THE NUCLEAR LIABILITY LIMIT IN THE OECD CONVENTIONS

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Abstract

In the nuclear industry, the operators have always benefited from a favourable liability regime concerning the risks they generate. Indeed, their civil liability in case of an accident on their installations is limited by a financial cap. For OECD countries, this cap is enacted by the Paris (1960) and the Brussels (1963) Conventions. This cap artificially reduces the operators' risk costs and impedes their full internalization and coverage. In this paper, we examine the idea that this liability limit may make the nuclear operators benefit from an implicit subsidy. We focus on the production nuclear operators. Using numerical curve-fitting techniques, this implicit subsidy is evaluated for France, as a representative example of the situation of OECD countries. We inspire from previous works done by Dubin and Rothwell (1990), for the USA, and by Heyes and Liston-Heyes (1998, 2000) for the USA and Canada and we improve their model. From our results, we analyse the economic impact of the implicit subsidy on the competitiveness of nuclear energy.

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1. Introduction

On January the 10th 2007, during the discussions about *A New Energy Policy for Europe: Energy for a Changing World*, the European Commission has repeated its support to nuclear energy, particularly with the view to reduce CO_2 emissions by 20% by 2020. On this occasion, Commissioner for Energy Policy, Andris Piebalgs said: "*If we take the right decisions now, Europe can lead the world to a new industrial revolution: the development of a low-carbon economy*"[2]. In the current context of climate change and depletion of fossil resources, the question on tomorrow's energies is central. In this respect, nuclear energy appears as a possible solution to meet future environmental and economic constraints. It is abundant, competitive and air-pollution free. Nevertheless, this solution must be carefully considered because nuclear energy generates risks for environment and health and because the OECD's nuclear operators have always benefited from a favourable liability regime concerning these risks. Indeed, since the 1960s, their civil liability (in case of an accident on their installations) is governed by international Conventions which limit it by a financial cap. As a result, these Conventions artificially reduce the operators' risk costs and impede their full internalization and coverage. The negative consequences of the partial internalization of the risk costs in terms of incentives, efficiency and compensation are well-known (Trebilcock and Winter, 1997; Faure and Skogh, 2003; Faure and Van den Bergh, 1990). In this respect, the case of France is particularly interesting because, proportionally to its total production, it produces the biggest share of nuclear energy in the world (80% with 58 operating reactors). Moreover, France is one of the first countries having ratified the nuclear liability Conventions within the OECD. As for the other ratifying countries, the liability of the French nuclear

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[2] (EC, 2007)

production operator, EDF[3], is thus financially limited in case of an accident on his plants. In this paper, we will examine the idea that this limit may make the nuclear operator benefit from an implicit subsidy. Besides, although previous research evaluated the nuclear liability implicit subsidy for the USA (Dubin and Rothwell, 1990; Heyes and Liston-Heyes, 1998) and for Canada (Heyes and Liston-Heyes, 2000), this subsidy has never been evaluated for France (nor has it been for the other European countries). Note that, as regards its nuclear liability regime, the French case is not specific. EDF is submitted to the same international Conventions than the other OECD nuclearized countries. We will use the French case simply as a representative example of the situation of these countries. Our results for France will thus have also implications for them. Such an evaluation may have an important indicative value to measure the magnitude of the non-internalized (and non-covered) risk costs by nuclear operators. For this purpose, we will rely on the Heyes and Liston-Heyes' model (1998; 2000). We will improve it by correcting some methodological mistakes they made. We will use numerical curve-fitting techniques using data from insurance premiums and from different expertise assessments regarding "worst-case" scenarios. This methodology is relevant for two reasons: first, it is consistent with our purposes and secondly, this will allow us to compare our results to those computed for other countries. Our contribution is twofold: on the one hand, we will improve the existing methodology by adding some necessary refinements and on the other hand, we will apply the refined methodology to the French case.

This paper proceeds as follows. First, we will present the OECD nuclear liability Conventions, focusing on French nuclear law. Hence, we will develop the idea that the French nuclear operator may benefit from an implicit subsidy, integrating the last legislative amendments of the 2004 Protocols. Secondly, we will attempt to evaluate the French nuclear implicit subsidy and the impact of the new amendments on it. Thirdly, we will comment upon our results and will give some perspectives, particularly analysing the impact of the implicit subsidy on the competitiveness of the nuclear kWh. Finally, we will conclude.

2. The Paris and Brussels Conventions: a subsidizing liability regime

The OECD legislation relative to the nuclear civil liability is governed by two international Conventions. First, the Paris Convention was drafted on July the 29th 1960 within the framework of the Nuclear Energy Agency (NEA) by the OECD. Its formal goal was to provide adequate and fair compensation to victims of nuclear damages. Ratified by 15 European countries, it was then supplemented, on January the 31st 1963, by the Brussels Convention which was ratified by 12 members of the Paris Convention[4]. These international treaties are transposed in the national legislations which benefit from an autonomous room for manoeuvre. States are, for example, allowed to provide more compensation than the amounts laid down in the Conventions.

In France, these Conventions are transposed in the Law n°68-943 passed on October the 30th 1968 (modified by the Law n°90-488 of June the 16th 1990). In pursuance of the Conventions and of this Law, the French nuclear operator's civil liability is strict and channelled. The strict liability means that the operator will always be hold liable, in case of an accident on his installations, whether he commits a negligence or not. The channelled liability

[3] *Electricité de France*

[4] A second regime came into being through the UN related IAEA (International Atomic Energy Agency). Within this framework, the Vienna Convention, relative to the civil liability for nuclear damages, was drafted and ratified on May the 21st 1963 by 32 countries of South America, Eastern Europe and Asia. Some States are members to the NEA regime, others to the Vienna Convention. A Common Protocols was signed in 1988, after the Chernobyl accident, to coordinate the scope of application of both Conventions.

to the operator means that, even though other actors might contribute to the accident, the operator will always be the sole official liable. But the most important is that the operator engages his liability only up to a limited amount. Indeed, his civil liability is financially capped[5]. This cap was first fixed by the Paris Convention in 1960 and has been modified many times since then. Before the last modification Protocols of the Paris and Brussels Conventions, drafted on February the 12th 2004 at the OECD Head Office in Paris, the operator's liability limit was fixed, in France, at 91 million €. This limit has been increased to 700 million €. The 2004 Protocols have not entered into force yet. However, they are about to be implemented since, on June the 13th 2006, the French government modified again the 1968 French nuclear Law, integrating the new cap[6].

Above this limit, the Brussels Convention[7] added a supplementary mechanism of compensation, based on public funds, for the cases where the liability amount fixed by the Paris Conventions would be insufficient. For this matter, two additional risk layers have been added beyond the operator's liability limit. Indeed, at a national level, if the operator's liability cap is not sufficient to compensate the victims and to repair the damages of an accident, the State where the accident occurred must finance reparations up to a certain limit. In French nuclear Law, this limit is currently fixed at 140 million €. Note that this second amount has been increased by the 2004 Protocols to 500 million € and has also been integrated in the recent amendments of the French Statute. At a supranational level, a third risk layer is enacted by the Conventions: if the cumulative reparations from the operator and the State are still deficient, the other members of the Conventions must jointly cover the exceeding damages (greater than 231 million €) up to 150 million €. The 2004 Protocols have increased this limit to 300 million €. The respective coverage caps of the operator, the State and the States, before and after the 2004 Protocols, are summed up in Table 1.

