules to correct for irrational attitudes towards various (not least environmental) hazards under specific extreme circumstances. Therefore, from an economic point of view, they are unobjectionable.

(Adjusted) Expected Value Analysis

The modest form of the *catastrophic harm precautionary principle* (CHPP1) is the implementation of a social decision rule based on expected value analysis. Psychological experiments and surveys show that individuals – although naturally assumed to exhibit risk-neutral or risk-averse preferences – tend to treat low-frequency events of catastrophic harm as if accident probabilities were actually zero (*cf.* Sunstein 2005: 28).

For illustration, Sunstein (2005: 29 *et seq.*) conducts the following experiment: test persons are asked to decide upon the priority between two environmental problems – the first ensued by a loss of 200 million lives at a likelihood of one in a million and zero losses with the complementary probability, the second ensued by the loss of 2000 lives at a probability of one in ten and zero otherwise. Both

[96] *See* previous Chapters 2, 3 and 4

problems entail expected losses of 200 deaths. Nevertheless, a relative majority of 41 percent declared that a government should spend more resources to avoid the second environmental problem accompanied with the *higher* probability of occurrence.

To correct this misperception of risk, a modest CHPP ensures that different events with equal expected losses are treated equally. Clearly, this principle is generally accepted in the context of nuclear energy generation. Policy makers do not neglect the supposedly small probability of a potential core melt accident. Operators are obliged to spend positive amounts on risk prevention and on provision against potential compensation requirements – either directly through the regulation of safety standards or indirectly through strict liability rules.

Nevertheless, it is, in general, questionable whether this weak principle of precaution can accommodate events of catastrophic dimension. Expected value analysis is insofar inadequate, as it treats each single unit of 'loss' equally. When it comes to the potential loss of thousands of human lives caused by catastrophic events like nuclear accidents, the 'social loss' might no longer be presumed to be a linear function.

Sunstein (2005: 31) refers to the notion of a "social amplification of risk", suggesting a *second round* of damage due to psychological, sociological and/or macroeconomic factors, which can potentially outweigh the initial effect of a catastrophic event. Such 'second round effects' are likely to occur in the context of nuclear accidents. For example, following the catastrophic event in Chernobyl, people within a wide area around the site of the accident had to abandon their homes. The exclusion zone will be uninhabitable for many future generations and – with the exception of certain "touristic projects" – will not be suitable for any economic activities for a long timespan.

Sunstein conjectures that individuals "might be willing to show a kind of catastrophe premium, stemming [...] from special distaste for risk of true disaster" (Sunstein 2005: 32). Importantly, Sunstein highlights that this distaste for catastrophic damage is unrelated with any risk or ambiguity aversion. Thus, the shape of people's preferences gives rise to arguments in favour of a *stronger* version of the *catastrophic harm precautionary principle* (CHPP2), adjusting the benefits of the precautionary measure by accounting for the potential second round cost savings. Nevertheless, for the latter principle to provide sufficient arguments in favour of precautionary measures, again, potential substitute risks have to be taken into account.

Worst-Case Analysis

It has been shown in the literature on decision-making under uncertainty that a strong PP in form of worst-case analysis, in general, cannot be entirely ruled out as a rational strategy for risk-avers decision makers (*cf.* Sunstein 2005: 33 *et seq.*).[97] Accordingly, the *maximin principle* (MP) is a decision rule, which chooses the alternative with the best worst-case scenario. Within the specific context, this would translate into an *immediate* phase-out of nuclear energy sources. It is important to highlight that, in contrast to the two weaker forms of the CHPP, the economic rationale behind the MP is the prevalence of (scientific) uncertainty.

Sunstein (2005: 37) presents a benchmark case that would, in principle, allow for the application of the MP. Firstly, an (environmental) decision problem is considered where at least one alternative entails worst-case scenarios of catastrophic extent. Secondly, it is assumed that uncertainty prevails about the likelihood of the scenarios. Thirdly, the costs of a certain precautionary measure is socially acceptable and, finally, there exists a scientific threshold of plausibility for catastrophic

[97] Sunstein *inter alia* refers to theoretical results by Arrow & Hurwicz (1972) and Woodward & Bishop (1997).

events to occur.

