Model Uncertainty and the Social Cost of Facing the Nuclear Lottery*

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Abstract

This paper proposes a theoretical framework for the assessment of the expected social cost of nuclear accidents, which accounts for the uncertainty that characterizes their probabilities of occurrence. In particular, using results from the theoretical literature dedicated to decision-making under model uncertainty, we generalize the definition of the social cost of a nuclear accident in order to account for the contradicting information provided by probabilistic risk assessments and statistical analyses of past occurrences of nuclear accidents. We then propose an application of this framework to the case of France . This application suggests that the social cost of nuclear accidents is 1.5 €$/MWh$. Some policy implications are derived.

Keywords: Nuclear accidents, Rare disasters, Expected-costs, Model uncertainty, Ambiguity.

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1 Introduction

When assessing the risk of large-scale nuclear disasters, two different sources of information regarding their probabilities of occurrence exist. On the one hand, probabilistic risk and reliability assessments (PRAs in the following) have been conducted by the nuclear industry and nuclear regulators since the WASH-1400 report produced by the U.S. Nuclear Regulatory Commission in 1975. These assessments are based on simulations and event trees, and aim to identify and correct safety weaknesses in the designs of nuclear reactors. They are still widely used today, by nuclear vendors, safety authorities, or policy-makers. This adoption of PRAs in the nuclear policy-making process has largely been described in the political-science literature (see e.g. Downer (2014) and references therein). Yet, the Fukushima-Daiichi accident raised concerns regarding the accuracy of the policy guidelines derived from their results (see e.g. Downer (2014) and Ramana (2011a,b)). To summarize briefly these concerns, even though PRAs do carry significant information regarding the safety of nuclear stations, they fail to capture some features of nuclear safety, such as human errors or beyond-design-basis[1] events. As these features characterize most nuclear accidents, PRAs seem to overlook significant risk factors.

On the other hand, numerous statistical analyses based on past nuclear events propose an alternative view on these events. Two recent reviews of the literature on the nuclear risk (e.g. D'Haeseleer (2013) for the European Commission, and Matsuo (2016) for the Japanese Institute for Energy Economics) show that the results obtained by these statistical studies are in sharp contradiction with results obtained by PRAs. They show that four orders of magnitude may exist between the assessed expected frequencies of future nuclear catastrophes.

Despite this lack of precision in the determination of these future probabilities, governments have to choose whether to rely on nuclear energy, investors have to decide which technology to finance, and utilities have to determine when to shut down old nuclear plants, or where to locate new ones. To better inform these decisions, this paper ques-

[1] A beyond design-basis event is an extreme event whose consequences are not designed to be withstood by the plant. An example of such an event is the 20-meter wave that hit the Fukushima-Daiichi reactor, which design was only planned to withstand waves as high as 10 meter.

tions the way we assess the risks associated with the use of nuclear power, and the basis on which choices among these alternatives are made.

When facing multiple and conflicting information regarding a risky prospect, comparing expected costs or benefits based on either of these conflicting sources of information may seem like an *ad hoc* choice, rather than a rational ground for making sound decisions. Indeed, Ellsberg (1961) first showed that uncertainty[2], or the absence of knowledge regarding the probabilities of some events, had an effect, distinct from the effect of risk, on individual behaviours. Since then, a wide body of evidence has been accumulated on the aversion of individual decision-makers towards the fuzziness of the information describing the stochastic processes governing the outcomes their decisions may bring about. See e.g. Barham et al. (2014) or Berger and Bosetti (2016) for more recent experiments.

This paper proposes a methodology for the assessment of the social cost of nuclear accidents, which accounts for the fact that these events cannot be properly described by a single probability distribution over monetary outcomes. To do so, we use the theoretical literature dedicated to decision-making under uncertainty. More precisely, scholars proposed various decision criteria that explicitly account for uncertainty, and for the attitude of individual decision-makers towards uncertainty. Examples of such criteria can be found in Schmeidler (1989); Gilboa and Schmeidler (1989); Bewley (2003); Epstein and Schneider (2003); Ghirardato et al. (2004) or Klibanoff et al. (2005, 2009). These criteria depart from Savage's subjective expected (SEU) utility framework, and allow for more general classes of preferences regarding risk and uncertainty. Using the smooth model of Klibanoff et al. (2005), we assess the expected social cost of nuclear power accidents, adjusted for individual attitudes towards risk and uncertainty. This expected social cost is defined as the certainty equivalent of a nuclear lottery characterized by model uncertainty - i.e. the existence of two distinct models regarding nuclear accident probabilities: PRAs and statistics based on past nuclear accidents. We then apply this method to the French case, based on the recent assessment of the damage caused by nuclear accidents

[2]In the present paper, following the terminology defined by Knight (1921), risk will refer to situations that can be represented as lotteries associated with known probabilities. Uncertainty and ambiguity will be used equivalently throughout the paper to refer to situations in which probabilities are vague or unknown.

performed by Rabl and Rabl (2013).