	Paris (1960) and Brussels Conventions (1963) (caps for France, 1968 law amended)	Modification Protocols of the Paris and Brussels Conventions (2004)
Operator's liability cap	91	700
State intervention	140	500
TOTAL at national level	*231*	*1200*
Contracting Parties coverage	150	300
TOTAL at international level	*381*	*1500*

Table 1. The different coverage caps before and after the 2004 Protocols (in million €)

In some respect, this legal regime can be considered as subsidizing the nuclear operator. Indeed, his liability financial limit is a privilege, given that the operator does not have to internalize his risk costs above the cap. In the pursuance of the OECD Conventions, the operator has the obligation to cover his liability through insurance or other means (financial guarantees…). Therefore, thanks to the cap, his coverage costs are lower than they would be if there was no cap. The operator is thus protected from the coverage of a share of his risk costs (beyond the cap). The difference between his current coverage cost and the coverage cost he would have to bear without the cap represents an implicit subsidy. This implicit subsidy is an externality which takes the form of a wealth transfer from the victims (and taxpayers) to the industry. Indeed, the origin of the subsidy is not the State but the

[5] The operator civil liability is also limited in time, that is, the victims must bring a suit for compensation against him with a prescription delay of 30 years after the accident, in case of death or individual damages, and with a prescription delay of 10 years for other damages (Paris Convention, article 8). The integral text of the Paris Conventions is online on http://www.nea.fr/html/law/nlparis_conv.html.
[6] The integral text of the French Law is online on http://aida.ineris.fr/textes/lois/text1000.htm
[7] The integral text of the Brussels Conventions is online on http://www.nea.fr/html/law/nlbrussels.html

victims who might be obliged to self-finance their own compensation if the cost of a nuclear accident exceeded the operator's cap.

Of course, the two additional layers implemented by the Brussels Convention (up to 1500 million €) would complete the compensation from the operator. However, the cost of a major accident is estimated between 10 billion € and 100 billion € (Dubin and Rothwell, 1989; ExternE, 1998; Schieber and Schneider, 2002, DGEMP Report, 2003), what is far higher than the total available amounts (see Table 1). As a consequence, even with the public funds, the victims' self-financing of their own compensation would remain high. Moreover, from the Coasian rule of internalisation viewpoint (Coase, 1960), the operator has to internalise and to cover all his risk costs. This rule guarantees accidents prevention *ex ante* and compensation *ex post*. With the liability cap, this rule is not respected. We can thus deduce that the OECD legal regime protects the operator, particularly against the duty to compensate for major nuclear accidents of which the costs might largely exceed his liability cap. This is implicitly admitted that, if a nuclear accident costs more than the limit, the operator will not be able to provide full compensation to the victims.

Finally, by financing a share of the operator's risk costs, the States pay for the reparations that the operator does not have to pay, in pursuance of the Conventions. They thus directly contribute to the lack of internalization of the risk costs by the operator. Moreover, they intervene *ex nihilo*, without making the operator pay for their intervention. They are thus not reinsurers but simple financial assistants. Yet, to be efficient and to respect the Coasian rule of internalisation, the States should require a reinsurance premium from the operators for these additional coverages. This mechanism exists, for example, for terrorism risk in France, with the GAREAT system or in UK with the Pool Re[8]. Doing so, the States relieve the nuclear operator from a reinsurance cost. As we will do for the operator's implicit subsidy, we will measure the magnitude of this cost. Note that the States interventions are not subsidies. The direct beneficiaries are the victims of nuclear accidents and not the operator himself. There is not a wealth transfer from the States to the industry but from the States to the damaged parties. Moreover, the reinsurance cost that the States should require from the operator is included in the operator's implicit subsidy. Although the 2004 Protocols have not entered into force yet, we mentioned that the operator's and the States' respective coverages have lately been revised upward. In this respect, it will thus be of prime importance, for the following of the analysis, to integrate this revision in the evaluation of the French nuclear implicit subsidy.

3. The evaluation of the French nuclear implicit subsidy

In this paper, we focus on the example of the implicit subsidy provided in French legislation, but the same implicit subsidy also exists in other legal systems which have a financial limit as the liability of the operator. The advantage of focussing on one particular example is that a rather concrete estimation of the implicit subsidy can be provided.

3.1. The methodology

In accordance with the Conventions and specifically with French nuclear Law, EDF has to cover the risks he generates up to 91million €. This capped coverage is made

[8] Within these systems, the insured firms pay an insurance premium to their insurers. Into this premium, a reinsurance premium is included, since the State reinsures the insurers for this risk, through a public-private partnership.

compulsory by the Law (article 7) and EDF meets his obligation in two distinct ways. For the first two thirds (60 million €), he guarantees his liability by his own financial reserves and for the last third (31 million €), he resorts to insurance[9] (Carrez, 2003). As his cap is currently fixed at 91million €, he thus benefits from an implicit subsidy corresponding to the costs of coverage of the damages exceeding this amount. What is considered herein as an *accident* implying the operator's civil liability is an accident of production, that is, the release of radioactive elements outside the nuclear plant, resulting from a failure of the reactor (fusion of the core). To evaluate the implicit subsidy, we rely on Heyes and Liston-Heyes' methodology (1998; 2000). Their model constitutes a reaction to Dubin and Rothwell (1990). We aim at fitting a curve (a function of probability density *f*) relating the magnitude of a nuclear accident (in terms of off-site damages) to its probability of occurrence (assessed by expert studies). For this purpose, we use data from the French nuclear insurance premium and from the probabilities of "worst-case" scenarios. This methodology consists in computing the coverage subsidy by extrapolating the current insurance premium. It is relevant from both analytical and technical viewpoints. Nevertheless, we will refine the Heyes and Liston-Heyes' model and correct it from several mathematical mistakes they made[10].

If *f(x)* is the probability distribution of an accident per reactor year[11] and *x* the damages corresponding to this accident, the expected liability of the EDF's insurer, in case of an accident, noted *E(x)* (in million € per reactor year), is:

$$E(x) = \int_{60}^{\infty} \min\{x;31\} f(x)\,dx \qquad x \in \Re^{+*} \qquad (1)$$

Every year, EDF pays an insurance premium of 6.4 million € to cover its risks up to 31 million € per accident in "excess loss" (Charpin, Dessus and Pellat, 2000; Carrez, 2003). That means that the insurer covers the damages of a nuclear accident only for the share between 60 million € (self-insured by EDF) and 91 million € (the liability cap). If the damages exceed 91 million €, the insurer will have to pay only 31 million €, whatever the costs are. As EDF operates 58 nuclear reactors, the insurance premium amounts to P = 110,345 € per reactor per year. The literature on insurance taught that the calculation of an insurance premium is, for the minimum, the sum of three elements: the expected value of losses *E(x)*, the insurer's loading costs[12] and a premium for risk aversion. The loading costs are commonly estimated to 30% of the total premium (Denenberg, 1973; Dubin and Rothwell, 1990; Heyes and Liston-Heyes, 1998, 2000). We note them $c = 0.3$. If we remove the loading costs c from P, the expected value of losses *E(x)* thus equals (in million € per reactor per year):

$$E(x) = P.(1- c) = 0.077241 \qquad (2)$$

Neither Dubin and Rothwell (1990) nor Heyes and Liston-Heyes (1998-2000) have included a premium for risk aversion in their evaluations. In our sense, this element is

[9] This liability insurance is contracted through 3 groups: the insurers Axa and AGF (inside Assuratome, the French nuclear insurance pool) and the European mutual ELINI (EDF, Document de Référence 2006).

[10] We will only present herein the main properties and results of our evaluation, and the interested reader will find further mathematical proofs in Appendix.

[11] The "reactor year" unit is a commonly used unit in the nuclear industry to make evaluations per reactor per year.