Nevertheless, from an economic perspective, at least two caveats regarding the MP have to be mentioned (*cf.* Sunstein: 38 *et seq.*). The first points to the existence of various 'substitute risks' followed by any precautionary measure. Within the specific context, an abrupt phase-out of nuclear energy sources poses the question about the adequate compensatory energy supply – at least in the short run. Currently, energy supply in most industrialised countries, to a predominant extent, is still guaranteed by fossil energy sources. Bearing in mind the potential catastrophic effects of global warming on economic development, an immediate change from nuclear to fossil energy sources might in fact not be justified on the basis of the MP. For that purpose, it would be necessary to *clearly* identify the actual worst-case scenarios of all alternatives. In the specific context, this is not the case. On the one hand, expert estimates of worst-case scenarios caused by nuclear accidents range from €10 billion to €100 billion. On the other hand, economists do not agree on potential worst-case scenarios in the domain of global warming.[98]

A second caveat points to the actual degree of uncertainty. There are many situations in an environmental context, in which there is no certain knowledge about actual probabilities but where it is possible to identify a plausible *range of probability* of a certain event to occur.[99] Sunstein (2005: 35) asks the question, whether the MP could simply be "a way of neglecting probability, and hence a form of irrationality". Taken seriously, the MP tends to develop a strong paralysing effect. Hence, in situations where a decision maker can assign probabilities to various

[98] For exapmple, Farber (2007: 17) highlights that estimated costs of reducing carbon emissions to levels implied by the Kyoto protocol vary by a factor of 500.

[99] For example, it is not possible to make a clear statement about the future development of global temperature levels, but the science community is able to conjecture that the probability of a temperature increase of less than 1.5 degree centigrade is above zero but below ten percent (*cf.* Weitzman 2007: 2).

outcomes, an MP cannot be justified, since it would otherwise be necessary to implausibly assume the decision maker to exhibit an *unlimited* degree of risk aversion (*cf. ibid.*: 36). Thus, as long as policy makers can resort to expert estimates on risk probabilities, an MP cannot serve as a rationale for precautionary policies in the domain of nuclear hazards.

Nevertheless, it has already been highlighted in Chapter 2 and Section 5.1 that nuclear risk management still has to overcome several difficulties in order to assess the influence of both human error and exogenous events like natural catastrophes and terrorist attacks on the genesis of nuclear accidents.

5.4.1. 'Tail Thickening Effect'

Finally, the following section lists the main results of a highly formal paper by Weitzman (2007), which provides a strong approval of the CHPP. Like the approaches presented in previous Sections 5.3.1 and 5.3.2, the Weitzman model examines the behaviour of rational decision makers under the presence of scientific uncertainty. However, the focus of the analysis lies on both the potentially catastrophic extent of the hazardous activity and pollution stocks, rather than on environmental irreversibilities.

The model's structure can briefly be outlined as follows: a decision maker with strictly 'relative risk averse' preferences is assumed to maximise expected lifetime utility over two periods. The consumption growth rate is supposed to be related to future changes in the environmental system. Weitzman applies the model within the context of global warming and the risk of carbon dioxide emission. Accordingly, future social welfare is assumed to be negatively correlated with a potential rise in global temperature levels.

Within the present thesis, it is argued that the model, to a certain extent, is applicable to the hazard entailed by the generation of nuclear energy. Correspondingly, the parameter 'temperature response' has to be replaced by the periodical change in society's exposure to nuclear radiation, respectively, by the change in societal exposure to the consequences of the employment of nuclear energy sources. Clearly, future exposedness to nuclear risk is positively correlated with initial levels of activity, i. e., with both the generation of nuclear waste, specifically, and the production of atomic energy, in general.

Importantly, the model postulates *uncertainty* about the final extent of this influence. On the one hand, the current production of nuclear waste could severely increase human exposition to nuclear radiation in the future. On the other hand, in the future period, problems regarding a *permanent disposal site* could satisfactorily be solved and major core melt accidents could have successfully been avoided during the first period, which would, of course, substantially diminish the actual sensitivity of economic development to high activity levels in the nuclear industry sector in the initial period. 'Uncertainty' is modelled as ignorance of the probability distribution of future sensitivity to present risk. Scientific progress is assumed to take place in form of 'inductive learning' – i. e., by means of scientific studies and experiments relying on empirical data – potentially reducing the degree of uncertainty over time. Clearly, if the number of scientific observations would go to infinity, it would be possible for the science community to make a clear statement about the sensitivity of economic development towards nuclear hazard and traditional cost-benefit analysis would be applicable within a risk-managing framework. However, not least in the context of atomic hazard, the potential for 'inductive learning' is restricted *a priori*. Especially, the "ability of empirical learning or inductive knowledge to shed light" on the probability of *extreme events* is fundamentally limited (Weitzman 2007: 17). As a consequence, extreme events, i. e., a high risk sensitivity and a sharp decline in the consumption growth rate, become more likely.[100]

This 'tail thickening effect' (TTE) has enormous implications on the results of expected utility theory. Weitzman is able to show that the amount of current consumption a rational risk-averse decision maker is willing to constraint in favour of a marginal unit of *certain* consumption in the future is indeed unlimited!