This paper contributes to the literature dedicated to the assessment of the nuclear risk. First, by introducing model-uncertainty in our analysis, we further the efforts of Eeckhoudt et al. (2000), who proposed a method to account for risk-aversion in the assessment of the external cost of nuclear power, but based their analysis on the information provided by probabilistic risk assessments alone.[3] Second, our analysis can be compared to the recent paper of Rangel and Lévêque (2014), who proposed a Bayesian-revision framework to derive a subjective assessment of the probability of the next Fukushima-like nuclear accident. These probabilities are derived by constructing a theoretical prior based on PRAs, and updating it using the historical observations of nuclear accidents. This approach is set in a classical subjective expected-utility framework, in which all available information is aggregated into a single probability distribution. We differ on the interpretation of the nature of these two sources of information, as we consider PRAs and statistical evidence as two competing models describing future possible occurrences of nuclear accidents, and propose a Bayesian[4] decision-theoretic framework, which accounts for the attitude of individuals towards the fuzziness of the information available regarding the likelihood of nuclear accidents.[5]

Second, we contribute to the aforementioned literature dedicated to nuclear probabilistic risk and reliability assessments (PRAs), and to their use in the policy-making process. Our model provides an assessment of the risk associated with the use of nuclear power which is not only based on PRAs, but also on recent statistical analyses of past events.

[3]Earlier references can be found in Gressman (1988) and Markandya (1995).

[4]A discussion of the Bayesian and non-Bayesian approaches to decision-making under uncertainty can be found in Gilboa (2004) and Marinacci (2015). The main three characteristics of Bayesian decision-making are that the probabilities associated with any state of the world are known, at least subjectively; that decision-makers use Bayes rule when they can; and that decision-makers make their decisions according to a decision rule that consist in maximizing an expected utility with respect to known probabilities. The smooth-model proposed by Klibanoff et al. (2005) is considered as a Bayesian model, in which two types of uncertainties are distinguished: physical uncertainty regarding the likelihood of occurrence of each state of the world and epistemic uncertainty regarding the adequate probabilistic model over the state space.

[5]Another branch of the literature dedicated to the analysis of the nuclear risk is based on the use of extended sets of past nuclear accidents, which include smaller events occurring at both power stations or fuel cycle facilities, in order to circumvent the limits associated with the analysis of extremely short statistical series. Hofert and Wüthrich (2011) or Wheatley et al. (2017), for instance, derived such estimations of the risk of nuclear accidents.

Thus, our figures acknowledge the existence of conflicting information regarding the risks of nuclear accidents, and could be better suited for making recommendations regarding nuclear policies. Second, under some parametric assumptions, our model allows to assess quantitatively how the negligence of the multiple failures of PRAs prevents policy-makers from making sound decisions related to nuclear power, accounting for all known uncertainties. Comparing our results to previous assessments of the nuclear risks shows that a significant part of the cost of nuclear accidents was overlooked in past PRA-based decisions. Policy implications regarding future decisions in France and OECD countries are also derived.

Finally, our paper participates to a growing number of applications of recent advances in decision theory. In the finance literature, the theory of decision under uncertainty has been used to study asset pricing and portfolio selection (see e.g. Dow and Werlang (1992); Epstein and Wang (1994); Chateauneuf et al. (1996) or Epstein and Schneider (2008)). Hansen and Sargent (2001) developed applications of this theory for robust control in macroeconomics. Additional applications to the evaluation of climate policies have been proposed by Gonzalez (2008); Athanassoglou and Xepapadeas (2012); Lemoine and Traeger (2012); Millner et al. (2013), or Berger et al. (2016).[6] To the best of our knowledge, our paper is the first attempt to apply this theoretical literature to the analysis of the risks associated with the use of nuclear power. Nevertheless, the framework we develop is similar to the frameworks used by Treich (2010) to study the effect of ambiguity aversion on the value of a statistical life, by Barham et al. (2014) to analyse the result of an experiment on farmers' behaviours aiming to elicit their attitude towards uncertainty, or by Alary et al. (2013) to study the effect of ambiguity-aversion on self-insurance and self-protection.

This paper is organised as follows. Section 2 will present our theoretical framework for the calculation of the expected social cost of rare nuclear disasters. Section 3 will present our numerical application of this method to the French case of nuclear new builds. Section

[6] Additional applications of theoretical decision criteria can be found in Paté-Cornell (1996) and Henry and Henry (2002), who advocated for the use of decision processes that acknowledge uncertainty and uncertainty-aversion in the study of epistemic risks, and in Gajdos et al. (2008) and Crès et al. (2011) who proposed methods for policy-makers to aggregate conflicting opinions of experts.

4 will discuss some policy implications and conclude.

2 Model uncertainty and the expected social cost of nuclear accidents

2.1 Existing assessments and evidence of model uncertainty

This section aims to present some evidence regarding the relevance of the notion of model uncertainty in the analysis of nuclear safety. To do so, and as mentioned in the introduction, table 1 summarizes the results of two literature reviews conducted by D'Haeseleer (2013) for the European Commission and by Matsuo (2016) for the Japanese Institute for Energy Economics. These reviews were both performed after the Fukushima-Daiichi accident, to present a description of state-of-the-art knowledge regarding the analysis of the risks and costs of major nuclear catastrophes, and to provide guidance for future investments in electricity generation technologies.

