Evaluating policies to attain the optimal exposure to nuclear risk

Jakob Eberl

Center for Economic Studies
University of Munich

Address: Schackstr. 4, D-80539 Munich
Phone: +49 (0) 89 21803105
Fax: +49 (0) 89 218017845
Email: jakob.eberl@lrz.uni-muenchen.de

Darko Jus
(presenting author)

Center for Economic Studies
University of Munich

Address: Schackstr. 4, D-80539 Munich
Phone: +49 (0) 89 21803104
Fax: +49 (0) 89 218017845
Email: darko.jus@lrz.uni-muenchen.de

ABSTRACT

This paper describes how limited liability leads to risk-loving behaviour in nuclear power companies and unsafe nuclear power plants. By reviewing current regulatory regimes, we show that this issue is not being sufficiently addressed today. Therefore, we evaluate five regulatory instruments: (1) safety regulation, (2) minimum equity requirements, (3) mandatory insurance, (4) risk-sharing pools, and (5) catastrophe bonds. We conclude that none of these instruments in its pure form can be recommended. Thus, we propose a new approach that, in its core, consists of a two-stage procedure. In the first stage, capital markets assess the risk stemming from each nuclear power plant via catastrophe bonds. In the second step, the regulator uses this private risk assessment and intervenes by charging an actuarially fair premium in the form of a Pigouvian risk fee. Society ultimately acts as an explicit insurer for nuclear risk and is, on average, fairly compensated for the risk it is taking over.

KEYWORDS: nuclear risk-taking, limited liability, catastrophe bonds

1 Introduction

Three Mile Island, Chernobyl, and Fukushima are terrifying events in the history of civilian nuclear power use, which goes back to the 1950s. The probability of a severe accident occurring at a nuclear power plant on a randomly chosen day is microscopically small, yet, many people are afraid of this risk. Nuclear power is still being used after those catastrophes because energy is essential for the functioning of modern societies and a way to generate a continuous supply of energy using other climate-friendly technologies at reasonable costs has not yet been found. It is important, however, that, if and as long as a society decides to use nuclear power, its risk be properly taken care of.

The Energy Roadmap 2050, published by the European Commission (EC) in December 2011, emphasises the current and future role of nuclear energy as an 'important part of Europe's power generation mix' and considers it to be 'needed to provide a significant contribution in the energy transformation process' (see EC, 2011). Thus, despite a general reassessment of nuclear risk after the Fukushima catastrophe, nuclear power is likely to remain a significant determinant of many European countries' electricity supply. On the downside, the Fukushima accident, with estimated costs of up to USD 250 billion (cf. JCER, 2011), has shown how strongly a society can be affected by the use of nuclear power while also sensitising people to the reality that many nuclear power plants may be carrying a substantial risk.

We argue in this paper that the problem at heart is the existence of *de facto* (through the amount of equity capital) or *de jure* (by law) limited liability for nuclear power companies (NPCs). The basic mechanism is the fact that an NPC cannot lose more than the legally defined liability capital or, in the worst case, its equity capital, even if the damage of a nuclear accident is much higher. This may reduce the incentive to invest in costly nuclear safety and lead to an inefficient safety level in nuclear power plants. For example, the Tokyo Electric Power Company (TEPCO) reported equity capital in the amount of JPY 2.6 trillion (about USD 19 billion) for 2011 (see TEPCO, 2011). This does not seem small at first glance; however, this amount does not even constitute ten per cent of the estimated costs of the Fukushima catastrophe, the rest of which cannot be borne by TEPCO and must therefore eventually be absorbed by Japanese society in a way yet to be specified. Similarly, the liability of other NPCs around the world is limited *de jure* or *de facto* (see Tab. 1 for a brief overview and Section 3 for a more detailed discussion).

Tab. 1: *De facto* vs. *de jure* limited liability, selected countries/NPCs

Selection of countries with *de jure* limited liability[a]		Countries with *de facto* limited liability[b]		
China	RMB 300 million	Germany	E.ON	EUR 39.6 billion
Czech Republic	CZK 8 billion		RWE	EUR 9.9 billion
France	EUR 91 million		EnBW	EUR 6.4 billion
India	INR 5 billion		Vattenfall	SEK 138.9 billion
United Kingdom	GBP 140 million	Japan	TEPCO	JPY 2.6 trillion
United States	USD 375 million	Switzerland	Alpiq	CHF 7.8 billion

[a] right column: *de jure* national liability limitation; [b] right column: NPCs' equity capital in 2011

One of the original goals of nuclear power liability regulation was and still is to protect NPCs against potentially ruinous claims by setting a limit to their liability. In this way, regulators increased the profitability of the industry and contributed to its development. Currently, the countries using nuclear power can be broken down into two groups. The first group of countries – Germany, Japan, and Switzerland – do not limit the NPCs' liability by law; NPCs can, at most, be made liable with their equity capital. The second group, comprising all other countries, impose strong *de jure* liability limitations.

A body of literature has analysed how limited liability affects individuals' decision making, finding that it induces a distortion towards risk-loving behaviour (see, for example, Sinn, 1983; Shavell, 1986). The literature on NPCs' risk choice similarly emphasises that it might be too excessive owing to limited liability (see Tyran and Zweifel, 1993; Strand, 1994; Trebilcock and Winter, 1997; van't Veld and Hutchinson, 2009, who also provide a review of other related literature). Further literature discusses both conventional and innovative remedies for overcoming this problem (see, for example, Tyran and Zweifel, 1993; Trebilcock and Winter, 1997; Radetzki and Radetzki, 2000; Faure, 2004; Cummins and Weiss, 2009). Particularly closely related to our work are Tyran and Zweifel (1993) and Radetzki and Radetzki (2000), who elaborate on the possibility of using capital markets to deal with limited liability and cover the potential damages from nuclear accidents.