Thus, within a cost-benefit framework, the social interest rate of a hazardous activity has to be substantially reduced in order to accommodate the predominance of scientific uncertainty. Even more, the factor of uncertainty may be dominant, so that the question about the discounting of potential losses in the future is completely negligible considering the possibility of severe catastrophic events. In a nutshell:

> The overarching general message is that from inductive experience alone one cannot acquire sufficiently accurate information about the probabilities of tail disasters to prevent the expected marginal utility of an extra sure unit of consumption from becoming unbounded for any utility function having strictly-positive relative risk aversion. (Weitzman 2007: 5)

This is an astonishingly strong result in favour of a generalised *precautionary principle*. Nevertheless, the result is sensitive to the expected catastrophic magnitude a (nuclear) disaster may entail. "[U]ncertainty about the unknown scale of a disaster has the potential to dominate expected-utility cost-benefit calculations *unless* there is some *a priori* knowledge limiting the scope [...] of such disasters relative to the amount of inductive knowledge" (Weitzman 2007: 20). Unfortunately, Weitzman does not provide a distinct criterion that would unambiguously

[100] Note that this is in contrast to the modelling of 'uncertainty' and 'scientific progress' within the economic approaches presented in Sections 5.3.1 and 5.3.2, where it was assumed that uncertainty unravels assuredly at the beginning of the second period.

justify the use of the model, suggesting the implementation of precautionary measures within a specific (environmental) context. The question as to how far nuclear risk involves *open-ended* catastrophic consequences cannot be answered within the present thesis. However, it can be argued – at least on a regional level – that a potentially unlimited scope of a nuclear catastrophe cannot be excluded *a priori*.

5.4.2. Concluding Remarks

It has to be highlighted that the research questions – similar to the case of the IHPP – cannot be answered completely within the present thesis. The previous discussion has shown that economic theory, in principle, is able to analyse the adequacy of different arguments in favour of a CHPP regarding nuclear hazard. Although the literature on environmental economics offers a variety of models that can be applied to the nuclear context, the criteria advising for precautionary measures, however, are too vague in order to make a final statement. To this end, it would be necessary to further adapt the models to the specific problem, which would go far beyond the scope of the present thesis. Conclusively, the obtained results can be summarised in the following way:

- Weak forms of the CHPP are generally accepted and implemented within nuclear policy. Within the specific context, however, economic theory cannot justify the use of an MP, since an immediate phase-out of nuclear energy sources creates substitute risks, which would themselves call for the implementation of precautionary measures.

- The presented economic approach, modelling decision-making under uncertainty while supposing scientific progress to take the form of inductive empirical learning, strongly provides arguments in favour of a generalised CHPP. In a situation of uncertainty, a decision maker exhibiting preferences of strict relative risk aversion would, in principle, sacrifice an *unlimited* amount of current consumption in order to prevent extremely improbable catastrophic events to occur.

- The latter result is sensitive to an open-endedness of the catastrophic event in relation to a limited potential of inductive knowledge. Nevertheless, although the model does not offer a clear criterion of applicability, it alleges qualitative arguments in favour of a CHPP in the context of the generation of nuclear energy. Thus, the results of the model imply that a risk-avers decision maker should follow a dynamic strategy to withdraw from the utilisation of nuclear energy sources.

6. Conclusion and Executive Summary

The main objective of the present thesis was to collect and to systematise the contributions of economic theory within the domain of NRM. Furthermore, based on these theoretic results, the thesis aimed at evaluating both the institutional framework provided by the German policy maker and the corresponding strategies chosen by German nuclear plant operators and potential victims of atomic hazard in order to comply with current statutory requirements.

A first challenge was to find an adequate framework that allowed to arrange both a variety of problems associated with nuclear hazard and corresponding possible solutions in a complete and consistent way. To this end, the approach of SRM turned out to serve as a valuable conceptual basis. It showed that a *direct* link between a certain type of social hazard like nuclear risk and expected future losses for society does not exist, in general. Social welfare, ultimately, depends on how society is able to adapt to the specific characteristics of a certain social risk. Within this context, the shape of institutions and the implementation of various policy measures play a substantial role. The concept of the 'risk vulnerability chain' illustrated the realisation process of social risk and drew attention to the possibilities a policy maker has in order to influence the social outcome of a risky event or of a hazardous economic activity like the generation of nuclear energy. Within the present thesis, four different types of SRM strategies have been identified: *firstly*, risk prevention strategies, which aim to reduce the probability of a catastrophic event to happen *ex ante*. *Secondly*, the measure of risk exposure reduction, which *ex ante* tries to alleviate the sensitivity of potential victims to specific types of risk. *Thirdly*, risk mitigation strategies, which constitute a commitment *ex ante* to reduce the potential adverse impacts of a future *realised* hazard. *Fourthly*, risk coping strategies, which *ex post* aim at alleviating the risk impact once a catastrophic event has occurred.