[12] The loading costs are the costs borne by the insurer relatively to his activity. They refer to his internal costs and expenses, the overheads generated by the normal functioning of his activity (administration charges, management costs…).

essential, especially in the insurance of catastrophic risks. However, it is difficult to measure because it is not the result of an objective calculation but a subjective estimation of the insurer himself. It represents what the insurer requires to cover the uncertainty to which the nuclear risk is subject. We note this risk premium r and we give two values to it: 5% and 10% of the total insurance premium. Hence, if we remove now the additional premium r from equation (2), $E(x)$ becomes:

$$E(x) = [P.\,(1-c)].(1-r) = \begin{cases} 0.073379 \text{ if } r = 5\% \\ 0.069517 \text{ if } r = 10\% \end{cases} \quad (3)$$

With these data, $E(x)$ can be evaluated and rewritten as follows:

$$\int_{60}^{91} (x-60).\,f(x)dx + \int_{91}^{X} 31.\,f(x)dx = \begin{cases} 0.073379 \text{ if } r = 5\% \\ 0.069517 \text{ if } r = 10\% \end{cases} \quad (4)$$

This equation represents the calculation of the expected value of losses of a nuclear accident by the insurer. Of course, we don't pretend that the nuclear insurer do precisely calculate his premium in this way, since we don't have access ourselves to its real computation. But we aim to mimic it with assumptions as realistic as possible. Equation (4) is consistent with the EDF's nuclear insurance contract, according to which, as we said above, the insurer has to cover damages between 60 million € and 91 million €, if the accident costs less than 91 million €, and he has to pay 31 million €, if the accident costs more than the cap.

X represents the damages of a major accident (considered as the maximum damages). By "major accident", we refer to radioactive emissions resulting from the fusion of the reactor core being likely to have serious consequences on third parties. More precisely, we refer to an accident of the "S3" ("Source term 3")[13] category defined by the Authorities of nuclear safety in France (Queniart, 1992; Spadaro and Rabl, 1998; Schieber and Schneider, 2002). On the International Nuclear Energy Scale (INES), "major" accidents correspond to the 7th category. The damages X have been evaluated by different expert studies through "worst-case" scenarios. They are hardly estimable and the studies are far from being consensual. As we said above, these major damages spread from 10 billion € to 100 billion € (Dubin and Rothwell, 1989; Spadaro and Rabl, 1998; Schieber and Schneider, 2002, DGEMP Report, 2003)[14]. Hence, in order to provide a rigorous survey of the different values the implicit subsidy can take, according to the magnitude of X, we select 4 levels of major damages (in million €): X_i, with i=1,…,4 such as: $X_i = \{10{,}000; 40{,}000; 70{,}000; 100{,}000\}$.

Moreover, the probability of accident, corresponding to the damages X, is also submitted to controversies. Nevertheless, the results of studies are more unanimous than for X. We rely on the three probabilities generally estimated by the Probability Risk Assessments (PRA): p_i such as i=1,2,3 with $p_1 = 10^{-4}$, $p_2 = 10^{-5}$ and $p_3 = 10^{-6}$ per reactor per year (USNRC, 1990; NEA/OECD, 1994; IRSN/EDF, 1990; Spadaro and Rabl, 1998). These probabilities are the probabilities of fusion of the reactor core, considered as the main source of a nuclear

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[13] This type of accident corresponds to the deferred break of the confinement barrier and radioactive releases latest 24 hours after the fusion of the reactor core with filtration. This type of accident is characterised by the release of 75% of inert gases (helium, neon, argon, krypton, xenon and radon) and about 1% of the most volatile elements (iodine, caesium and strontium).

[14] From a technical viewpoint, all the studies we rely on are valuable. Their differences mainly relate to their choice of hypothesis, from the reactors size and the nature of the impacts (environmental and/or sanitary) taken into account in the calculations and from the discount rate applied.

accident[15]. Although Heyes and alii used this type of probabilities in their own evaluations, they omitted an important element. Indeed, we have to add conditional probabilities to them, that is, probabilities that radioactive elements are released into the atmosphere *after the fusion of the reactor core*. The first probabilities are not sufficient to determine the probabilities of accidents *having* consequences on third parties. They only define the likelihoods that the reactor overheats and fails. Yet, these events don't necessarily imply that radioactive elements are released outside the plant. In this respect, conditional probabilities are crucial since they determine the magnitude of damages on third parties after the fusion of the reactor core. The different PRA, lead in several countries, estimate them such as $p_j^{'}$ with j=1,2 and $p_1^{'}$= 0.81 for "minor" releases and $p_2^{'}$= 0.19 for "major" releases (USNRC, 1990; NEA/OECD, 1994; Spadaro and Rabl, 1998). The differences between these probabilities reflect the quantity of radioactive releases outside the plant associated to an accident, and hence the severity of the accident. In order to make the evaluation of the implicit nuclear subsidy more realistic than Heyes and alii did, we thus integrate this second category of probabilities in the calculation (by multiplying them to the first probabilities). More particularly, we use $p_2^{'}$ since it corresponds to major accidents of damages X_i.

As Heyes and Liston-Heyes relevantly did it, largely inspired by Chow and Oliver (1988) and Chow and alii (1990), we determine *f(x)* following a Bayesian escalation model[16]. With this model, *f(x)* defines the function of probability density relative to the probability of occurrence of "extraordinary events" of which the losses X_i can exceed 10 billion €. After a selection process, we follow their choice of the logistic distribution in order to approach *f(x)*[17]. The form of the standard logistic distribution and its cumulative are the following:

$$f(x) = \frac{e^{-x}}{(1+e^{-x})^2} \quad (5) \quad \text{and} \quad F(x) = \frac{1}{(1+e^{-x})} \quad (6) \qquad x \in \Re^{+*}$$

We also follow the logarithmic transformation $x \rightarrow a+b.\ln(x)$, since the damages x are always strictly positive. Equation (6) thus becomes:

$$F(x) = \frac{1}{(1+e^{-(a+b\ln x)})} \quad (7) \qquad a \in \Re \text{ and } b \in \Re^{+*}$$

[15] We exclude from our analysis the accidents resulting from external events (natural catastrophes or hostilities) since these events are hardly foreseeable and thus cannot be affected by a probability.

[16] This type of model is particularly consistent with our evaluation because it implies that serious accidents occur as a result of a sequence of successive independent failures rather than as the result of only one failure. This is the case commonly admitted for severe nuclear accidents. As a consequence, major accidents have probabilities of occurrence lower than minor accidents.

[17] Few continuous distributions of probabilities satisfy to the requirements of the nuclear accidents. Among the most commonly used, statistics offers the uniform, normal, log-normal, logistic, gamma and beta distributions. The uniform, normal and log-normal distributions are performing for the modelling of random, frequent and small size events. Therefore, they don't fit. They are thus eliminated. The logistic, gamma and beta distributions are the only ones to be possible candidates. The gamma and beta distributions are commonly used in finance and physics to model low-probability events. However, they are also eliminated because they don't permit to explicitly extract a cumulative function *F(x)* as the primitive of the density function *f(x)* (Johnson et alii, 1994). Moreover, they require a quite important sample of data. Concerning the logistic distribution, it is the most appropriate to model nuclear accidents. Indeed, it allows approaching low-frequency and high-severity events because it can integrate extreme values. For more details, see Johnson and Kotz (1970).