Both paper review the existing assessments of nuclear accident probabilities. We gather their results here and specify how these figures were derived. As we focus on the damage associated with large releases of radioactive materials in the environment, we focus on the studies reviewed that assess these probabilities. For instance, we omit the work of Hofert and Wüthrich (2011); Rangel and Lévêque (2014) and Wheatley et al. (2017) as they more generally tackle the issue of core-meltdowns rather than that of large releases of radioactivity outside the containment vessel of a nuclear reactor.

Probabilities of nuclear accidents are here expressed per reactor.year. For a 400-reactor fleet, these figures can be interpreted in terms of expected frequency of occurrences of events. For instance, a probability of occurrence of 10^{-4} per reactor.year is equivalent to witnessing one event every 25 year.

From the observation of table 1, it first appears that three to four orders of magnitude can separate the most optimistic estimations from the most pessimistic ones. Second, two main models describing the occurrence of nuclear accidents emerge from these reviews:

Review	Study	Frequency of large releases	Method used
D'Haeseleer (2013)	NEA (2003)	$1{,}90\ 10^{-6}$	ExternE (i.e. PRAs)
	Rabl and Rabl (2013)	$1\ 10^{-4}$	1 accident every 25 year (Chernobyl-Fukushima)
	IRSN (2013)	$1\ 10^{-5}$ to $1\ 10^{-6}$	AIEA targets (based on PRAs)
	IER (2013)	$1\ 10^{-7}$	PRAs
	D'Haeseleer (2013)	$1.7\ 10^{-5}$	Bayesian update of PRAs using observations
	ExternE (Dreicer et al., 1995)	$1\ 10^{-5}$	PRAs
Matsuo (2016)	Japanese Cost Analysis Committee (2015)	$1\ 10^{-5}$	AIEA targets (based on PRAs)
		$2.1\ 10^{-4}$	3 accidents and world nuclear experience
		$3.5\ 10^{-4}$	5 accidents and world nuclear experience
		$6.7\ 10^{-4}$	1 accidents and japanese experience
		$2\ 10^{-3}$	3 accidents and japanese experience
	Cour des Comptes (2014)	$4.3\ 10^{-4}$	1 accident in 40 years in the French fleet
	Eeckhoudt et al. (2000)	$1\ 10^{-6}$	ExternE (based on PRAs)

Table 1: Various assessments of nuclear accident probabilities

probabilistic risk assessments and statistical analyses of past events. PRA-based results range between 10^{-6} and 10^{-7} accident per reactor.year, while statistical studies yield results in between 10^{-3} and 10^{-4} accident per reactor.year. Lévêque (2015) or Downer (2014) explain these differences by noting that PRAs fail to account for human errors, regulatory capture or *beyond-design-basis* events[7], while statistical analyses of past accidents cannot account for local specificities and safety upgrades that are continuously implemented in nuclear stations.

These observations constitute the main motivation of the following of this paper. Given the existence of these competing models, and given the range of values they provide, it is unclear which information should be relied upon to determine the costs and benefits associated with the use of nuclear energy.

The existence of multiple models providing large ranges of possible values regarding some important decision parameters has been tackled by Millner et al. (2013) in the case of climate sensitivity, where a survey of the opinions of multiple scientists shows large discrepancies. Similarly, we argue that the existence of conflicting models ought to be taken into account when comparing energy production technologies. The following sections propose a methodology that does so.

2.2 A generalized framework for the study of the cost of nuclear accidents

2.2.1 The model

Consider N individuals living in a society facing the possible use of nuclear power. Let $\mathbb{S}$ be a measurable state space, and X be the set of outcomes. Canonically, we define lotteries as mappings from the state space into the space of outcomes. Let $\mathcal{L} = X^S$ be the set of lotteries. In the following, l generally refers to an element of $\mathcal{L}$. Individual preferences among lotteries are assumed to be homogeneous across all individuals, and to be well

[7]A beyond-design-basis event is an event that has not been planned for during the design of the plant, and whose likelihood and potential consequences are not accounted for in risk assessments. The simultaneous flood of the emergency coolant system and shut-down of the national electricity network which led to the Fukushima-Daiichi accident was a beyond-design-basis event.

represented by the smooth model of decision-making proposed by Klibanoff et al. (2005) (KMM in the following). According to this non-expected-utility criterion, individual preferences are no longer represented by a utility function and a subjective probability distribution over states of the world, but by a set of probability distributions, and by two functions that respectively capture the attitude of the decision-maker towards risk and ambiguity, where ambiguity captures the decision-maker's lack of knowledge regarding the probabilities describing the outcomes of his decision. This criterion allows to account for the extended body of evidence showing that people behave in ways that cannot be explained by classical expected-utility frameworks when facing ambiguous risks. The most well-known type of behaviours was first described by Ellsberg (1961) in his seminal urn experiments.

According to the KMM framework, individual preferences can be represented by a set M of probability distributions over $\mathcal{S}$, a probability distribution μ over M, and two functions u and ϕ respectively defined over X and $\mathbb{R}$. Then, for any individual i, and any two lotteries l_1 and l_2, lottery l_1 is strictly preferred to lottery l_2 if and only if $V_i(l_1) > V_i(l_2)$, where the functional V_i is defined by:

$$\forall l \in \mathcal{L},\ V_i(l) = \sum_{m \in M} \mu(m)\ \phi\left(\sum_{s \in S} m_s\ u(l(s))\right). \tag{1}$$

In the following, we assume that M, μ, u and ϕ are common to all individuals.