Based on this framework, the main tasks of NRM could be clearly identified, namely, to reach an optimal level of risk prevention *ex ante* and to guarantee an adequate amount of compensation *ex post*. Within the context of NRM, four important points should be kept in mind: *firstly*, although potentially improving the social distribution of nuclear risk, all risk management strategies entail real as well as opportunity costs to a substantial extent, which have to be explicitly taken into consideration from a policy maker's perspective. *Secondly*, in order to reach an efficient distribution of risk, the policy maker can either rely on a command-and-control approach or create economic incentives that urge agents within the risk generating process to search for efficient solutions themselves. *Thirdly*, the success of each individual risk management strategy cannot be identified independently from the implementation of all other regulative instruments; examples have been presented in order to illustrate the complexity of the strategies, which exacerbates the policy maker's objective to reach a socially preferable risk distribution. *Fourthly*, in the specific context of nuclear hazard, the statutory framework causes reactions both on the supply side of nuclear energy and on the side of potential victims of nuclear technology, the latter, in principle, also representing the demand side of atomic energy.

The subsequent discussion addressed various policy measures aiming at the economically efficient level of risk prevention. It showed that economic theory prefers the policy instrument of economic incentive effects to a regulative command-and-control approach. A conceptual objection against regulation highlights its inflexibility in the sense that it prevents nuclear plant operators to search for, and to implement cost-efficient solutions. According to the principle of 'least-cost avoidance', however, nuclear operators would be best informed to efficiently decide upon both methods and levels of risk prevention. A second objection points to the legal authority's limited capacity to monitor plant operators, which substantially impedes an efficient regulation process. By contrast, economic theory is able to define a distinct optimality criterion for an efficient level of risk prevention: from an economic perspective, nuclear plant operators have to extend their precautionary effort up to the point where the marginal costs of prevention are equal to the victims' marginal benefit – a condition, which is satisfied as long as the supply side of the generation of nuclear energy fully internalises risk costs including all negative externalities caused by the hazardous activity.

It showed that these theoretical reflections can be transferred into the discussion on optimal civil liability rules. By means of an economic model of tort-law, the thesis opposed two different liability rules, namely, *strict liability* and the *negligence rule*, respectively. In the specific case of nuclear risk, it transpired that it is economically efficient to hold nulcear plant operators strictly liable without limit, since only strict liability guarantees full cost internalisation. Correspondingly, due to the adequate legal and economic incentive, nuclear plant operators voluntarily choose the efficient level of risk prevention. The market equilibrium price incorporating all external risk costs, furthermore, sends the right signal for consumers to demand the socially desirable amount of nuclear energy. Form an economic viewpoint, a negligence rule has to be rejected, since it creates the perverse incentive for nuclear operators to escape full cost internalisation by acting non-negligently. Thus, in respect of the optimal level of risk prevention, the thesis emphasised two important results of economic theory: *firstly*, since strict liability creates optimal economic incentives on the supply side of nuclear energy, it should be preferred to a negligence rule. *Secondly*, for similar reasons liability for nuclear plant operators should be unlimited; according to economic literature, this result does not change, no matter whether basic assumptions of the benchmark case are weakened – e. g., the assumption of an 'unilateral accident' –, the obligation of safety standards is included into the analysis or the important issue of the 'insolvency problem' is considered. Furthermore, it has been argued within the thesis that besides these theoretical aspects, strict liability entails practical advantages; it reduces administrative costs within the litigation process and encourages potential victims to engage in lawsuits, which in turn increases the pressure for nuclear operators to ensure efficient precautionary levels.

In a next step, the thesis summarised and evaluated the basic principles and the organisational structure of the main international nuclear liability regimes. On the one hand, economic theory would advocate the international agreement on 'strict liability', the principle of 'exclusive jurisdiction' as well as the obligation of nuclear operators to purchase financial coverage to meet future compensation requirements. On the other hand, from an economic viewpoint, it has to be criticised that liability, in general, is limited in amount and in time, since restrictions of liability constitute distorting (indirect) subsidisations to the nuclear industry. Furthermore, it turned out that the principle of 'exclusive liability', i. e., the channelling of liability to the downstream supplier of nuclear energy, can lead to wrong incentives for prevention in the cases of limited liability or presumed insolvency of the nuclear operator in the case of an accident.