We contribute to this literature in three ways: First, we provide a strong argument on how limited liability affects the risk-taking behaviour of NPCs and illustrate it by reviewing current regulation, showing that this is not a theoretical nature but a real one. Second, we consider various regulatory instruments and evaluate their ability to set the desired incentives such that NPCs choose the optimal level of risk. We conclude that none of them in its pure form can be recommended. Third, we propose a new approach superior to other instruments. The core of our proposal consists of a two-stage approach, in the first of which capital markets evaluate the risk stemming from each power plant via catastrophe bonds; in the second step, the regulator uses this private risk assessment and intervenes by charging an actuarially fair premium, thereby inducing the optimal level of risk-taking. Society then acts as an explicit insurer for nuclear risk but is, on average, fairly compensated.

The remainder of this paper is structured as follows: in Section 2, we outline an aspect of the theory of limited liability that is important for our argument and define the negative externality stemming from excessive risk-taking. In Section 3, nuclear power liability regulation around the world is briefly summarised, serving as a framework within which to evaluate several regulatory instruments on their ability to internalise excessive risk-taking in the nuclear industry in Section 4. In Section 5, we elaborate a new regulatory proposal, a market-based nuclear risk fee. We conclude in Section 6.

2 Limited liability and risk-taking of an NPC

This section develops a theoretical argument about how the limited liability of NPCs affects their risk-taking behaviour. According to Sinn (1982, 1983), the existence of limited liability generates a kink in a firm's or individual's utility function, as all losses beyond the factual or legal liability are truncated and thus not taken care of. This also applies to NPCs, which are liable, at most, with their equity capital. As nuclear catastrophes imply extremely large economic losses and as the equity capital of NPCs is comparatively tiny (see Tab. 1), the nuclear industry is a prime example of firms operating under limited liability. This is intensified when the liability is *de jure* limited to an even smaller amount.

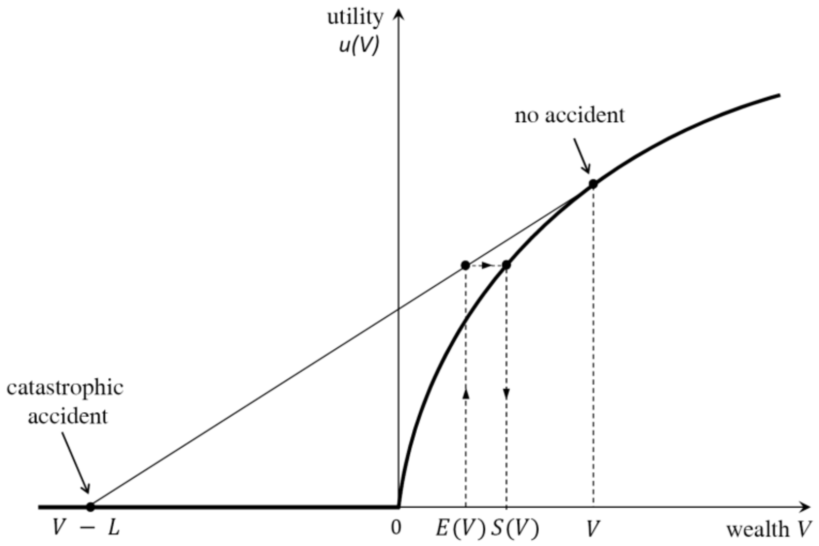
A kinked, or *de facto* convex, utility function may imply risk-loving behaviour if potential losses exceed the NPC's liability. This is true for both risk-averse and risk-neutral NPCs. The *de facto* convexity of the NPC's utility function (see Fig. 1) has two important implications for its behaviour, both of which will be discussed in terms of a risk-averse NPC (for the case of risk neutrality, see, for instance, Sinn, 2003).

2.1 The NPC takes excessive risk

An NPC's loss cannot exceed its equity capital. This may reduce its incentive to engage in measures that lower the probability of catastrophic accidents, which, by their nature, lead to costs that exceed the amount for which the NPC is liable. The socially inefficient excessive risk-taking resulting from private profit maximisation under limited liability is illustrated in Fig. 1 and explained in the following.[1]

Two states of the world are possible, one in which 'no accident' occurs and a 'catastrophic accident'-state. The abscissa shows the NPC's actual wealth *V* determined by its equity capital while the ordinate depicts its corresponding utility *u(V)*. If no accident occurs, the NPC's wealth is given by *V*, whereas, in the case of an accident, the NPC is confronted with losses in the amount of L that reduces its wealth to *V–L*. If the losses exceed its initial equity, the NPC's liability is (*de facto*) limited to its amount of equity. According to Shavell (1986), the NPC is in this case 'judgment proof'. Thus, because of limited liability, the NPC's utility function is horizontal for any negative amount of wealth as zero is the lower bound.

Fig. 1: Limited liability and kinked utility, cf. Sinn (1983)



[1] For an analysis of how liability rules and insurance affect incentives for risk-taking and the allocation of such risks, see Shavell (1982). In contrast to Sinn (1983) and Shavell (1986), who emphasise the role of limited liability on the individual's risk-taking decision, Shavell (1982) evaluates two different kinds of liability rules – when liability is strict and when it is based on the negligence rule. Furthermore, it elaborates on the influence of these forms of liability and the presence of insurance markets on the incentives to engage in inefficient risk-taking.

To determine the NPC's risk preference, let us consider its expected wealth $E(V)$ and the corresponding safety equivalent $S(V)$ given the two-point distribution of possible states of the world. If the potential loss L is sufficiently large, the utility function becomes effectively convex, which implies risk-loving behaviour in the sense that the safety equivalent of the NPC's wealth distribution exceeds its expected wealth. The NPC then chooses a socially excessive risk level by taking into account that a share of the loss would not need to be borne by it but could be shifted to a third party. The social optimum would be achieved if the NPC were fully liable for any outcome and the full social costs of nuclear power thus internalised. Otherwise, a substantial misallocation of resources to nuclear power may result.

Two schools of thought, both developed in the twentieth century, could be applied to the existence of a negative externality like the one described here. The first one, the Coasian solution (drawing from Coase, 1960), would argue that defining property rights and letting the involved parties negotiate potential outcomes would solve the problem at hand. The other one, the Pigouvian approach, calls for (stronger) government intervention in the form of setting a price on the activity generating the externality.