Here is the major mistake of Dubin and Rothwell (1990) and Heyes and Liston-Heyes (1998, 2000). Indeed, after the logarithmic transformation, they directly transposed $a+b.\ln(x)$ in equation (5) without recalculating *f(x)*, which is the derivative of equation (7). They thus wrote : $f(x) = \frac{e^{-(a+b\ln x)}}{(1+e^{-(a+b\ln x)})^2}$, which is mathematically wrong. We correct this mistake and write the new (and right) *f(x)* as:

$$f(x) = \frac{b}{x} \cdot \frac{e^{-(a+b\ln x)}}{(1+e^{-(a+b\ln x)})^2} \qquad (8)$$

a and *b* are the parameters to determine. As a consequence of Dubin and alii's mistake, they found values of b<0, which is not consistent with the logistic distribution curve.

Once the parameters *a* and *b* are determined (see Appendix), we evaluate the values of the current French nuclear implicit subsidy with the following equation:

$$\int_{91}^{X} x.f(x)dx - \int_{91}^{X} 91.f(x)dx \qquad (9)$$

The reinsurance costs exonerated by the French State and the States are respectively evaluated with the following equations:

$$\int_{91}^{231} x.f(x)dx + \int_{231}^{X} 140.f(x)dx \qquad (10) \quad \text{and} \quad \int_{231}^{381} x.f(x)dx + \int_{381}^{X} 150.f(x)dx \qquad (11)$$

140 (million €) being the French State's coverage cap and 150 (million €) being the States joint coverage cap (see Table 1).

What are the results of the evaluation?

3.2. The results

According to the values of the parameters *a* and *b*, *r*, *X* and p_i, equation (9) gives the following values for the French implicit nuclear subsidy:

	$p_1 = 10^{-4}$; $p'_2 = 0.19$		$p_2 = 10^{-5}$; $p'_2 = 0.19$		$p_3 = 10^{-6}$; $p'_2 = 0.19$	
Major Accidents	*r=5%*	*r=10%*	*r =5%*	*r =10%*	*r =5%*	*r =10%*
$X_1 = 10000$	0.67	0.650	0.290	0.280	0.150	0.140
$X_2 = 40000$	1.69	1.670	0.610	0.590	0.530	0.490
$X_3 = 70000$	2.56	2.500	0.880	0.850	0.650	0.630
$X_4 = 100000$	3.3	3.200	1.090	1.010	0.870	0.830

Table 2. The current amounts of the French nuclear implicit subsidy (in m€/reactor/year)

One can note that the evaluation of the "worst-case" damages is of prime importance because it highly influences the value of the implicit subsidy. Where X_i is multiplied by 10, the implicit subsidy is multiplied by 5. We thus repeat how crucial it is to take into account the different possible scenarios in order to provide relevant and meaningful results. The impact of the premium for risk aversion on the implicit subsidy is also clear. The higher the risk premium, the lower *E(x)* is and therefore, the lower the implicit subsidy is. As regards the impact of the probability of fusion of the core p_i, the higher it is, the more the subsidy decreases. Between p_1 and p_3, the subsidy decreases in average of -74%. This is consistent with the decreasing of the log-logistic distribution with the magnitude of the damages *x* (see Appendix). When p_i is lower, the expected value of the damages is lower as well, and so is the insurance premium. As a consequence, the coverage subsidy is smaller and smaller. This characteristic is explained by the extreme values property of the log-logistic distribution.

As regards the values of the potential reinsurance cost for the French State's and the States' coverage, the resolution of equations (10) and (11) gives:

	$p_1 = 10^{-4}$; $p'_2 = 0.19$		$p_2 = 10^{-5}$; $p'_2 = 0.19$		$p_3 = 10^{-6}$; $p'_2 = 0.19$	
Major Accidents (m€)	r=5%	r=10%	r =5%	r =10%	r =5%	r =10%
X_1 = 10000	165	157	120	116	90	86
X_2 = 40000	190	180	150	142	143	130
X_3 = 70000	200	190	159	150	148	140
X_4 = 100000	210	195	160	158	160	150

Table 3. The exonerated reinsurance cost by the French State (thousands€/r/y)

	$p_1 = 10^{-4}$; $p'_2 = 0.19$		$p_2 = 10^{-5}$; $p'_2 = 0.19$		$p_3 = 10^{-6}$; $p'_2 = 0.19$	
Major Accidents (m€)	r=5%	r=10%	r =5%	r =10%	r =5%	r =10%
X_1 = 10000	88	84	47	45	23	24
X_2 = 40000	120	110	71	70	66	60
X_3 = 70000	131	120	80	79	72	70
X_4 = 100000	132	130	90	86	80	76

Table 4. The exonerated joint reinsurance cost by the States (thousands€/r/y)

These reinsurance costs increase from X_1 to X_4. This result is logic since the French State and the States intervene for a larger share of damages, when X_i increases.

Before analysing the consequences of such an implicit subsidy, a last stage has to be accomplished. As we underlined in section 2, the EDF's civil liability is currently limited to 91million € whereas the official limit in the Conventions has recently been increased up to 700 million €, by the 2004 Protocols. Through this important increase, the signatory countries have revealed a real concern to compel the nuclear operators to bear more of their risk costs. Since EDF will have to apply this new cap very soon, one can wonder what will be the consequences of such a change in terms of implicit subsidy and of coverage costs.

3.3. The impact of the 2004 Protocols

As the new operator's liability cap is higher, the implicit subsidy provided up to now is expected to decrease. Nevertheless, since the States cover henceforth a larger share of the nuclear risk, the reinsurance costs they should require from the operator should increase. Two simultaneous variations thus occur: on the one hand, the operator will internalize a higher share of his risk costs, what is, from the efficiency viewpoint, a positive impact of the 2004 Protocols. On the other hand, the State will take in charge a higher amount of damages which remain non-internalized by the operator. We propose to evaluate, with the values previously found for the different proxies, the level of these two trends.

For this purpose, we carry out a few appropriate changes on equations (9), (10) and (11) and we obtain[18]:

$$\int_{700}^{X} x.f(x)dx - \int_{700}^{X} 700.f(x)dx \qquad (12)$$ for the new implicit subsidy

$$\int_{700}^{1200} x.f(x)dx + \int_{1200}^{X} 500.f(x)dx \qquad (13)$$ for the new French State's exonerated reinsurance cost

$$\int_{1200}^{1500} x.f(x)dx + \int_{1500}^{X} 300.f(x)dx \qquad (14)$$ for the new States' exonerated reinsurance cost

700 (million €) being the new operator's liability cap, 500 (million €) is the new French State's coverage and (300 million €) is the new States' joint coverage (see Table 1).

The results for the new French implicit subsidy, given by equation (12), are:

	$p_1=10^{-4}$; $p'_2=0.19$		$p_2=10^{-5}$; $p'_2=0.19$		$p_3=10^{-6}$; $p'_2=0.19$	
Major Accidents	*r=5%*	*r=10%*	*r =5%*	*r =10%*	*r =5%*	*r =10%*
X_1 = 10000	0.320	0.310	0.080	0.079	0.020	0.019
X_2 = 40000	1.230	1.220	0.315	0.310	0.250	0.230
X_3 = 70000	2.040	1.900	0.540	0.530	0.360	0.350
X_4 = 100000	2.800	2.700	0.730	0.670	0.540	0.510

Table 5. The future amounts of the French nuclear implicit subsidy (in m€/r/y)

As expected, this Table shows a reduction of the French nuclear implicit subsidy.

[18] By taking back the previous values of *a* and *b*, we implicitly assume herein that the new operator liability cap will not be financed, at least not immediately, through an increased resort to insurance, and thus, that the insurer coverage (31 million €) and the premium (75,932 € per reactor year) will remain the same. This assumption is restrictive but however necessary in our analysis, in order to compare the levels of the subsidy (before and after 2004) on the same calculation basis. The evaluation of the impact of the new caps (the operator's and the State's) on the insurance premium remains thus an open issue (Charpin, Dessus and Pellat, 2000).