The legal system in Germany distributes nuclear liability among three levels. It is important to highlight that, in contrast to most international liability regimes, all tiers of financial provision for future victim remuneration are funded privately. The first tier accounts for €256 million and is guaranteed *via* the compulsory purchase of liability insurance by the individual operators. The second tier is ensured by means of a mutual risk-sharing pool organised by German energy groups and amounts to € 2,244 million. Additionally, German operators are held liable without limit with their entire assets, which is, in fact, a unique jurisdiction supported by economic theory. Nevertheless, *de facto* it is the operator's expected net worth *ex post*, i. e., once an accident has occurred, that constitutes an implicit cap on liability. Hence, the evaluation of the German nuclear liability regime can be summarised as follows: *firstly*, German legislation in reference to *direct* financial provision in amount of €2.5 billion does not create optimal incentives for nuclear risk prevention. *Secondly*, regardless of the policy of unlimited liability, NRM in Germany does not guarantee the optimal level of risk prevention as long as the 'insolvency problem' has not been solved satisfactorily; especially, this is the case if recourse claims of potential victims can only resort to capital funds of the *operating companies*. *Thirdly*, in order to solve the 'insolvency problem', the policy maker would either have to ensure adequate arrangements for victim compensation *ex ante* or to guarantee that victims can resort to the capital funds of the *parent companies* of the operators.

In a next step, the thesis discussed the different instruments to guarantee adequate financial means for victim compensation – namely, liability insurance, financial reserves, risk-sharing pools, first party insurance, government provided compensation and NCBs – and analysed the role of the policy maker in order to promote these approaches. Three evaluation criteria were defined in order to compare the instruments and, based on economic reasoning, to identify the favourable compensation approach within the context of the generation of nuclear energy in Germany: *firstly*, cost-effectiveness and sustainability on the side of nuclear energy supply. *Secondly*, complete coverage for potential victims of nuclear accidents; the threshold level was set to €10 billion, which coincides with low-end expert estimates of damage entailed by nuclear catastrophes. *Thirdly*, lowest possible effort on the side of the policy maker in order to guarantee each instrument's effectiveness.

Third party liability insurance obtained by nuclear operators turned out to be an inadequate instrument for victim compensation. The thesis provided a list of conceptual reasons that explain the exceptional role nuclear risk is playing within the insurance industry, among other things, the non-actuarial nature of nuclear risk, the monopolistic and nationally restricted organisational structure of nuclear (re)insurance pools and the insurance industry's limited opportunity of building financial reserves in the domain of nuclear hazards. From an NRM perspective, the German situation could be summarised in the following way: *firstly*, Germany's nuclear policy regime is inefficient from a supply side point of view; resorting to private liability insurance to cover parts of potential compensation requirements entails excessive costs for nuclear operators if the 'fair' insurance premium serves as reference value. *Secondly*, from the perspective of potential victims, too, the instrument is inappropriate; the insurance industry would not be able to cover victims' entire financial needs and an increase in direct provision for compensation would not be financially sustainable for nuclear operators.

Economic literature has pointed to several advantages of an alternative instrument, namely, the building of financial reserves on the part of nuclear operators. Most importantly and in contrast to liability insurance premiums, reserve building avoids excessive 'sunk costs' for the operators. Nevertheless, since resources are temporarily immobilised, the compensation method entails substantial opportunity costs. In order to estimate those costs, the thesis relied on the concept of the

CAPM. The analysis emphasised three main findings: *firstly*, in order to qualify the building of financial reserves as an adequate instrument for financial victim remuneration, it is a crucial task of legal authorities to effectively restrict the use of the funds entirely to third party liability requirements. *Secondly*, as opposed to liability insurance, reserve building constitutes a more favourable instrument on the supply side; nevertheless, the analysis implied that cost saving potentials in Germany are lower than, e. g., saving potentials for the nuclear industry in France as indicated in comparable economic studies. *Thirdly*, given that nulcear operators' parent companies can be obliged to take over responsibility and supposing that legal provision binds reserves to liability claims, financial reserves still do not constitute a sustainable solution for adequate victim compensation.

It has been shown that the instrument of a risk-sharing pool – a mutual agreement *ex ante* between nuclear operators in order to distribute the liability of each single operator to all members of the risk pool – is supported by results of economic theory. From a theoretic perspective, it was argued that, given the legal opportunity, potential risk pool members will efficiently reach a mutual agreement in order to differentiate nuclear risk. The thesis presented economic results implying that the identification of efficient risk differentiation criteria as well as the effective monitoring process of the pool members are guaranteed through economic incentive effects. Thus, the instrument avoids the presumed loss of efficiency in the context of an alternative command-and-control approach. The present thesis analysed the three different ways to organise a risk-sharing pool, namely, the building of financial reserves *ex ante*, contribution payments *ex ante* and contribution payments *ex post*, respectively. Furthermore, it estimated the corresponding (opportunity) costs for members of the nuclear risk pool in Germany and evaluated the different approaches according to an NRM perspective. It has been shown that, in general, pool members would prefer to contribute on an *ex post* basis, which constitutes the cost-effective approach from a supply-side perspective. From the point of view of potential victims, however, pool members should be obliged to effect contributions *ex ante*, in order to guarantee and to alleviate access to the funds in the case of an accident and to avoid perverse incentives on the part of nuclear operators within the process of risk prevention. Currently, nuclear policy in Germany successfully employs the compensation instrument, giving German energy groups the legal opportunity to organise a nuclear risk-sharing pool to cover potential liability requirements in the obligatory amount of €2,244 million per accident. According to theoretical reflections within economic literature and based on specific methods to estimate the operators' (opportunity) costs of a risk-sharing pool, the thesis indicated three suggested improvements within this respect: *firstly*, the German risk-sharing pool should be legally based on statutory obligation in order to guarantee the availability of financial compensation funds and to reinforce economic incentive effects for risk prevention. *Secondly*, to avoid moral hazard issues and to protect the demands of potential victims, the pool should be financed by means of contribution payments *ex ante*; suppliers of atomic energy in Germany could bear the additional costs. *Thirdly*, from the standpoint of victim compensation, direct financial provision by German energy groups should be substantially extended; according to estimation results, this policy would be sustainable for the supply side, since production costs of atomic energy would only increase marginally, leaving the relative competitiveness of the nuclear industry rather unaffected.