Each probability distribution m in M can be thought of as an objective[8] model representing the stochastic process governing the result of the lotteries. μ represents a common subjective belief regarding the plausibility of each model. u is a utility function that captures the attitude of the decision maker with respect to risk, whereas ϕ captures his attitude regarding ambiguity, e.g. how the likelihood of obtaining each outcome of the lottery varies across the different possible models.

In the following, we interpret lotteries as describing uncertain prospects faced by

[8] A model is said to be objective in the sense that it is known to everyone, and based on scientific evidence. Though, an objective model may not be accurate in describing the realization of some events, which is the source of model uncertainty.

individuals. In particular, lotteries can be used to describe the risks borne by citizens due to the use of nuclear power. For instance, if various states of the world describe various scenarios leading to nuclear accidents, then a lottery l_i can associate these states with the loss of wealth incurred by individual i due to the associated releases of radioactive materials. If each individual is assumed to hold initial wealth W, and if $l_i(s)$ describes the loss of wealth incurred in state s by individual i due to the operation of a nuclear reactor, then the ex-ante utility derived by i from this lottery can be noted:

$$V_i(l_i) = \sum_{m \in M} \mu(m)\ \phi\left(\sum_{s \in S} m_s\ u(W - l_i(s))\right) \tag{2}$$

Before defining more clearly the cost of a nuclear accident, we first define the certainty equivalent $C_{A,i}(l_i)$ of lottery l_i as the quantity that verifies $\phi(u(W - C_{A,i}(l_i))) = V_i(l_i)$. Equivalently, we have:

$$C_{A,i}(l_i) = W - u^{-1}\left[\phi^{-1}\left(\sum_{m \in M} \mu(m)\ \phi\left(\sum_{s \in S} m_s\ u(W - l_i(s))\right)\right)\right] \tag{3}$$

In other words, $C_{A,i}(l_i)$ is the maximum amount of money individual i would be ready to forego in order to avoid facing lottery l_i. This definition is identical to the willingness-to-pay for risk elimination defined in the literature on the effect of ambiguity and ambiguity aversion on the demand for self-insurance and self-protection (see e.g. Alary et al. (2013) and Berger (2015)).[9]

The adverse consequences of using nuclear power on a population can be multiple. Nuclear accidents may lead to the relocation of people living near the power station, it may also have a global impact on the economy which will affect every individuals. Therefore, in the most general case, a given use of nuclear power will lead each individual to face a different lottery describing the potential harm faced when a nuclear accident occurs. To capture this variability across individuals, we define a *nuclear lottery* as an N-tuple of lotteries $L = (l_i)_{1 \le i \le N} \in \mathcal{L}^N$, in which l_i is the lottery faced by individual

[9] It is also close in spirit to the equivalent certain baseline mortality risk defined by Treich (2010) as the pure risk that equates the utility derived by an individual from an ambiguous mortality risk.

i. Thus, a nuclear lottery can be though of as a given policy involving nuclear power stations. For instance, when deciding where to locate a new nuclear power station, a public planner has to choose between a set of nuclear lotteries, in which each possible location can be associated with a nuclear lottery.

Following Eeckhoudt et al. (2000), we define the expected social cost of facing a nuclear lottery L, $SC(L)$, as the sum of the certainty equivalents $C_{A,i}(l_i)$ defined in equation (3). In other words, we have:

$$\forall L \in \mathcal{L}^N, \; SC(L) = \sum_{i=1}^{N} C_{A,i}(l_i) \tag{4}$$

$SC(L)$ captures the sum of the individual willingness-to-pay to avoid the nuclear risk. This is an ex ante measure of the cost of facing the possibility of a future nuclear accident, that accounts for the two important features of these events: the fact that their consequences may be catastrophic in some states of the world, and the fact that the probabilities associated with these states are fuzzily known.

2.2.2 The expected social cost of nuclear lotteries

By introducing the collection M and the common belief μ over models in M, our setting generalizes the setting of Eeckhoudt et al. (2000), in which individual preferences were represented using a classical expected-utility approach. To see this more clearly, and using the notation $v = \phi \circ u$, equation (1) can be rewritten:

$$\forall l_i \in \mathcal{L}, \; V_i(l_i) = \sum_{m \in M} \mu(m) v\left(W - C_{R,i,m}(l_i)\right) \tag{5}$$

$$with \; C_{R,i,m}(l_i) = W - u^{-1}\left(\sum_{s \in S} m_s \, u(W - l_i(s))\right) \tag{6}$$

In equation (5), the argument of function v, noted $W - C_{R,i,m}(l_i)$, can be interpreted as the certainty equivalent of lottery l_i for an expected-utility-maximizer who would hold model m as his subjective belief over the state space. Therefore, the interpretation of functions v and ϕ are different. First, v is defined over outcomes, while ϕ is defined over utility levels. Second, function v captures the aversion of individuals to the variations across models of the certainty equivalents of a given lottery, whereas ϕ captures more generally their aversion towards the variations across models of their expected utility. Canonically, v is said to capture aversion to model-uncertainty, whereas ϕ more generally captures aversion to ambiguity.