As regards the new values of the exonerated reinsurance costs by the French State and the States, equations (13) and (14) give the following results:

	$p_1 = 10^{-4}$; $p'_2 = 0.19$		$p_2 = 10^{-5}$; $p'_2 = 0.19$		$p_3 = 10^{-6}$; $p'_2 = 0.19$	
Major Accidents (m€)	*r=5%*	*r=10%*	*r =5%*	*r =10%*	*r =5%*	*r =10%*
X_1 = 10000	89	87	30	28	9,1	9
X_2 = 40000	160	150	64	62	60	50
X_3 = 70000	190	180	85	80	64	60
X_4 = 100000	204	202	97	90	80	76

Table 6. The new exonerated reinsurance cost by the French State (thousands€/r/y)

	$p_1 = 10^{-4}$; $p'_2 = 0.19$		$p_2 = 10^{-5}$; $p'_2 = 0.19$		$p_3 = 10^{-6}$; $p'_2 = 0.19$	
Major Accidents (m€)	*r=5%*	*r=10%*	*r =5%*	*r =10%*	*r =5%*	*r =10%*
X_1 = 10000	36	35	9,9	9	2,6	2,5
X_2 = 40000	71	70	25	20	21	19
X_3 = 70000	87	84	34	30	25	24
X_4 = 100000	94	93	40	39	30	30

Table 7. The new exonerated joint reinsurance cost by the States (thousands€/r/y)

Tables 6 and 7 show that the reinsurance costs that the operator should pay for the French State's and the States' coverage have decreased. How to explain such an evolution whereas the French State's and the States' coverage have increased with the 2004 Protocols? This is due to the form of the log-logistic distribution *f(x)* (see Appendix). Indeed, the probability *f(x)* is lower and lower as *x* increases. Therefore, the more the French State and the States intervene far on the right tail of the curve (far from the origin), the smaller is the expected value of the losses they cover. As a result, given that with the 2004 Protocols they now respectively cover damages above 700 million € and 1200 million € instead of 91 million € and 231 million € (as before), the expected value of their intervention is now lower and so is the reinsurance costs they should require from the operator.

Hence, what is the global assessment of the 2004 Protocols? To highlight their impact, we need to calculate the respective growth rate of the implicit subsidy and the French State's and the States' reinsurance costs. We thus have:

Average impact in terms of implicit subsidy	Impact in terms of exonerated reinsurance cost by the French State	Impact in terms of exonerated joint reinsurance cost by the States
-336	-61,8	-42,6

Table 8. Evaluation of the average impact of the 2004 Protocols (in thousands€/r/y)

This Table show that, with the new amendments, the French operator will cover in average an additional share of 336,000€/reactor/year of his risk costs. His implicit subsidy will be reduced of this amount. In terms of average growth rate, it will decrease of -44.2%. The operator will thus internalize a larger share of his risk costs. The French State and the other States will keep on paying a big share of damages, and even a bigger share than today. Moreover, the States will still intervene free of charge in the coverage of the nuclear risk. We can note, however, that their reinsurance costs exoneration will be lower, for the reasons invoked above. This exoneration will decrease of 61,800€/reactor/year for the French State and of 42,600€/reactor/year for the other States. In terms of average growth rate, these exonerations will be respectively reduced of -45.2% and -58.7%.

Which recommendations can we make from this evaluation? What are the consequences of such results?

4. Interpretation of the results and recommendations

The main important question is: what are the consequences of the implicit subsidy on the competitiveness of nuclear energy? We will examine if the current nuclear kWh cost is artificially low (4.1). Then, we will analyse the impact of the implicit subsidy on the competitiveness of nuclear energy *vis-à-vis* its alternatives (4.2).

4.1. An artificially low nuclear kWh cost?

As we showed above, if EDF seems to benefit from a large implicit subsidy today, its situation will be slightly less favourable when the new cap enters into force. Hence, one can wonder what would be the impact of the full internalization (and the full coverage) of the risk costs on the operator's profitability. In other words, if the liability cap was removed, would the full coverage be financially sustainable for him? What would be the consequences on the nuclear kWh cost and thus on the nuclear energy competitiveness? These questions are relevant since the coverage cost (through the insurance premium) is included in the operator's operating costs. Every increase of his coverage cost thus generates an increase of his operating costs. As the nuclear kWh cost (and price) is constituted *inter alia* by the operator's operating costs, we can compute the impact of the full coverage of the risk costs on the nuclear kWh cost.

Knowing that a French nuclear plant (of an average capacity of 1000 MW) produces about 7 billion kWh per year[19], we thus obtain, with the values previously found for France, the following result:

	$p_1 = 10^{-4}$; $p'_2 = 0.19$		$p_2 = 10^{-5}$; $p'_2 = 0.19$		$p_3 = 10^{-6}$; $p'_2 = 0.19$	
Major Accidents (m€)	r=5%	r=10%	r =5%	r =10%	r =5%	r =10%
X_1 = 10000	0.0000957	0.0000929	0.0000414	0.0000400	0.0000214	0.0000200
X_2 = 40000	0.0002414	0.0002386	0.0000871	0.0000843	0.0000757	0.0000700
X_3 = 70000	0.0003657	0.0003571	0.0001257	0.0001214	0.0000929	0.0000900
X_4 = 100000	0.0004714	0.0004571	0.0001557	0.0001443	0.0001243	0.0001186

Table 9.Current amounts of the implicit subsidy per kWh (€/year)

These amounts vary between 0.00002€/year and 0.0004714€/year. They thus stand for only few thousandths of cents per year in the nuclear kWh cost.

[19] According to EIA (2006), *World Electricity Data*, http://www.eia.doe.gov/iea/elec.html

	p_1 =10^{-4} ; p'_2 = 0.19		p_2 =10^{-5} ; p'_2 = 0.19		p_3 =10^{-6} ; p'_2 = 0.19	
Major Accidents (m€)	r=5%	r=10%	r =5%	r =10%	r =5%	r =10%
X_1 = 10000	0.0000457	0.0000443	0.0000114	0.0000113	0.0000029	0.0000027
X_2 = 40000	0.0001757	0.0001743	0.0000450	0.0000443	0.0000357	0.0000329
X_3 = 70000	0.0002914	0.0002714	0.0000771	0.0000757	0.0000514	0.0000500
X_4 = 100000	0.0004000	0.0003857	0.0001043	0.0000957	0.0000771	0.0000729

Table 10. Future amounts of the implicit subsidy per kWh (€)

These amounts vary between 0.0000027€/year and 0.0004€/year. Consistently with our previous results, they have decreased with the 2004 Protocols.