The thesis, furthermore, turned the focus on alternative compensation mechanisms, namely, first party insurance and government provided compensation, respectively. Based on theoretical reasoning, it had been argued that in contrast to natural catastrophes such as hurricanes or earthquakes, where first party insurance is a feasible option favoured by economic theory, nuclear catastrophes generally do not allow for the adoption of this demand-side compensation instrument.

Government-provided victim compensation empirically appeared to be an important pillar in the aftermath of major nuclear catastrophes. Basically, public intervention *ex post* is provided through two different institutional channels, namely, the social security system and specific catastrophe funds. The thesis presented the potential financial extent of these compensation instruments and analysed corresponding caveats from both a legal and a socio-economic perspective, which have to be considered by the policy maker within an NRM context. It showed that NRM in Germany incorporates the main results of economic analysis in respect of state-aided victim compensation in the sense that it tries to support potential victims at the maximum level while, as far as possible, it maintains efficient incentives for risk prevention on the part of nuclear energy supply.

To complete the discussion on both nuclear policies aiming at adequate financial victim remuneration and various compensation mechanisms, respectively, the thesis addressed the instrument of an NCB. In principle, the implementation of NCBs could be a valuable strategy considering the incapability of both the insurance industry and the community of nuclear operators to provide financial funds covering the *entire* losses implied by nuclear accidents. Although financial markets have already gained some experience regarding risk diversification of *natural* risks, NRM has, so far, not considered financial markets as a possible option within the context of victim compensation. Therefore, it has been argued within the present thesis that the outcome of a policy promoting private solutions *via* the financial market cannot be identified *a priori*. An NCB has to be tested empirically before it is possible to evaluate this strategy. It has been emphasised, however, that the success of the implementation of specific NCBs crucially depends on the policy maker's effort to avoid the 'insolvency problem'.

Within the final part of the thesis, the scope of the analysis was augmented by considering the prevalence of (scientific) uncertainty. While the part on NRM only referred to the risk of a reactor core accident, the last section conceptually incorporated various types of nuclear hazards regarding ultimate storage and disposal of radioactive waste. With reference to the current political debate in Germany about the legal extension of a nuclear installation's operational lifespan, the thesis tried to answer the question about the adequacy of a PP within the regulation process of atomic energy generation from an economic viewpoint. In particular, it was tried to identify the economic motives that could serve as a rationale of a PP in the specific context. To this end, the objective was to analyse various existing economic models of 'decision-making under uncertainty' and to identify the adequacy of the models within the nuclear context.

In a first step, the discussion gave an overview of certain fundamental problems that jointly arise with the generation of nuclear energy, namely, the extraordinary time horizon to be dealt with, the accumulating stock of nuclear waste and the controversial question about ultimate waste disposal. Furthermore, various forms of both ecological and economical irreversibilities associated with the generation of nuclear energy were addressed. The thesis continued with an conceptual explanation of the PP, provided the principle's historical background and presented the corresponding points of critique from the perspective of economic analysis. Based on results of economic literature, it has been argued that, on the one hand, the PP in its weakest conceptualisation is a generally accepted assumption of human behaviour. On the other hand, it has been shown that, taken literally, the PP consequently creates 'substitute risks', which in turn would contradict the very idea of precaution; therefore, the principle is widely criticised to take a paralysing effect.