Applying the former framework to the nuclear industry, one could interpret the limiting of liability as a Coasian solution. It gives NPCs the right to choose a risk level without being liable for all consequences. Thus, implicitly, the property rights for everything that becomes a loss after a catastrophic accident are given to the NPC; one could argue that negotiations between potential victims and the NPC could result in a Pareto-optimal level of risk-taking. However, this kind of negotiation is hardly practicable since nuclear risk is dispersed over very many individuals and any attempt to specify private contracts over an efficient risk level would suffer from the public good problem. Hence, society is not able to obtain a contractual relationship with the

NPC, and the NPC could thus not be forced to pay for a potential damage *ex ante*, whereas *ex post* liability is limited to its equity capital. Therefore, Coasian irrelevance does not apply, and the risk allocation can be improved only if the government, representing the interest of society, implements a Pigouvian type of price mechanism on the activity that causes the externality.

2.2 The NPC's insurance-buying decision is downward biased

As was explained with the help of Fig. 1, if the potential loss L is sufficiently large, the NPC's safety equivalent *S(V)* exceeds its expected wealth *E(V)*, and the subjective price of risk, the risk premium *E(V)–S(V)*, becomes negative.[2] As any insurer demands a premium at least equal to the expected indemnification payment, the NPC prefers to be underinsured, although it might in fact be risk-averse according to its preferences. Therefore, as a second implication of limited liability, the NPC's motivation to purchase liability insurance diminishes[3] because part of the costly insurance would protect the NPC against the losses it would not have to bear.

3 Liability regulation of the nuclear power industry

A major goal of nuclear liability regulation is to protect NPCs against potentially ruinous claims. By introducing a limit up to which they can be made liable, liability is passed from the NPC to a third party for any damage beyond this limit. In essence, this limitation recognised the social benefits of nuclear power and society's tacit acceptance of nuclear risk while also increasing the profitability of the nuclear industry, thereby fostering its development.

---

[2] It shall be noted, therefore, that only the risk aversion of NPCs could justify the existence of nuclear insurance markets.

[3] Another possible reason for this result was given by Camerer and Kunreuther (1989), who argue that individuals' decisions seem confused and perverse when they are confronted by very low frequency events, for example, catastrophic nuclear accidents. See also Kunreuther et al. (2001).

In what follows, we sketch the development of nuclear power liability regulation and its current state. We refer to Faure and Vanden Borre (2008) for an extensive analysis of international nuclear liability.

The so-called Price-Anderson Act (cf. US NRC, 2012), passed in the United States in 1957, was the first comprehensive nuclear liability law and has been central to the issue of liability in nuclear accidents. It has repeatedly been renewed (with amendments), the last time in 2005 for another 20 years; the defined amount of NPC liability has increased gradually over time. Today, coverage in the case of accident is provided by the nuclear industry itself on a two-tier basis. On the first layer, all NPCs are strictly and individually liable, being required to purchase USD 375 million of liability coverage, provided by a private insurance pool. On the second layer, coverage is supplied by a mutual and solidary risk-sharing agreement among the NPCs. This risk-sharing pool is funded through retrospective payments in the case of a nuclear accident, which can reach up to USD 112 million per reactor. In total, this two-tier system provides an aggregate sum of USD 12 billion of liability capital. Beyond this amount, society implicitly acts as an insurer of last resort.

Liability regulation of the nuclear industry outside the United States is based on two conventions, the Paris Convention (OECD, 1960) and the Vienna Convention (IAEA, 1963). The basic characteristics of the Paris Convention can be summarised as follows: (1) nuclear companies are strictly liable for any third-party damage; thus, their liability is irrespective of own fault;[4] (2) liability is fully channelled to the NPCs; thus, only they can be sued; and (3) liability is limited to a pre-defined amount and a specified period of time within which claims can be made. More specifically, liability

---

[4] Cf. Shavell (1980) for a comprehensive analysis of the incentives strict liability and negligence rules have on risk-taking.

is limited to SDR 15 million;[5] however, national legislation can provide for a higher, but necessarily limited, amount. Finally, (4) the liability has to be covered by mandatory insurance or some other financial security, to be held by the NPCs.

In 1963, the Brussels Convention, supplementing the Paris Convention, established a three-tier system of nuclear accident liability: on the first layer, the NPCs are individually liable according to the Paris Convention. On the second tier, the state in which the nuclear accident occurs is liable for any damage up to SDR 70 million. Finally, on the third tier, all signatory states are jointly liable for claims, whereby each state is obliged to supply up to SDR 50 million.

Parallel to the Paris and Brussels conventions, which mainly covered Western European countries, the IAEA's Vienna Convention of 1963 introduced a regulatory framework signed by countries outside of Western Europe. It shares the basic principles of the Paris Convention, but the amount at which the NPCs can be made liable is more tightly limited.

Following the 1986 nuclear accident at Chernobyl, efforts to establish a more comprehensive nuclear liability regime were undertaken. As a result, a Joint Protocol bringing together the Paris Convention and the Vienna Convention was adopted in 1988 and has since united the member states of the two conventions. In 1997, two new legal instruments aimed at increasing the liability of NPCs were adopted by the IAEA: the Protocol to Amend the Vienna Convention and, a new convention, the Convention on Supplementary Compensation. The latter has also been signed (though not yet brought into force) by the United States, which had up to that point not been party to an international nuclear liability convention. In 2004, the contracting parties of the Paris Convention (and of the Brussels Convention) signed an amendment bringing the Paris Convention more in line with the amended Vienna Convention. The main objective of

[5] A Special Drawing Right (SDR) is a unit defined by the International Monetary Fund. As of March 2012, the value of one SDR equals USD 0.66, EUR 0.423, JPY 12.1, and GBP 0.111.

this amendment was to shift more liability to the nuclear industry. The 2004 amendment is supposed to remove the requirement to restrict the NPCs' liability, allowing for *de jure* unlimited liability at the national level. However, this amendment has not yet been ratified by enough countries to take effect.