As a remark, one can notice that by summing the quantity $C_{R,i,m}(l_i)$ over individuals, we obtain exactly the definition of the cost of a nuclear accident proposed by Eeckhoudt et al. (2000), who suggest to calculate these certainty equivalents using a unique probabilistic model derived from PRAs.

Our framework generalizes this definition to the cases in which several models are available, as the unambiguous certainty equivalent $C_{A,i}(l_i)$ of lottery l_i can be rewritten as a function of the ambiguous certainty equivalents $C_{R,i,m}(l_i)$:

$$C_{A,i}(l_i) = W - v^{-1}\left[\sum_{m \in M} \mu(m) v\left(W - C_{R,i,m}(l_i)\right)\right] \tag{7}$$

Equation (7) generalizes the definition of the cost of a nuclear accident proposed by Eeckhoudt et al. (2000), as it accounts for both the physical uncertainty contained in each lottery l_i (i.e. the risk described by any given model), but also accounts for the epistemic uncertainty characterizing l_i (i.e. the existence of model uncertainty).

Our framework can be formally reduced to the framework of Eeckhoudt et al. (2000) in four cases, which have distinct interpretations. First, and perhaps most convincingly, if the support of μ in equation (1) is a singleton, then our framework is equivalent to a SEU framework à la Savage, in which decision-makers dogmatically believe one particular model to be true. This is a way to describe the original paper of Eeckhoudt et al. (2000), who only rely on PRAs in their description of the likelihood of nuclear accidents.

Second, if ϕ is the identity function, then utility $V_i(l_i)$ reduces to $\sum_s m^\star(s)u(l_i(s))$ with $m^\star$ denoting the compound probability distribution obtained by computing the weighted average of the various models in M. For each state s, we have $m^\star(s) = \sum_m \mu(m)m(s)$. In this case, our unambiguous certainty equivalent $C_{A,i}(l_i)$ formally reduces to the definition proposed by Eeckhoudt. Nevertheless, it uses the compound probability distribution $m^\star$, whereas Eeckhoudt's framework relied on PRAs to elicit the probabilities associated with the various individual outcomes of the nuclear lottery.

Third, if M were a singleton, then we would be back to a classical risky model à la Von Neumann-Morgenstern, in which there exists an objectively unique model describing the likelihood of each state of the world. In this case, as ϕ is increasing, individual preferences can be represented by the argument of function ϕ in equation (1). In this case, our notations match the original notations used in Eeckhoudt et al. (2000), but this reduction seems colloquial as the discrepancy between PRAs and statistical analyses of past events was acknowledged as early as after the Chernobyl accident (Downer, 2014).

Finally, it can be noted that if M was a collection of Dirac distributions over particular states of the world, we would be in a situation of epistemic uncertainty devoid of physical uncertainty (see e.g. Marinacci (2015) for the origin of this terminology). In this case, let's note $s(m)$ the support of each $m \in M$. Preferences would then be represented by $V_i = \sum_{m \in M} \mu(m)\phi \circ u(l(s(m)))$. This representation is identical to that of Eeckhoudt et al. (2000) once we identify their utility function with our functional $\phi \circ u$, and their probabilities of occurrence of nuclear events with our belief function $\mu(m)$. Although our model indeed reduces to Eeckhoudt's under this hypothesis, claiming that nuclear accidents are devoid of any physical uncertainty is not a convincing assumption, as the various models at our disposal have non-singleton support. Indeed, both statistical analyses and PRAs do consider that the operation of a nuclear reactor can lead to several outcomes corresponding to various types of accidents.

2.2.3 Relation to other frameworks

In most other papers tackling the assessment of the cost of nuclear power accidents, the authors either try to provide an estimation of the total damage caused by the accidents, or to estimate an expected cost defined as the product of the accidents monetary consequences by their respective probabilities of occurrence. The former approach is not directly related to our question, as we take nuclear lotteries as exogenously determined.

On the other hand, the latter approach, used for instance in Rabl and Rabl (2013), IRSN (2013), D'Haeseleer (2013) and Matsuo (2016), can be generalized within our framework.

Several sets of conditions are sufficient for our definition of $SC(L)$ to boil down to the classic expected sum of monetary consequences of the accident. These conditions nevertheless differ on the probabilities that are then associated with each outcome of the lottery. First, if X is a subset of $\mathbb{R}$, and u and ϕ are the identity function, then $C_{A,i}$ is equal to the expected sum of the consequences of the lottery l_i, where each outcome $l_i(s)$ is associated with its compound probability of occurrence $m^\star(s)$. Second, if u is the identity function and either the support of μ is a singleton or M is itself a singleton, then $C_{A,i}$ is equal to the expected sum of the $l_i(s)$, where each outcome is associated with the probability m_s defined by the single element in either M or the support of function μ.

Our definition of the cost of a nuclear accident is broader than the ones used in the literature, as it accommodates a larger set of possible behaviours. Indeed, as was discussed in the previous paragraphs, using Eeckhoudt's sum of risk-corrected certainty equivalents as a guideline for nuclear policy-making is equivalent to assuming that all individuals in the population dogmatically believe in PRAs, although this belief has been extensively criticized after the Fukushima-Daiichi accident. Likewise, using the sum of the expected monetary consequences of nuclear accidents as a guideline for nuclear policy-making would be equivalent to making the assumption that all individuals in the population are either risk-neutral and model-uncertainty-neutral, or that individuals are risk-neutral and that nuclear accidents are not characterized by model uncertainty, or that the whole population dogmatically believes in PRAs. As our framework does not require all of these assumptions, we believe it to be descriptively more accurate than the ones that preceded it.