To structure the analysis, the thesis first addressed the notion of an IHPP according to which it is economically efficient to pay a positive premium in order to avoid non-reversible damage and to preserve flexibility. The review of economic models in the domain of 'option value theory' led to the following results in response to the initial research question: *firstly*, the theory of the OV within the context of environmental economics is a valuable extension of traditional cost-benefit analysis in the case of structural scientific uncertainty. *Secondly*, economic models exist that also indicate the presence of an OV in a context of the generation of nuclear energy; under well-defined circumstances, it is rational for a risk-avers decision maker to adjust the expected return of a *reversible* alternative by a positive premium, which constitutes the opportunity cost of maintaining flexible in the future; thus, it would be efficient to (temporarily) refrain from nuclear energy sources in order to profit on improved scientific information in the future. *Thirdly*, OV theory faces conceptual difficulties in the case of irreversibilities (both environmental and economical) pointing in opposite directions, which is the case in the specific context. *Thirdly*, economic approaches exist that are able, in principle, to overcome these conceptual problems; such methods, however, have so far not been applied to the context of nuclear risk.

The analysis of related economic models of 'decision-making under uncertainty', which incorporate the occurrence of negative externalities in form of stock pollution and which, therefore, resemble the specific characteristics of nuclear risk, allowed to further differentiate the possible economic motives behind precautionary strategies. The thesis emphasised six main results: *firstly*, two distinct economic motives in favour of a PP can be identified, namely, the IE according to which a decision maker wants to maintain flexibility in the future in order to profit from better future information and the PE according to which a decision maker wants to forearm oneself against future exogenous risks. *Secondly*, these potential driving forces behind a precautionary approach cannot be identified independently from the decision maker's preferences. *Thirdly*, economic theory points to a WE according to which – against the spirit of precaution and even under uncertainty – a risk-avers decision maker may prefer to extend the potentially hazardous activity in order to avoid heterogeneity in consumption patterns. *Fourthly*, results crucially depend on the specific way scientific progress is formulated within the economic models implying that the decision maker will *certainly* be able to take *efficient* decisions in the future. *Fifthly*, if it is the case that the decision maker's preferences exhibit a coefficient of relative risk aversion smaller than unity – an assumption which cannot be excluded in the case of nuclear risk *a priori* – both the IE and the PE imply that uncertainty and scientific learning affect rational decision-making in the direction of an IHPP. *Sixthly*, further empirical research on the specific social preferences towards nuclear risk needs to be undertaken; thus, based on the results of the analysed economic models, is was not possible to make a final statement on the adequacy of a PP in the nuclear context.

Finally, the thesis tried to answer the question whether in the context of nuclear risk economic theory provides arguments in favour of a CHPP according to which it is a rational strategy to give special attention to hazards that are associated with tremendous worst-case scenarios. In this respect, the thesis provided a brief discussion on three theoretical concepts serving as a potential basis for the CHPP, namely, traditional expected value analysis, an adjusted form of expected value analysis, which additionally accounts for potential second round losses from the aftermath of a catastrophic event, and worse-case analysis, respectively. Furthermore, the results of an economic model were presented, which involve arguments in favour of the CHPP in the nuclear context. The obtained findings can conclusively be summarised as follows: *firstly*, weak conceptualisations of the CHPP are generally accepted and implemented within NRM; however, an immediate phase-out of nuclear energy sources creates substantial 'substitute risks', which would themselves call for the implementation of precautionary measures; therefore, it has been argued that within the context of nuclear risk, economic theory cannot justify the use of an MP stating that the alternative entailing the best worst-case scenario should be chosen. *Secondly*, based on results of an economic model of 'decision-making under uncertainty', which assumes scientific progress to take the form of inductive empirical learning, a generalised form of the CHPP can be supported; in a situation of uncertainty, a rational risk-avers decision maker would be willing to sacrifice an *unlimited* amount of current consumption in order to prevent extremely improbable but explicitly disastrous events like nuclear accidents from occurring. *Thirdly*, this strong claim is sensitive to the assumption of catastrophic losses to an unlimited extent in relation to a rather limited potential for scientific progress; therefore, the model does not offer a clear criterion for the applicability of the CHPP. *Finally*, the model, nevertheless, alleges qualitative arguments in favour of a CHPP in the context of the generation of atomic energy; thus, results imply that a risk-avers decision maker should follow a dynamic strategy to withdraw from the utilisation of nuclear energy sources.

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B. English Abstract

The present thesis tries to shed light on the question about the adequate institutional and commercial attitude towards nuclear risk. The first purpose is to collect and to systematise the contributions of economic theory within the domain of *nuclear risk management*. Secondly, it is tried to identify optimal policy measures that guarantee a socially efficient diversification of nuclear risk. Based on theoretic results, in particular, the thesis aims at evaluating both the institutional framework provided by the German policy maker and the corresponding strategies chosen by German nuclear plant operators and potential victims of nuclear accidents in order to comply with current statutory requirements.

The first part of the thesis (Chapter 2) introduces the concept of *social risk management* (SRM) and provides an insight into SRM related strategies, namely, risk prevention, risk exposure reduction, risk mitigation and risk coping, respectively. Furthermore, it states the specific objectives and challenges of *nuclear risk management* (NRM).