The nuclear kWh cost, which is a levelized cost[20], currently amounts to 0.03€. What would thus be the effect of the implicit subsidy on the competitiveness of nuclear energy? To answer this question, let us examine now the repercussion of the amounts of subsidy in the nuclear kWh cost:

	p_1 =10^{-4} ; p'_2 = 0.19		p_2 =10^{-5} ; p'_2 = 0.19		p_3 =10^{-6} ; p'_2 = 0.19	
Major Accidents (m€)	r=5%	r=10%	r =5%	r =10%	r =5%	r =10%
X_1 = 10000	0.030096	0.030093	0.030041	0.030040	0.030021	0.030020
X_2 = 40000	0.030241	0.030239	0.030087	0.030084	0.030076	0.030070
X_3 = 70000	0.030366	0.030357	0.030126	0.030121	0.030093	0.030090
X_4 = 100000	0.030471	0.030457	0.030156	0.030144	0.030124	0.030119

Table 11. The "non subsidized" nuclear kWh cost before the 2004 Protocols (€/year)

The "non subsidized" nuclear kWh cost would thus amount between 0.030020€/year and 0.030471€/year.

	p_1 =10^{-4} ; p'_2 = 0.19		p_2 =10^{-5} ; p'_2 = 0.19		p_3 =10^{-6} ; p'_2 = 0.19	
Major Accidents (m€)	r=5%	r=10%	r =5%	r =10%	r =5%	r =10%
X_1 = 10000	0.0300457	0.0300443	0.0300114	0.0300113	0.0300029	0.0300027
X_2 = 40000	0.0301757	0.0301743	0.0300450	0.0300443	0.0300357	0.0300329
X_3 = 70000	0.0302914	0.0302714	0.0300771	0.0300757	0.0300514	0.0300500
X_4 = 100000	0.0304000	0.0303857	0.0301043	0.0300957	0.0300771	0.0300729

Table 12. The "non subsidized" nuclear kWh cost after the 2004 Protocols (€/year)

With the 2004 amendments, the "non subsidized" nuclear kWh cost would be (logically) lower and would amount between 0.0300027€ and 0.0304€.

Looking at Tables 11 and 12, we can conclude that the impact of the integral coverage of all risk costs by the nuclear operator would be negligible. Indeed, before the 2004 Protocols, the kWh cost would equal 0.030516€ in average, that is, an increase of barely 0.5% comparatively to the "subsidized" kWh cost (0.03€). With the amendments, this increase is barely of 0.4%. Consistently with our previous results, the most important increases are due to

[20] A levelized cost is the present value of the total cost of building and operating a generating plant over its economic life, converted to equal annual payments. Costs are levelized in real euros, that is, adjusted to remove the impact of inflation.

the most pessimistic scenario (X_4). In this case, the nuclear kWh cost indeed rises respectively of 1.6% and 1.3% before and after 2004.

Hence, although the increase of the nuclear kWh cost is weak, is the competitiveness of nuclear energy *vis-à-vis* its alternatives maintained?

4.2. Which impact on the competitiveness of nuclear energy?

For the comparison, the main energy sources which can be considered as competitors to nuclear energy are retained. They are fossil sources such as coal, gas and fuel oil and renewables such as hydraulic, wind, geothermic, biomass and solar energies. The following Table shows the kWh cost of these different electricity sources.

Electricity Source	kWh cost
Nuclear	0.03
Coal	0.0337
Gas	0.035
Hydraulic	0.04
Fuel oil[21]	$\geq$ 0.05
Wind	0.06
Geothermic	0.06
Biomass	0.10
Solar	0.15

Table 13. The kWh costs of different electricity sources in 2007 (€)

As regards this Table, we can see that nuclear energy is today the most competitive energy source. Hence, to compare the "non subsidized" nuclear cost with its alternatives, we must also calculate the "non subsidized" cost of these latter. For this, we must take into account their externalities in terms of air-pollution and, particularly, the fossil sources' releases of carbon gas (CO_2). Indeed, these releases are not currently reflected in their cost. In this respect, we can thus consider that their kWh cost is also implicitly subsidized[22]. In order to calculate the fossil sources' "non subsidized" kWh cost, we have thus to add to the costs of Table 13, their external costs in terms of carbon releases. These external costs have been estimated in several European studies (ExternE), summed up in the DGEMP Report (2003). These studies give the following results:

	Carbon valuing	
	4€/ton CO_2	20€/ton CO_2
Gas (combined cycle)	0.0014	0.0071
Coal	0.0029	0.0146
Fuel oil	0.0035	0.0176

Table 14. The external costs of fossil resources in 2007 according to ExternE (€/kWh)

21 Fuel oil is a fuel derived from oil distillation. Its cost is thus strongly dependent on oil price fluctuations. This explains why the cost 0.05€/kWh must be understood as an indicative value likely to fluctuate upward..

22 Today, the only existing instrument which aims at preventing the use of this type of polluting energy sources is the implementation of taxes. We can find, for example in France, the TICGN (*Taxe Intérieure sur la Consommation du Gaz Naturel*), the TIPP (*Taxe Intérieure de consommation sur les Produits Pétroliers*) or the TGAP (*Taxe Générale sur les Activités Polluantes*). These taxes are added to the kWh cost to determine the kWh ATI (All Taxes Included). However, theses taxes are not *stricto sensu* carbon taxes. The question of the implementation of a carbon tax in Europe is currently discussed.

As regards the renewables, studies are generally consensual about the fact that they are polluting and that their external costs are close to zero[23].

Integrating the fossil sources' external costs into their kWh costs, we can now compare all "non subsidized" energy sources and their relative position in the following Tables, for the two different carbon valuings of Table 14:

		"Non subsidized" energy sources					
		$p_1 = 10^{-4}$; $p'_2 = 0.19$		$p_2 = 10^{-5}$; $p'_2 = 0.19$		$p_3 = 10^{-6}$; $p'_2 = 0.19$	
Rank		*r=5%*	*r=10%*	*r=5%*	*r=10%*	*r=5%*	*r=10%*
		Source (cost)	Source (cost)	Source (cost)	Source (cost)	Source (cost)	Source (cost)
1		Nuclear	Nuclear	Nuclear	Nuclear	Nuclear	Nuclear
	X_1	0.0300457	0.0300443	0.0300114	0.0300113	0.0300029	0.0300027
	X_2	0.0301757	0.0301743	0.0300450	0.0300443	0.0300357	0.0300329
	X_3	0.0302914	0.0302714	0.0300771	0.0300757	0.0300514	0.0300500
	X_4	0.0304	0.0303857	0.0301043	0.0300957	0.0300771	0.0300729
2		Gas (0.0364)	Gas (0.0364)	Gas (0.0364)	Gas (0.0364)	Gas (0.0364)	Gas (0.0364)
3		Coal (0.0366)	Coal (0.0366)	Coal (0.0366)	Coal (0.0366)	Coal (0.0366)	Coal (0.0366)
4		Hydraulic (0.04)	Hydraulic (0.04)	Hydraulic (0.04)	Hydraulic (0.04)	Hydraulic (0.04)	Hydraulic (0.04)
5		Fuel Oil ($\geq$0.0535)	Fuel Oil ($\geq$0.0535)	Fuel Oil ($\geq$0.0535)	Fuel Oil ($\geq$0.0535)	Fuel Oil ($\geq$0.0535)	Fuel Oil ($\geq$0.0535)
6		Wind (0.06)	Wind (0.06)	Wind (0.06)	Wind (0.06)	Wind (0.06)	Wind (0.06)
		Geothermic (0.06)	Geothermic (0.06)	Geothermic (0.06)	Geothermic (0.06)	Geothermic (0.06)	Geothermic (0.06)
7		Biomass (0.1)	Biomass (0.1)	Biomass (0.1)	Biomass (0.1)	Biomass (0.1)	Biomass (0.1)
8		Solar (0.15)	Solar (0.15)	Solar (0.15)	Solar (0.15)	Solar (0.15)	Solar (0.15)

Table 15. The relative position of the "non-subsidized" energy sources (for a carbon valuing of 4€/ton CO_2) (€/kWh)

Although the kWh cost of the other energy sources is made heavier by the integration of their external costs, the relative competitiveness of nuclear energy (even non subsidized) remains unchanged. Only the position of its alternatives between one another is modified. As regards Table 15, for a carbon valuing of 4€/ton CO_2, gas becomes cheaper than coal and wins the second rank after nuclear energy. Hydraulic energy keeps its fourth place after coal. The favourable position of fuel oil *vis-à-vis* the other renewables is preserved.