The implementation of the international conventions varies substantially across nations. In Germany, for example, liability legislation far exceeds the requirements of the (amended) Paris Convention. It requires financial security in the amount of EUR 2.5 billion per power plant to be guaranteed by both a nuclear insurance pool and a risk-sharing agreement between the NPCs on the US model. In addition to financial security, the European Union provides EUR 300 million in accordance with the Brussels Convention in case of an accident. For any loss exceeding the aggregate amount, the NPCs' liability is legally unlimited, thereby contradicting the basic principles of the Paris Convention. However, this definition of unlimited liability constitutes only a legal property that cannot actually be sustained, as liability is *de facto* limited to an NPC's equity capital; society eventually takes over liability for nuclear damages exceeding the *de facto* liability limitation. This is also the case in Switzerland, where companies are *de jure* unlimitedly liable and are required to hold financial security in the amount of CHF 1 billion. In France, by contrast, the liability regulation of NPCs is weaker: the liability of the state-owned NPC[6] is *de jure* limited to an amount of EUR 91 million per power plant (projected to increase to EUR 700 million according to the 2004 amendment), which must be insured. This is also the case in the Czech Republic, where the *de jure* liability limit of CZK 8 billion necessitates insurance.

As they are not party to any international conventions, China and Japan have a special position in global nuclear liability legislation. China passed an interim law on

[6] As of March 2012, the French state holds 84.8 per cent of the shares of Électricité de France (EdF), the owner of all French nuclear power plants.

nuclear liability in 1986 that contains the basic properties of the international conventions. In 2007, NPCs' liability limit was increased to RMB 300 million, above which the state is legally liable up to RMB 800 million. This legal regime is under revision, however. Along with its nuclear expansion, China aims to modify its nuclear energy law (see WNA, 2012a). In Japan, NPCs' liability is strict, exclusive, and legally unlimited. Furthermore, a financial security in the amount of JPY 120 billion must be provided. In addition, Japan's 1961 Act on Compensation for Nuclear Damage (cf. NSC of Japan, 1961) allows for an NPC to be relieved of liability in claims resulting from 'a grave natural disaster of an exceptional character', the relevance of which came under discussion after the Fukushima catastrophe. That catastrophe has, however, regardless of this paragraph, provided evidence that the costs of a large-scale nuclear accident can easily exceed the means of an NPC and that governments must eventually step in. In this context, the Japanese government decided to provide financial assistance for massive compensation payments and clean-up costs, for which it demands an annual fee. In this way, TEPCO is supposed to maintain adequate power supply and ensure the safety of its plants. According to government estimates, TEPCO will be able to complete its repayments in 10 to 13 years, after which it is supposed to revert to being a fully private company with no government involvement (cf. WNA, 2012b).

The main insight gleaned from studying nuclear liability regulation around the world is that the liability for losses from catastrophic accidents is either *de facto* limited by the NPCs' equity capital (as in Germany, Switzerland, and Japan) or *de jure* limited by national legislation (as in all other nuclear countries). Thus, some countries have chosen to limit NPCs' liability explicitly while, in other countries, firms by their nature are liable, at most, with their equity capital. In both cases, the consequences of limited liability, as discussed in Section 2, become relevant. Taking this as a cue, the following section critically discusses the regulatory instruments that could be applied by a regulatory authority.

4 Evaluating regulatory instruments

In Section 2, we explained the possibly severe implications of limited liability for NPCs’ risk-taking decisions. Section 3 has shown that current liability regulation does not sufficiently address these problems and that, therefore, nuclear risk might not be properly taken care of. This section reviews various regulatory approaches and evaluates their ability to reduce the NPCs’ incentives to take excessive risks.

4.1 Safety regulation

Aside from the question of liability regulation, another string of literature proposes setting safety standards. Public intervention to directly regulate the extent of precautionary measures includes the definition of a full set of measures leading to the optimal level of precaution, thereby avoiding the problem of excessive risk-taking.

The usual criticism that (central) regulatory authorities face is that they possess imperfect information and are therefore unable to define safety regulation properly (see, for instance, Baumol and Oates, 1971; Shavell, 1984). This may hold even more strongly for the regulation of nuclear power, which is by nature very complex. This problem of complexity and its implications for regulation are discussed by Trebilcock and Winter (1997) and comprehensively analysed in the context of several countries by Bredimas and Nuttall (2008).

Nuclear safety regulation concerns the initial construction of a power plant but also comprises the continual monitoring and reassessments of precautionary measures. Among others, Faure and Skogh (1990) point out that obtaining necessary information is difficult for a regulator, who might eventually depend on information provided by the nuclear industry itself. Since the industry acts in its own interest, it may provide inaccurate signals; regulation may then become too lax in some respects and too strict in others.

In general, safety and liability regulation have been considered substitutes for correcting externalities; consequentially, the usual policy recommendation has been to choose the instrument that causes the least administrative cost for achieving a given goal (see, for example, Calabresi, 1970, for an early discussion of related issues). In practice, however, both instruments are often used jointly, in nuclear power regulation, for example. Building upon this observation, Shavell (1984) and Kolstad et al. (1990) find that safety regulation and liability rules may complement each other, as their joint use can correct the inefficiencies of using either of the two alone.

Whereas a complementary use of direct safety regulation could reduce the problems associated with limited liability, one cannot assume – owing to the underlying complexity – that it can solve the problem. In addition, command-and-control measures are often accused of creating enormous inefficiencies, up to the point that some scholars, such as Coase (1960), argue that direct regulation might not necessarily provide better results than leaving the problem to the market.

4.2 Minimum equity capital requirements

Defining minimum equity requirements (in equity-to-assets ratio terms) is an instrument commonly used to regulate the problem of limited liability in the banking sector (cf. Sinn, 2003). Although the causes and consequences in the banking sector appear to be very similar, there is one crucial difference in the nuclear industry: whereas a bank's maximum third-party loss, even under the assumption of perfectly correlated risks, is at maximum defined by the bank's liabilities (stated in the balance sheet), the potentially catastrophic damages of a large-scale nuclear accident are not represented on an NPC's balance sheet. Thus, even the requirement to finance all assets with 100 per cent liable equity capital would not fully internalise excessive nuclear risk-taking. Hence, we conclude that it could lower the extent of the negative externality, since the NPCs' *de facto* liability capital would increase, but that it would not be as effective as in the banking industry.