The second part of the thesis (Chapters 3 and 4) covers the specific nuclear risk of a core melt accident. In a first step, policy measures aiming at risk prevention are addressed. Based on economic criteria, the thesis discusses the optimal design of civil liability rules in the context of the generation of nuclear energy. The nuclear liability regime in Germany is critically addressed. It shows, most importantly, that the *insolvency problem* has not yet been solved satisfactorily, which in turn substantially lowers the incentive effect for efficient risk prevention on the side of German nuclear operators. In a second step, the thesis focuses on strategies aiming at an optimal level of victim compensation, namely, liability insurance, the building of financial reserves, risk-sharing pools, government provided compensation and financial market solutions, respectively. Both efficiency and applicability of each strategy are analysed in the context of atomic energy in Germany. Based on theoretic results and according to estimates regarding nuclear operators' (opportunity) costs of applying different compensation instruments, the thesis provides a list of suggested improvements within the context of efficient victim compensation in Germany.

The final part of the thesis (Chapter 5) includes forms of nuclear risk like the ultimate disposal of radioactive waste, which are, to a certain extent, still in the domain of scientific uncertainty. Correspondingly, the thesis turns its attention to the question about the adequacy of a *precautionary principle* within the context of nuclear policy. Economic arguments in favour of, and against a *precautionary principle* are analysed, which could serve as a guideline for political landmark decisions in the field of nuclear energy.

C. Deutsche Zusammenfassung

Die vorliegende Diplomarbeit stellt die Frage nach dem adäquaten institutionellen und kommerziellen Umgang mit nuklearem Risiko. Es wird versucht, Resultate ökonomischer Theorie im Zusammenhang mit *Nuklearem Rikomanagement* systematisch darzustellen und jene regulativen Maßnahmen zu identifizieren, die eine gesellschaftlich effiziente Verteilung von nuklearem Risiko gewährleisten. Darauf aufbauend werden diesbezügliche gesetzliche Rahmenbedingungen in Deutschland evaluiert und diverse Strategien auf Seiten von KKW-Betreibern und von potenziellen Opfern nuklearer Unfälle einer ökonomischen Analyse unterzogen.

Der erste Teil der Diplomarbeit (Kapitel 2) fasst das Konzept von *Nuklearem Risikomanagement* zusammen, thematisiert die damit verbundenen Herausforderungen und diskutiert die unterschiedlichen Strategien, die in diesem Zusammenhang vom politischen Entscheidungsträger unternommen werden können.

Die Analyse des zweiten Teils (Kapitel 3 und 4) beschränkt sich auf die nukleare Gefahr einer potenziellen Kernschmelze. In einem ersten Schritt werden regulative Maßnahmen mit dem Ziel effizienter Risikoprävention untersucht. Hierbei werden vor allem die in Deutschland geltenden Regelungen zur zivilen Haftbarkeit im Kontext atomarer Energiegewinnung evaluiert. Es wird gemäß ökonomischen Kriterien argumentiert, dass KKW-Betreiber verschuldensunabhängig und unbegrenzt für potenzielle Schäden haftbar gemacht werden sollen. Die Analyse zeigt, dass die gesetzlichen Regelungen in Deutschland das *Insolvenzproblem* nicht gänzlich verhindern. Dies reduziert die Anreizwirkung zur effizienten Risikoprävention auf Seiten der Betreiberfiremen. In einem zweiten Schritt werden verschiedene Strategien zur Gewährleistung von Entschädigungszahlungen analysiert (Haftpflichtversicherungen, finanzielle Rücklagen, Risk-sharing Pools, staatliche Kompensationsfonds und Finanzmarktinstrumente). Im Besonderen wird auf die Eignung dieser Strategien innerhalb des deutschen Atomenergiesektors eingegangen und es werden – aufgrund theoretischer Überlegungen und basierend auf Schätzungen von (Opportunitäts)kosten der deutschen Betreiberfirmen – einige Verbesserungsvorschläge zu einer effizienteren und umfassenderen Opferentschädigung vorgebracht.

Der letzte Teil der Diplomarbeit (Kapitel 5) integriert auch jene Formen nuklearen Risikos in die Analyse (beispielsweise die Endlagerung radioaktiven Mülls), welche zu einem gewissen Teil noch immer im Bereich wissenschaftlicher Unsicherheit liegen. In Anbetracht der Debatte über eine Laufzeitverlängerung deutscher Reaktoren wird der Frage nachgegangen, inwieweit das *Vorsorgeprinzip* innerhalb politischer Grundsatzentscheidungen zur Anwendung kommen sollte. Zu diesem Zweck werden, basierend auf den Resultaten umweltökonomischer Modelle, Argumente für und wider das *Vorsorgeprinzip* im Kontext der Nutzung nuklearer Energieformen vorgebracht und kritisch diskutiert.

D. Curriculum Vitae

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