[23] Some studies show that they generate external costs. Indeed, although the production of electricity from renewable energies is not polluting in itself, some studies consider that the implementation and the construction of renewable installations (dams, windmills, etc) cause polluting releases. These externalities are qualified as "second order" externalities.

The results for a carbon valuing of 20€/ton CO_2 are presented in Table 16 below.

		"Non subsidized" energy sources					
		p_1 =10^{-4} ; *p'_2= 0.19*		*p_2* =10^{-5} ; *p'_2 = 0.19*		*p_3* =10^{-6} ; *p'_2 = 0.19*	
Rank		*r=5%*	*r=10%*	*r=5%*	*r=10%*	*r=5%*	*r=10%*
		Source (cost)	Source (cost)	Source (cost)	Source (cost)	Source (cost)	Source (cost)
1		Nuclear	Nuclear	Nuclear	Nuclear	Nuclear	Nuclear
	X_1	0.0300457	0.0300443	0.0300114	0.0300113	0.0300029	0.0300027
	X_2	0.0301757	0.0301743	0.0300450	0.0300443	0.0300357	0.0300329
	X_3	0.0302914	0.0302714	0.0300771	0.0300757	0.0300514	0.0300500
	X_4	0.0304	0.0303857	0.0301043	0.0300957	0.0300771	0.0300729
2		Hydraulic (0.04)	Hydraulic (0.04)	Hydraulic (0.04)	Hydraulic (0.04)	Hydraulic (0.04)	Hydraulic (0.04)
3		Gas (0.0421)	Gas (0.0421)	Gas (0.0421)	Gas (0.0421)	Gas (0.0421)	Gas (0.0421)
4		Coal (0.0483)	Coal (0.0483)	Coal (0.0483)	Coal (0.0483)	Coal (0.0483)	Coal (0.0483)
5		Wind (0.06)	Wind (0.06)	Wind (0.06)	Wind (0.06)	Wind (0.06)	Wind (0.06)
		Geothermic (0.06)	Geothermic (0.06)	Geothermic (0.06)	Geothermic (0.06)	Geothermic (0.06)	Geothermic (0.06)
6		Fuel oil ($\geq$0.0676)	Fuel oil ($\geq$0.0676)	Fuel oil ($\geq$0.0676)	Fuel oil ($\geq$0.0676)	Fuel oil ($\geq$0.0676)	Fuel oil ($\geq$0.0676)
7		Biomasse (0.1)	Biomasse (0.1)	Biomasse (0.1)	Biomasse (0.1)	Biomasse (0.1)	Biomasse (0.1)
8		Solar (0.15)	Solar (0.15)	Solar (0.15)	Solar (0.15)	Solar (0.15)	Solar (0.15)

Table 16. The relative position of the "non-subsidized" energy sources (for a carbon valuing of 20€/ton CO_2) (€/kWh)

The nuclear kWh cost remains obviously unchanged comparatively to Table 15. And, again, nuclear energy keeps its competitiveness at the first place. The gap is even bigger between the first rank and the second rank. The carbon valuing of 20€/ton CO_2 has penalized fossil sources and has highlighted the advantages of hydraulic energy which is now at the second place after nuclear energy. Gas goes down at the third rank but remains before coal. Fuel oil suffers from the biggest loss of competitiveness. Indeed, it becomes more expensive than wind and geothermic energies which move up to the fifth place. We can guess that we the continuous rise of oil price, fuel oil could even become more costly than biomass and solar energy, in the future.

In sum, the full coverage of the risk costs by the nuclear operator would generate barely higher coverage (and operating) costs and would not decrease the competitiveness of nuclear energy.

5. Conclusion

Our paper focussed on the civil liability of the nuclear operator, in case of an accident on his installations. As we showed, this liability is particular, in the sense that the operator is only exposed to a fraction of the damages. We believe that beyond the mathematical exercise, our analysis gives some new insights of the problems raised by nuclear power implicit subsidies, specifically in the French case. Even though they rely on the French case, we remind that our findings are also applicable for other countries within the OECD-NEA nuclear liability regime. As far as the methodology used is concerned, we share the Heyes and

Liston-Heyes' remarks. This methodology has great advantages and is particularly adapted to our problem. For more realism and relevance, we refined it, adding conditional probabilities and a premium for risk aversion, and we corrected it, rectifying a mathematical mistake. However, this method could still be further refined: the results depend in major part on the initial assumptions about the "worst-case" damages and probabilities. Moreover, the calculation relies on the extrapolation of insurance premium. This implies that the current premiums are set at their correct (efficient) level.

The results of our evaluation for the French nuclear operator's implicit subsidy are conclusive. Indeed, we showed that the operator benefits from a quite important implicit subsidy, due to his liability cap. The Coasian rule of internalization is thus unrespected. Moreover, we showed that the French State and the States exonerated the operator from quite high reinsurance costs for their (free) interventions. However, despite these inefficiencies, the conclusion is not that pessimistic. Indeed, we showed that the competitiveness of nuclear energy would not be affected by the removal of the implicit subsidy, that is, by the removal of the liability cap or at least, a substantial increase of it. The nuclear kWh cost would remain low comparatively to its alternatives. Therefore, our conclusion is the following: the integral coverage of the risk costs (between 10 billion € and 100 billion €) by the operator would thus be largely feasible and financially sustainable, for an operator like EDF. Indeed, for the last years 2000-2006, EDF displayed an annual average profit of 1.7 billion €[24] (EDF, 2000, 2001, 2002, 2003, 2004a, 2005, 2006). So, if he faced an increase of his operating costs (due to an increase of the insurance premium), the operator would have two options. First, the operator could maintain artificially the nuclear kWh cost at 0.03€ in order to not penalize his consumers. In this case, the nuclear kWh price would still be indirectly subsidized but the damages of an accident would be totally covered by the author of the risk. His profit would be reduced of the amount of his insurance premium increase (represented by the amount of implicit subsidies). As regards EDF's financial reports 2000-2006, this amount would amount between 0.06% and 11.26% of his annual average profit. This weigh would be largely sustainable for him. However, there would remain a distortion in the rule of internalization, since the nuclear kWh price would not reflect the real producer's costs. The second option would thus consist for the operator in passing on his additional coverage cost in the price and thus on the consumers. The price of electricity would thus be at its "correct" level and would become a non subsidized price. The consequence would be doubly advantageous: the consumers would pay barely more their electricity, and the damages of an accident would be exclusively covered by the operator. Against a consumption price slightly higher, consumers would have the guarantee they would be compensated in case of a nuclear accident (if the consumers are (relevantly) considered as the potential victims of a nuclear accident). Finally, the public funds unused for compensation would be as much as taxes they would not have to pay. This solution would thus be beneficial from the standpoints of economic efficiency and social welfare.