4.3 Mandatory insurance

The existence of limited liability diminishes the NPC's incentive to purchase liability insurance for potential large-scale accidents (see Section 2). As a solution for this, and to reduce the incentives for excessive risk-taking, Trebilcock and Winter (1997) suggest mandatory liability insurance. Requiring the entire potential nuclear damage to be insured, thereby transferring the risk from the NPC to a third party, could induce an efficient outcome, as the NPC would have to pay a premium at least equal to the expected loss.[7] In this way, the NPC would be charged by the insurer for excessive risk-taking, which would become costly, and the negative externality would vanish.

However, imposing a full mandatory insurance for potential nuclear accidents has several shortcomings. First of all, there is the well-known problem of insurance-induced moral hazard, as the insurance market is likely not able to obtain as much information about care and risks as the NPC has.[8] Moreover, the insurability of catastrophic events – characterised by a low occurrence frequency but highly severe impacts – has generally been questioned by the literature.[9] As a prime example, nuclear risk has been repeatedly regarded as non-actuarial (see, for example, Litzenberger et

[7] The idea to require the purchase of liability insurance to correct for certain inefficiencies is widespread; consider, for example, automobile or professional liability insurance.
[8] For comprehensive analyses, see, for instance, Pauly (1974) and Shavell (1982).
[9] This is the case for both natural and man-made catastrophes, to different extents. See, among others, Kunreuther (1997) and Cutler and Zeckhauser (1999).

al., 1996; Kunreuther, 1997; Cutler and Zeckhauser, 1999; Radetzki and Radetzki, 2000).[10]

The most important reason why mandatory insurance might not be a reasonable alternative, however, is that the capital resources available to the insurance industry might well be insufficient to cover the damages of nuclear catastrophes. As insurance companies are also judgment-proof, they might not have the incentives to calculate and charge actuarially correct premiums (even if this were possible) but would also maximise their profits taking into account their own limited liability. In this case, the insurance premiums charged upon the nuclear industry would not reflect the true expected damages. Consequently, some of limited liability's effect on risk-taking would shift from one industry to another, without solving the core problem (see Buck and Jus, 2009, for a similar argument concerning the banking industry).

4.4 Mutual risk-sharing pools

In contrast to insurance, where risk is transferred to a third party, the risk in a mutual risk-sharing pool is shared among the parties creating the risk. Here, the NPCs agree on an *ex post* sharing of the costs of a catastrophic accident. Whereas insurance presumes an *ex ante* pricing of nuclear risk, mutual risk-sharing has an advantage: just paying the actual costs eliminates the need to estimate potential damages and probabilities in advance. The advantages of mutual risk-sharing over insurance have been extensively discussed and emphasised by, among others, Skogh (1999), Faure (2004), Faure and Fiore (2008), and Skogh (2008), who elaborates on the theoretical foundation of mutual risk-sharing.

Skogh (1999) describes mutual risk-sharing as beneficial since it does not require the assignment of subjective probabilities of accidents and explains why it is

[10] One may also refer to Section 2 for a discussion of inefficiencies on the insurance demand side. Limited liability and the low-probability characteristic of nuclear accidents lead to a biased individual insurance decision.

advisable for parties facing similar risks to share these in common pools. Faure (2004) investigates whether an extended mutual agreement between NPCs could serve as an alternative to the nuclear power liability regulation in place today. Faure and Fiore (2008) discuss possible structures and the potential for a more comprehensive mutual risk-sharing agreement among Europe's NPCs.

An example of a mutual risk-sharing agreement for NPCs comprises part of the US Price-Anderson Act. The US nuclear insurance market is supplemented by two mutual risk-sharing agreements (often referred to as 'mutuals'): the Nuclear Electric Insurance Limited (NEIL), created by NPCs in 1980, and the Overseas NEIL (ONEIL), established in 1999 in partnership with European NPCs. In Europe, NPCs have created mutual insurance schemes as a reaction to the amended nuclear liability regulation to jointly ensure a higher availability of liability capital. The first was the European Mutual Association for the Nuclear Industry (EMANI), founded in 1978; the second mutual, the European Liability Insurance for the Nuclear Industry (ELINI), was created in 2002. At the national level, NPCs in Germany guarantee mutual support in case of an accident up to EUR 2.35 billion.

In general, mutual risk-sharing creates a collective responsibility for risk-taking. Making companies liable generates incentives to prevent accidents, which implies a reduction of excessive risk-taking to decrease costs. However, risk-sharing pools suffer from the fundamental problem of collective action: the higher the number of NPCs financing the pool, the stronger the tendency towards free-riding, as individual responsibility shrinks and peer-monitoring becomes more costly. Demanding a fixed size risk-sharing pool to which each NPC must contribute according to certain indicators (the number of power plants, for example) increases the capital that the NPC loses in an accident. At the same time, however, the effectiveness of this kind of regulation diminishes as an NPC's share of the pool declines or if the opacity is so high that individual action is not easily observable.

4.5 Catastrophe bonds

Catastrophe (cat) bonds represent one way to spread the risk of potentially large losses via financial instruments (i.e. capital markets). A cat bond offers investors a return above the risk-free rate when a specified catastrophic event does not occur but requires the sacrifice of interest or principal otherwise. The general idea of cat bonds is explained by Cummins and Weiss (2009), who also give an overview of the relevant literature (for analyses of other alternative, and private, arrangements for transferring risk, see Wagner, 1998; Radetzki and Radetzki, 2000). So far, cat bonds have generally been used by insurers as an alternative to traditional re-insurance or by re-insurers, usually to atomise the risk of natural catastrophes such as earthquakes or hurricanes (see Evans, 2011; for a comparison between cat bonds and re-insurance, see Gibson et al., 2007; Cummins, 2012). Mexico was the first sovereign to offer cat bonds, thereby protecting itself against the risk of natural catastrophes (see, for example, Cardenas et al., 2007; Michel-Kerjan et al., 2011). An overview of the development and current state of cat bond markets can be found in Cummins (2012) and Swiss Re (2012). It can be clearly seen that issuance volumes declined sharply in 2008 owing to the financial crisis and have still not fully recovered. In 2011, they reached a volume of USD 5 billion.