2.2.4 The uncertainty premium

In their experimentation dedicated to the elicitation of ambiguity-averse behaviours in farmers' decisions to adopt new genetically modified seeds, Barham et al. (2014) define the uncertainty premium associated with any given prospect as the difference between the expected value of the prospect under the compound probability distribution $m^\star$ and its certainty equivalent. Following their definitions, the ambiguity premium associated with a lottery l_i would be $C_{A,i}(l_i) - \sum_s m^\star l_i(s)$.

We propose to go one step further and to break down this uncertainty premium in two parts. To do so, we first define the *compound expected cost* $C_{i,m^\star}(l_i)$ of lottery l_i as the sum of its monetary consequences:

$$C_{i,m^\star}(l_i) = \sum_{s \in S} m^\star(s)\ l_i(s) \tag{8}$$

Then, we define the *compound certainty equivalent* of l_i as:

$$C_{R,i,m^\star}(l_i) = W - u^{-1}\left(\sum_{s \in S} m^\star(s) u(W - l_i(s))\right) \tag{9}$$

Then, following the definition of Barham et al. (2014), we define the individual uncertainty-premium P_i associated with lottery l_i as:

$$P_i(l_i) = P_{MU,i}(l_i) + P_{R,i}(l_i) = (C_{A,i}(l_i) - C_{R,i,m^\star}(l_i)) + (C_{R,i,m^\star}(l_i) - C_{i,m^\star}(l_i))\,. \tag{10}$$

$P_{R,i}$, the second term of the right-hand side of equation (10), captures the risk-premium associated with lottery l_i, when assessed by a classical expected-utility maximizers holding the compound distribution $m^\star$ as a prior over states of the world. To obtain the uncertainty premium P_i, one should add to $P_{R,i}$ another premium $P_{MU,i}$, which captures how the various models in M vary around the compound distribution $m^\star$. The interesting feature of this breakdown of the premium P_i is that $P_{R,i}$ only depends on the compound distribution, while the level of model uncertainty present in M is fully captured by $P_{MU,i}$. Summing P_i over individuals, we can define the same premiums P, P_{MU} and P_R at the level of society.

Finally, given the expression of the certainty equivalent $C_{A,i}(l_i)$ expressed in equation (7) and provided that u and ϕ are concave functions, e.g. if individuals exhibit both risk and uncertainty aversion, then we can argue that:

$$\forall l_i \in \mathcal{L},\ C_{i,m^\star}(l_i) \leq C_{R,i,m^\star}(l_i) \leq C_{A,i}(l_i) \tag{11}$$

From equation (11), we directly deduce that under risk and uncertainty aversion, all the premiums defined above will be positive. Moreover, one can simply show that, if we define increases in risk or uncertainty aversion as respective concave transformations of functions u and ϕ, then the compound-risk premia will be increasing in risk aversion, while uncertainty premiums will be increasing in uncertainty-aversion. Therefore, to a public decision-maker, the size of P can be understood as a measure of the importance of risk and uncertainty in individual preferences. In other words, the greater P, the more a decision based solely on the compound expected sum of the monetary consequences will neglect individual preferences towards risk and uncertainty.

2.2.5 Social welfare and normative scope of the cost of nuclear accidents

As noted by Eeckhoudt et al. (2000), our definition of the expected social cost of nuclear accidents corresponds to a compensatory approach, in which we acknowledge the gap between the sum of the monetary consequences of an accident, and the individual willingness-to-pay to avoid it. One question that has gone unanswered so far is whether these definitions of an expected social cost of a nuclear accident can serve as a welfare measure. In other words, it is not clear whether minimizing the expected social cost of a nuclear accident is a sound objective for a policy-maker. To tackle this question, we focus on the choices a policy-maker would make according to our criterion, and compare them to other possible welfare measures.

Assume that a decision-maker (DM) faces a choice among several nuclear lotteries - for instance when deciding where to locate a new plant - and that the objective of this decision maker is to minimize the total willingness-to-pay of individuals to avoid facing nuclear accidents. In other words, this DM minimizes the expected social cost of nuclear accidents. Formally, this objective can be written:

$$\min_{L \in \mathcal{L}^N} \sum_i C_{A,i}(l_i) \tag{12}$$

Using the notations introduced in the former paragraphs, this program is equivalent to:

$$\max_{L \in \mathcal{L}^N} W_S(L) = \sum_i v^{-1}(V_i(l_i)) \tag{13}$$

In the following we refer to the objective $W_S(L)$ as the social choice function.