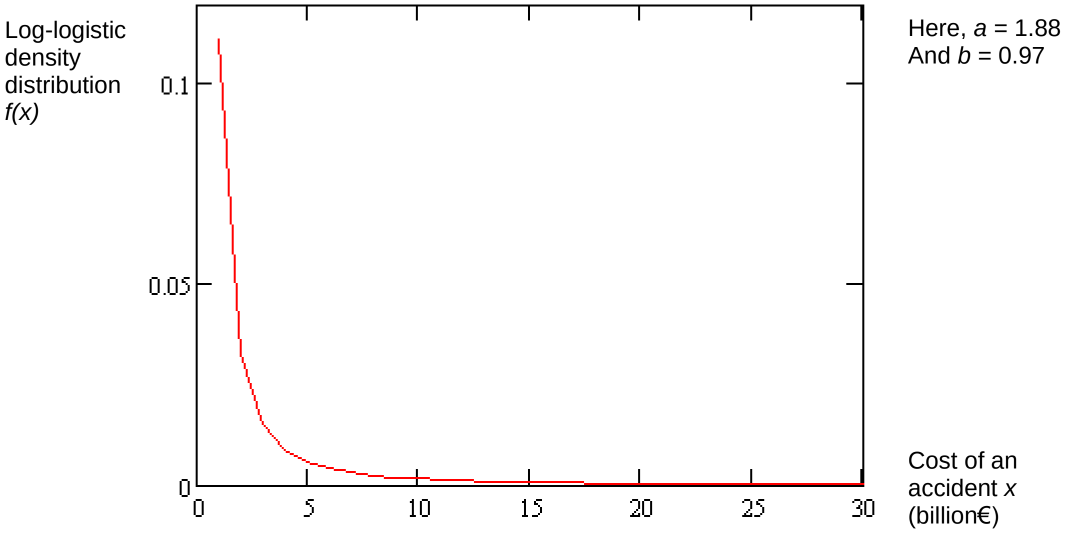
The findings in this paper leave several questions unanswered that merit further research. One of them is particularly the evaluation of the implicit subsidy for other OECD countries or other types of non-internalised nuclear external costs. We can mention, for example, the problem of waste management which is not completely solved yet and which could be considered as an implicit subsidy as well. One can wonder also why the international community accepted this favourable regime for the nuclear industry 50 years ago and more particularly why this is still accepted today, whereas the argument to protect a newly developing industry does not seem to justify any longer the financial cap. Probably a serious public choice analysis into the influence of the nuclear industry on the (international)

[24] The annual profit (in billion €) are, indeed, the following: 1.141 in 2000, 0.841 in 2001, 0.481 in 2002, 0.857 in 2003, 1.3 in 2004, 3.2 in 2005 and 5.6 in 2006. See www.edf.fr

legislation may be useful in this respect. Moreover, at the normative level the question arises whether alternative regimes could be put into place in order to provide better compensation to victims and better internalization of the nuclear risk costs without the disadvantages of the present regime. These are additional issues we hope to address in subsequent research.

Appendix

Equation (8) gives a curve with the following form:



As the values of the major damages of an accident are known as *X*, we can write:

$$\int_X^{\infty} f(x)dx = p_i . p_j^{'} \qquad (\alpha)$$

This equation must be read as follows: the probability that a nuclear accident costs at least *X* is $p_i . p_j^{'}$, with *i*=1,2,3 and *j*=2 (for major accidents). With the functional form of *F(x)* given by equation (7), equation (α) becomes:

$$1 - F(X) = p_i . p_j^{'} \qquad (\beta)$$

The parameters *a* and *b* are to be determined. They must be chosen in order to satisfy simultaneously equations (4) and (β), such as:

$$\begin{cases} \int_{60}^{91} (x - 60). f(x) dx + \int_{91}^{X} 31. f(x) dx = \begin{cases} 0.073379 \text{if } r = 5\% \\ 0.069517 \text{if } r = 10\% \end{cases} \\ 1 - F(X) = p_i . p_2^{'} \end{cases}$$

References

Bataille C. and Birraux C. (2003), La durée de vie des centrales nucléaires et les nouveaux types de réacteurs, Rapport de l'Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques, n°832.

Bataille C. and Galley R. (1997/1998), L'aval du cycle nucléaire, Rapport de l'Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques, n° 612.

Bataille C. and Galley R. (1999), Rapport sur l'aval du cycle nucléaire, Tome II : Les coûts de production de l'électricité, Chapitre III, Report n°1359 de l'Assemblée Nationale

Carrez G. (2003), rapport Assemblée Nationale n°1266, fait au nom de la Commission des Finances, de l'Economie Générale et du Plan sur le projet de loi de finances rectificative pour 2003 (n° 1234), tome II.

Charpin, J.M., Dessus B. and Pellat R. (2000), Étude économique prospective de la filière électrique nucléaire, Rapport au premier ministre.

Chow T.C. and Oliver R.M. (1988), “Predicting nuclear incidents”, International Journal of Forecasting, 7 (1), pp. 49–61.

Chow, T.C. Oliver R.M. and Vignaux, G.A. (1990), “A Bayesian escalation model to predict nuclear accidents and risk”, Operations Research, 38 (2), pp. 265–277.

Coase, R. (1960), "The Problem of Social Cost", *Journal of Law and Economics*, vol.3, pp.1-44.

Denenberg, H. (1973), "Testimony before the atomic safety and licensing board, licensing hearing for Three Mile Island nuclear power plant”, november 7, reprinted in US congress Joint Committee Atomic Energy, *Possible Modification or extension of the Price-Anderson insurance and indemnity Act*, 93th congress, January 31, march 27-28, 1974, pp. 226-240.

DGEMP Report (2003), *Les coûts de référence de la production électrique*.

Dubin J.A. and Rothwell G.S. (1989), "Risk and reactor safety systems adoption", Journal of Econometrics, vol. 42 (2), October, pp. 201-218.

Dubin J.A. and Rothwell G.S. (1990), "Subsidy to nuclear power through Price-Anderson liability limit", Contemporary Economic Policy, Vol. 8 (3), pp. 73-79.

EDF (*Electricité de France*), *Document de Référence*, 2006 (www.edf.fr).

EIA (Energy Information Administration) (2006), *World Electricity Data*, http://www.eia.doe.gov/iea/elec.html.

European Commission (2007), *A New Energy Policy for Europe: Energy for a Changing World*, 10/01/2007, http://ec.europa.eu/energy/energy_policy/index_en.htm.

Faure M. and Skogh G. (2003), *Economic Analysis of environmental Law: An Introduction*, Edward Elgar Pub.

Faure, M. and Van den Bergh, R. (1990), "Liability for Nuclear Accidents in Belgium from an Interest Group Perspective", *International Review of Law and Economics*, vol. 10, pp. 241-254.

Heyes, A. and Liston-Heyes C. (1998), "Subsidy to Nuclear Power through Price-Anderson Liability Limit: Comment," *Contemporary Economic Policy*, Oxford University Press, vol. 16(1), pp. 122-24.

Heyes, A. and Liston-Heyes C. (2000), "An empirical analysis of the Nuclear Liability Act (1970) in Canada", *Resource and Energy Economics*, vol. 22(1), pp. 91-101.

IRSN (*Institut de Radioprotection et de Sûreté Nucléaire*)/EDF (*Electricité de France*) (1990), "Etudes probabilistes de sûreté en France. Quelle probabilité de fusion du cœur des REP ?", Journées SFEN, 16 mai 1990.

Johnson, N.L. and Kotz, S. (1970), *Continuous Univariate Distributions*, I, John Wiley & sons, New York.

NEA/OECD (1994), *Power Generation Choices: Costs, Risks and Externalities*, OCDE, Paris, France.

Queniart, D. (1992), *Safety of Future Reactors in France*, IPSN Report, n°92/02.

Schieber C. and Schneider T. (2002), *Valorisation monétaire des impacts sanitaires et environnementaux d'un accident nucléaire. Synthèse des études ExternE, intérêts et limites de développements complémentaires*, report n°275, CEPN.

Spadaro J.V. and Rabl A. (1998), *External costs of energy: application of the ExternE methodology in France*.

Trebilcock M. and Winter, R.A (1997), "The economics of nuclear accident law", International Review of Law and Economics, Vol. 17 (2), pp. 215-243.

US Nuclear Regulatory Commission (1990), *Severe Accident Risks: An Assessment for Five US Nuclear Power Reactors*, final summary report, NUREG-1150, Vol. 1, Washington, DC, USA