The idea to employ cat bonds for not only natural catastrophes but also large-scale nuclear accidents is discussed by Tyran and Zweifel (1993). They give an elaborate description of how to internalise environmental risks such as potential nuclear catastrophes via capital markets. More specifically, they observe that NPCs could emit cat bonds by which nuclear risk is spread among a large number of investors. The principal received for each cat bond issued is supposed to be placed in risk-free assets, for example, in certain treasury bonds. The spread between the cat bond interest and the interest on a risk-free bond represents the market assessment of the risk of a nuclear accident, if this is specified as the trigger for the cat bonds' default. Hence, as nuclear risk is priced by the capital markets, risk-taking becomes costly for the NPCs, incentivising them to reconsider their risk-taking decision. Consequently, NPCs taking excessive risk may either revise their strategy to reduce the premiums to be paid on cat bonds or even leave the market if this business is too costly for them after the risk is priced. Radetzki and Radetzki (2000) give an overview of the alternatives that use capital markets to cover nuclear damages.

Leaving the well-known problems of cat bonds (such as high transactions costs) aside, the main issue in the case of nuclear power is that NPCs would not voluntarily emit cat bonds. Paying a premium on cat bonds would imply additional costs and undermine the benefits of limited liability. Thus, the regulatory authority would need to stipulate the emission of a certain volume of cat bonds, hoping that a market for them emerges, which could be, in principle, only a matter of the price of the cat bonds.

Arguments can be advanced, however, that cat bonds as they are currently employed can hardly solve the problem of limited liability entirely. Stipulating full coverage for the potential losses of each nuclear power plant operating worldwide would result in unimaginable amounts. Given the currently estimated damages of the Fukushima accident, the regulatory authority could demand a cat bonds emission of USD 200 billion. This would certainly outbalance any reasonable scope of this market given that there are more than 400 nuclear power plants operating worldwide and that in excess of USD 80 trillion would need to be invested in cat bonds. Therefore, although the idea of cat bonds sounds very promising, the nature of their implementation would need to be debated. The next section offers a proposal that partly relies on cat bonds but could potentially overcome the above-stated problem.

5 A market-based (rolling) nuclear risk fee

After having pointed out that current liability regulation might imply severe incentives for excessive risk-taking and having reviewed various regulatory instruments, we now propose a new way for liability in the nuclear industry to be regulated. The aim is to internalise the externality of excessive risk-taking, which we think is best accomplished by combining the strength of private markets with Pigouvian-type public intervention. We propose to use the ability of capital markets to evaluate risk-taking and society's reserve capacity to absorb high risks in order to achieve the desired level of nuclear power plant safety.

Our basic idea can be summarised as a two-stage approach in which, in the first stage, capital markets, by pricing a specified volume of cat bonds, provide an assessment of the risk stemming from each power plant. In the second stage, the regulatory authority employs this observable risk assessment and intervenes by charging a Pigouvian fee equal to an actuarially fair premium, thereby inducing the socially optimal level of risk-taking. Eventually, society adopts the role of an explicit insurer for nuclear risk. We sketch the main arguments in favour of this solution below before discussing the details relevant to its implementation.

Our analysis has pointed out several issues leading us to the conclusion that neither public safety regulation nor private participation alone would solve the problem of excessive nuclear risk-taking. In contrast to Tyran and Zweifel (1993), our approach does not aim to establish full loss coverage on capital markets. Instead, our idea uses cat bond markets for risk assessment only and delegates any further responsibility to the regulator (i.e. society). Specifically, our proposal demands that NPCs be obliged to issue cat bonds for each power plant in a volume that represents a (small) fraction of the potential costs of a large-scale accident. One could estimate an amount of about USD 100 million, which has already proven to be absorbable by capital markets, while assessing the probability of default by the spread over a risk-free interest rate (for example, LIBOR). This has two advantages: (1) it overcomes potential liquidity/capacity problems in capital markets, thus isolating the actual risk from those of other capital market deficiencies, and, (2) as the cat bond issuance is plant-specific, the risk assessment is transparent and the risks of various power plants become comparable. Moreover, even if the cat bonds amount to only a fraction of the potential cost, each single bond has a 'default' probability independent of the total number of bonds issued. Hence, the interest premium to be paid on the cat bonds by the NPC for a specific power plant reflects the true risk of a large-scale accident, in a case where the trigger of the cat bond would be pulled and the NPC would default on the cat bonds. The ability of capital markets to rate assets has been stressed by Fama (1991). Moreover, it is generally believed that investors are likely to perform better at assessing risk than regulators, who are not investing own capital and therefore may lack the incentive to obtain costly information. Furthermore, it is argued by Cummins and Weiss (2009) that securities markets are more efficient at reducing information asymmetries and facilitating price formation than insurance markets.

Having outlined the first stage of our proposal, we will now explain what the regulatory authority should do in the second stage. We emphasise again that a Coasian solution to the problem is not feasible and that the regulator must intervene in a Pigouvian way (see Section 2). Observing the plant-specific interest premium of a cat bond over a risk-free bond, the regulator defines a fee for each nuclear power plant to be paid by the NPC. The fee is proportional to the interest premium, hence lower for safer plants and higher for those assessed to pose a higher risk. In this way, the regulator, representing society, becomes the insurer for the nuclear risk by charging a premium that depends on actual risk and in return agrees to absorb the costs of large-scale accidents. This proposal overcomes the negative consequences of limited liability, as the true risk becomes the crucial factor in the fee an NPC has to pay. Society, on the other hand, has the capacity to absorb the costs of nuclear accidents – a better capacity, in any case, than any privately owned company (like an insurance company). Societies have always managed to overcome severe catastrophes and will also look for the best possible way to deal with a nuclear accident