If individuals are assumed to be both risk averse and uncertainty averse, then v^{-1} is a convex, non-decreasing functional. Hence, the social choice function used by our DM will lead him to make decisions that are incoherent with *ex ante* egalitarian principles.[10] Indeed, imagine a society constituted of two individuals, Ann (A) and Bob (B), facing to nuclear lotteries L_1 and L_2, respectively associated with individual lotteries $(l_{1,i})$ and $(l_{2,i})$, $\forall i \in \{A, B\}$. Assume that L_2 is a mean-preserving spread of L_1 in terms of individual expected utilities V_i, e.g. that $V_A(l_{2,A}) < V_A(l_{1,A}) < V_B(l_{1,B}) < V_B(l_{2,B})$ and $V_A(l_{1,A}) + V_B(l_{1,B}) = V_A(l_{2,A}) + V_B(l_{2,B})$. By the convexity of v^{-1}, we have that $W(L_2) > W(L_1)$. This example shows that a decision-maker that would minimize the expected social cost of nuclear accidents would prefer, ex ante, to transfer the burden of nuclear accidents to a single agent or group of agents. This remark also holds for the social cost function defined by Eeckhoudt et al. (2000).[11]

The social choice function defined in equation (13) can be compared to the social choice function that would be obtained under an aggregation of individual utilities à la

[10] According to Diamond (1967), an ex-ante egalitarian social planner maximizes a social choice function that can be written, for instance, $\sum_i \psi(\mathbb{E}(u_i))$, in which $\mathbb{E}(u_i)$ is the expected utility of individual i and ψ is a concave function. Under this criterion, the social planner will exhibit aversion to ex-ante inequality, that is to variations of expected utilities across individuals. Adler and Sanchirico (2006) also define *ex post* egalitarianism as the action of a social planner that would maximize the expected value of a welfare function defined as $\sum_i \psi(u_i(s))$. As this criterion first aggregates individual utilities in each state and then computes the expectation of this state-wise welfare function, it cannot be compared with our criterion, which computes expectations at the individual levels before aggregating it into a welfare function.

[11] Minimizing the social cost of nuclear accidents defined by Eeckhoudt et al. (2000) would define a welfare function $W_E(L) = \sum_i u^{-1}\left(\sum_s m_{PRA}(s) u(W - l_i(s))\right)$, in which m_{PRA} is the probability distribution they consider (based on PRAs), and u^{-1} is a convex non-decreasing function, as individuals are assumed to be risk-averse.

Harsanyi (1955), such that:

$$\forall L \in \mathcal{L}^N,\ W_H(L) = \sum_i \alpha_i V_i(l_i) \tag{14}$$

For tractability, let us assume that the distributional weights α_i are all equal to 1. For any two nuclear lotteries L_1, and L_2 in $\mathcal{L}^N$, we are interested in comparing the ordering of the two lotteries according to W_H and W_S. In general, there is no reason for W_H and W_S to rank these nuclear lotteries in the same order, as W_S features as strictly convex function v^{-1}. If we consider our previous example, W_H holds both prospects equivalent, as they are both described by the same sum of individual utilities.

A sufficient condition for two nuclear lotteries L_1 and L_2 to be ranked in the same way by W_S and W_H is that, for any individual and any model m in M, the lottery $l_{1,i}$ second-order stochastically dominates $l_{2,i}$ according to model m.[12] If this condition is met, then for any individual i we have $V_i(l_1) \geq V_i(l_2)$, which implies that both $W_S(L_1) > W_S(L_2)$ and $W_H(L_1) > W_H(L_2)$.

The fact that minimizing the expected social cost of nuclear accidents fails to satisfy egalitarian principles is conform to the intuition that nuclear stations should be located in areas characterized by low population densities. However, this result also undermines the normative scope of our assessment, as minimizing the social cost of nuclear accidents could lead social-planners to choose unfair policies, for instance by bringing the costs associated with present decisions onto future generations.

In order to address the possible unequal allocation of resources caused by policies characterized by uncertain prospects, Fleurbaey and Zuber (2017) propose an aggregation criterion that accommodates ambiguity-averse preferences while satisfying inequality aversion. Assuming that all individuals are maxmin expected utility (MEU in the following) maximizers à la Gilboa and Schmeidler (1989), expected welfare is computed as the expected utility that would be derived by a virtual individual facing the worst possible outcome in every states of the world, characterized by the most risk-averse preferences

[12] As a clarification, we say that l_1 second-order stochastically dominates l_2 according to model m if and only if for all increasing and concave function u we have $\sum_s m(s)u(l_1(s)) \geq \sum_s m(s)u(l_2(s))$.

present in the population, and under the worst-case prior considered among the joint beliefs of the whole population.

This egalitarian welfare criterion - referred to as W_{eq} in the following - can be adapted to our setting. Assuming that ϕ is such that individuals are maxmin-expected-utility maximizers, we have:

$$\forall L \in \mathcal{L}^N,\ W_{eq}(L) = \min_{m \in M} \left(\sum_{s \in \mathcal{S}} \min_{i \leq N} m_s u(W - l_i(s)) \right) \tag{15}$$

Hence, using our assumption that all individuals have the same beliefs and the same attitude towards risk (i.e. the same utility function), we can define the egalitarian certainty equivalent of any nuclear lottery L as the quantity $C_{eq}(L)$ that satisfies:

$$C_{eq}(L) = W - u^{-1} \left(\min_{m \in M} \sum_{s \in \mathcal{S}} m_s \min_{i \leq N} u(W - l_i(s)) \right) \tag{16}$$

The welfare measure defined in (15) is based on the computation of the utility derived by a virtual individual, rather than by aggregating the utilities derived by each individual in the society. This implies that C_{eq} cannot be directly compared with the expected social cost defined above, which is obtained after summing individuals certainty equivalents. Hence, in the following section, we directly compare the egalitarian certainty equivalent of a nuclear lottery $C_{eq}(L)$ with the comparable individual certainty equivalents obtained under equation (3).