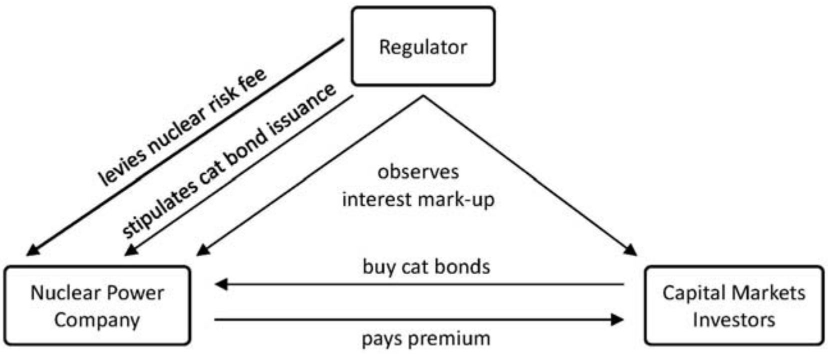
The advantage of the outlined proposal is that nuclear power companies are internalising the entire social costs of their activity, and society is, on average, fairly compensated for the risk it is taking over. This is all that can be demanded from an economic perspective, and it remains up to the NPCs to decide whether it is still profitable to run nuclear power plants. Of course, this decision would also be influenced by developments in electricity prices, which could rise if an unsafe nuclear power plant had to close, thereby making safer ones sufficiently profitable even though the fee would have to be paid. By the same token, renewable energy sources would also profit, as running nuclear power plants would become more costly owing to this proposal.

Finally, we will discuss more details of our approach. Its functional design is summarised in Fig. 2. Based on the observed risk premium, the regulator computes the Pigouvian nuclear risk fee, which equals the expected nuclear damage as the result of multiplying the probability of a large-scale accident (extracted from the interest spread between the cat bond and a risk-free bond), with its pre-defined potential costs less the volume of cat bonds that has been emitted.[11] Moreover, to give NPCs the opportunity to improve their assessment and thus reduce the Pigouvian fee that is to be paid, cat

[11] The potential costs can be plant-specific, depending on proximity to cities or production methods, for instance. Specifying the potential costs of a nuclear accident is a topic for future research.

bond issuance and the determination of the fee could be repeated according to a pre-defined schedule, every two or three years, for instance. The maturity of the bonds could also be defined according to this schedule.

Fig. 2: A market-based (rolling) nuclear risk fee



Finally, two further aspects shall be considered. First, compared to the general design of cat bonds, the question of how to specify the default – how the investor's impairment is triggered – will be discussed. Finken and Laux (2009) give an overview of the possibilities and discuss their benefits and weaknesses. One alternative would be to link the default trigger to the intensity of a nuclear accident as rated, for example, by the IAEA, according to the International Nuclear Event Scale. Second, existing rating agencies and new, more specialised agencies could rate the risk of nuclear power plants and provide this information to potential investors, as done for other financial products.

6 Conclusions

Currently, NPCs enjoy limited liability with respect to potential catastrophic nuclear accidents. This has been seen as necessary to protect NPCs from ruinous claims and was essential for the development of this industry, but it may nowadays be re-interpreted as a major source of excessively risky nuclear power plants. As the number of nuclear power plants worldwide is expected to rise over the next decades, it is all the more important to discuss ways in which the use of nuclear power can be made safer. Therefore, we have evaluated several known instruments and pointed out that all have weaknesses or are simply not able to reduce excessive risk-taking. We have thus proposed a new regulatory approach, based on the general idea of catastrophe bonds, that may be superior to the other instruments. The core of our proposal consists of a two-stage procedure: In the first stage, capital markets evaluate the risk stemming from each power plant via catastrophe bonds issued on a smaller scale than actually required to cover the potential losses but whose value can be used as an indicator for the riskiness of a nuclear power plant. In the second stage, the regulator uses this private risk assessment and intervenes by charging an actuarially fair premium that induces the optimal level of risk-taking. Society then acts as an explicit insurer for nuclear risk and is, on average, fairly compensated for the risk it is taking over. The implementation of such a scheme would make the use of nuclear power (privately) more expensive, since the risk of accidents would now also be priced. Consequently, some nuclear power plants (in particular the unsafe ones) may become unprofitable and could disappear from the market. The other ones that remain privately profitable are then also socially profitable according to the monetary risk they are imposing on society. Neither the ethical nor the moral arguments against nuclear power have been considered at this stage; even after the optimal level of risk-taking is implemented, society may decide not to use nuclear power. This decision must not be taken on the basis of nuclear power plants that are too risky, however, but given that the level of care is chosen optimally. Therefore, solving the problem of limited liability and excessive risk-taking is both an important element of the future use of nuclear power and a necessary basis for decisions regarding nuclear phase-outs.

References

Baumol, W., Oates, W., 1971. The use of standards and prices for protection of the environment. *Swedish Journal of Economics*, 73, 42-54.

Buck, F., Jus, D., 2009. Liability regimes, deposit insurance and the subprime crisis. *Economic Policy and Global Recession*, 2, 13-23.

Bredimas, A., Nuttall, W., 2008. An international comparison of regulatory organizations and licensing procedures for new nuclear power plants. *Energy Policy*, 36, 1344-1354.

Calabresi, G., 1970. *The Costs of Accidents*. Yale University Press, New Haven.

Camerer, C., Kunreuther, H., 1989. Decision processes for low probability events: Policy implications. *Journal of Policy Analysis and Management*, 8, 565-592.

Cardenas, V., Hochrainer, S., Mechler, R., Pflug, G., Linnerooth-Bayer, J., 2007. Sovereign financial disaster risk management: The case of Mexico. *Environmental Hazards*, 7, 40-53.

Coase, R., 1960. The problem of social cost. *Journal of Law and Economics*, 3, 1-44.

Cummins, J., 2012. CAT bonds and other risk-linked securities: Product design and evolution of the market, *SSRN Working Paper Series*.

Cummins, J., Weiss, M., 2009. Convergence of insurance and financial markets: hybrid and securitized risk-transfer solutions. *Journal of Risk and Insurance*, 76, 493-545.

Cutler, D., Zeckhauser, R., 1999. Reinsurance for catastrophes and cataclysms, in: Froot, K., (Ed.), *The Financing of Catastrophic Risk*, University of Chicago Press, Chicago, pp. 233-274.

EC 2011. Energy roadmap 2050, December 2011, http://ec.europa.eu/energy/energy2020/roadmap.

Evans, S., 2011. Catastrophe bond & insurance-linked securities deal directory, April 2011, http://www.artemis.bm/deal_directory.

Fama, E., 1991. Efficient capital markets: II, *Journal of Finance*, 46, 1575-1617.

Faure, M., 2004. Alternative compensation mechanisms as remedies for uninsurability of liability. *Geneva Papers on Risk and Insurance*, 29, 455-489.

Faure, M., Vanden Borre, T., 2008. Compensating nuclear damage: A comparative economic analysis of the U.S. and international liability schemes. *William & Mary Environmental Law and Policy Review*, 33.

Faure, M., Fiore, K., 2008. The coverage of the unclear risk in Europe: Which alternative? *Geneva Papers on Risk and Insurance*, 33, 288-322.

Faure, M., Skogh, G., 1992. Compensation for damages caused by nuclear accidents: A convention as insurance. *Geneva Papers on Risk and Insurance*, 17, 499-513.

Finken, S., Laux, C., 2009. Catastrophe bonds and reinsurance: The competitive effect of information-insensitive triggers. *Journal of Risk and Insurance*, 76, 579-605.

Gibson, R., Habib, M., Ziegler, A., 2007. Why have exchange-traded catastrophe instruments failed to displace reinsurance? *SSRN Working Paper Series*.

IAEA, 1963. *Vienna Convention on Civil Liability for Nuclear Damage*, Vienna, Austria, May 1963.

JCER, 2011. FY2020 nuclear generating cost treble pre-accident level, *Thinking Costs of Generating Electricity*, July 2011, http://www.jcer.or.jp/eng/research/pdf/pe(kobayashi20110719)e.pdf.

Kolstad, C., Ulen, T., Johnson, G., 1990. Ex post liability for harm vs. ex ante safety regulation: Substitutes or complements? *American Economic Review*, 80, 888-901.

Kunreuther, H. 1997. Rethinking society’s management of catastrophic risks. *Geneva Papers on Risk and Insurance*, 22, 151-176.

Kunreuther, H., Novemsky, N., Kahnemann, D., 2001. Making low probabilities useful. *Journal of Risk and Uncertainty*, 23, 103-120.

Litzenberger, R., Beaglehole, D., Reynolds, C., 1996. Assessing catastrophe reinsurance-linked securities as a new asset class. *Journal of Portfolio Management, Special Issue*, December, 89-98.

Michel-Kerjan, E., Zelenko, I., Cardenas, V., Turgel, D., 2011. Catastrophe financing for governments: Learning from the 2009-2012 MultiCat program in Mexico, OECD Working Papers on Finance, Insurance and Private Pensions, 2011.

NSC of Japan, 1961. Law on compensation for nuclear damage, June 1961, http://www.nsc.go.jp.

OECD, 1960. Convention on third party liability in the field of nuclear energy, Paris, France, July 1960.

Pauly, M., 1974. Overinsurance and public provision of insurance: The roles of moral hazard and adverse selection. *Quarterly Journal of Economics*, 88, 44-62.

Radetzki, M., Radetzki, M., 2000. Private arrangements to cover large-scale liabilities caused by nuclear and other industrial catastrophes. *Geneva Papers on Risk and Insurance*, 25, 180-195.

Shavell, S., 1980. Strict liability versus negligence. *Journal of Legal Studies*, 9, 1-25.

Shavell, S., 1982. On liability and insurance. *Bell Journal of Economics*, 13, 120-132.

Shavell, S. (1984), A model of the optimal use of liability and safety regulation. *Rand Journal of Economics*, 15, 271-280.

Shavell, S., 1986. The judgment proof problem. *International Review of Law and Economics*, 6, 45-58.

Sinn, H.-W., 1982. Kinked utility and the demand for human wealth and liability insurance. *European Economic Review*, 17, 149-162.

Sinn, H.-W., 1983. *Economic Decisions under Uncertainty*. North-Holland Publishing Company, Amsterdam.

Sinn, H.-W., 2003. Risktaking, limited liability, and the competition of bank regulators. *FinanzArchiv: Public Finance Analysis*, 59, 305-329.

Skogh, G., 1999. Risk-sharing institutions for unpredictable losses. *Journal of Institutional and Theoretical Economics*, 155, 505-515.

Skogh, G., 2008. A European nuclear accident pool. *Geneva Papers on Risk and Insurance*, 33, 274-288.

Strand, J., 1994. Environmental accidents under moral hazard and limited firm liability. *Environmental and Resource Economics*, 4, 495-509.

Swiss Re, 2012. *Insurance-Linked Securities Market Update, XVII*, Zurich, Switzerland, January 2012.

TEPCO, (2011). *Annual Report 2011*, March 2011, *http://www.tepco.co.jp*.

Trebilcock, M., Winter, R., 1997. The economics of nuclear accident law. *International Review of Law and Economics*, 17, 215-243.

Tyran, J.-R., Zweifel, P., 1993. Environmental risk internalization through capital markets (ERICAM): The case of nuclear power. *International Review of Law and Economics*, 13, 431-444.

US NRC, 2012. Fact sheet on nuclear insurance and disaster relief funds, March 2012, http://www.nrc.gov.

Van't Veld, K., Hutchinson, E., 2009. Excessive spending by firms to avoid accidents: Is it a concern in practice? *International Review of Law and Economics*, 29, 324-335.

Wagner, F., 1998. Risk securitization: An alternative of risk transfer of insurance companies. *Geneva Papers on Risk and Insurance*, 23, 540-607.

WNA, 2012a. Liability for nuclear damage, March 2012, http://www.world-nuclear.org/info/inf67.html.

WNA, 2012b. Fukushima accident 2011, April 2012, http://www.world-nuclear.org/info/fukushima_accident_inf129.html.