This discussion clarifies the role of accident cost estimations in the making of public policies. If egalitarian policy-makers ought not to base their nuclear policies on the expected social cost defined in the previous sections, acknowledging the existence of a gap between the expected cost and the willingness-to-pay of individuals not to adopt a technology could be a useful information. In this sense, the cost defined in this framework is a descriptive indicator of individual willingness to avoid some technology, or to adopt others. A piece of anecdotal evidence is the case of the French “Superphenix” reactor, a fast-breeder reactor, had to shut down in 1996 after only ten years of operation due to intense social protests. This waste of public resources may have been avoided if policy-makers had been able to better assess the opposition that this project would later encounter.

3 A numerical application to the French case

In the following section, we propose to estimate the expected social cost of a nuclear accident in a new-build for the French case. To do so, we make several parametric assumptions for the tractability of the framework presented above. First, we elicit M on the basis of the existing literature on the assessment of the risk of nuclear disasters. Then, invoking the principle of insufficient reason (à la Millner et al. (2013)), we assume that μ is the uniform distribution over M. Finally, we specify two parametric forms for functions u and v, and use the damage estimation provided in the most recent academic evaluation of the cost of nuclear accidents, e.g. Rabl and Rabl (2013), and recent French demographic data to define a general nuclear lottery L. We then use these assumptions to derive an estimation of the expected social cost of nuclear accidents $SC(L)$, and of its egalitarian counterpart $SC_{eq}(L)$.

3.1 Elicitation of beliefs

In order to elicit the models constituting M, we rely on the variations in scientific assessments of the likelihood of nuclear accidents. Given this, two options are available: either consider that each study that ever produced an estimation of the probability of a nuclear event can constitute a model in M, or consider that the methodologies used to obtain these assessments should be used to derive the different models in M. The former is the option chosen by Millner et al. (2013) to study the impact of the uncertainty characterizing the climate sensitivity parameter on the optimal climate change mitigation efforts. The authors consider each experts' opinion as a different model describing the possible value of the climate sensitivity. We argue in favour of the latter, as different assessments of the nuclear risk that use the same methodology may differ for reasons that are not related to model uncertainty, but rather to the specifics of the question tackled. As an example, the PRA-based studies listed in table 1 on page 7 differ in their estimations of the probabilities of nuclear accidents. This is not particularly striking, as these studies focus on different reactor technologies and different countries subject to different regulations.

Therefore, we first propose to use PRAs to establish a first model describing the probability of occurrence of a major nuclear accident. Then, we use the other studies presented above to derive a second model in M based on statistical evidence drawn from past events. As PRAs and statistical analyses are the main two sources of information regarding nuclear safety, M will only contain two models in this application. In the following, m_{PRA} will refer to the first model derived from probabilistic risk and reliability assessments. m_{SA} will refer to the second model derived from statistical analyses of past events.

In order to elicit m_{PRA}, we use the results of AREVA's PRA studies for the British nuclear safety authority and the EPR design specification. According to this source, the objective set by the British nuclear safety authority regarding the probability of an accident leading to more than 100 fatalities is 10^{-7} per reactor.year. According to this same source, the firm achieved an even higher target, as it is claimed that the probability of a core-meltdown associated with more than 100 fatalities for the current design of the EPR is 6.10^{-8} per reactor.year. The results from these PRAs are provided in the appendices. In order to provide a conservative assessment, we will use the British objective of 10^{-7} as the probability of a major nuclear according to the PRA model.

Regarding m_{SA}, we use the approximation performed in Rabl and Rabl (2013) and use a probability of a major accident of 10^{-4} per reactor.year, which corresponds to observing one major accident every 25 year. This assessment is based on the observation of Chernobyl and Fukushima-Daiichi. A similar assessment is made in Matsuo (2016), in which the frequency of 2.1×10^{-4} per reactor.year is calculated based on the observation of three major accidents[13] and the total experience of the world fleet.

The elicitation of m_{SA} is based on a simple identification of the past frequency of

[13] These three accidents include the Three Mile Island event, the Chernobyl accident and the Fukushima-Daiichi accident. This calculation is based on the assumption that the Fukushima-Daiichi accident counts as one event, even though three reactors were destroyed. We dismiss the other estimations reported in table 2.1 in Matsuo (2016) as they only consider the Japanese nuclear operating experience.

nuclear accidents. The rationale for this identification is twofold. First, it is coherent with our aim to provide a method that allows social planners to combine the engineering knowledge captured in PRAs with the information learnt from nuclear accidents. In particular, this model captures the likelihood of occurrence of events that fail to be accounted for in PRAs, such as human failures or beyond-design-basis events. Hence, it makes sense to apply this model to new reactors, even though they appear safer than the ones responsible for past events. Second, more sophisticated statistical analyses have been carried out (see e.g. Hofert and Wüthrich (2011) and Wheatley et al. (2017)). Yet, these studies are based on events of much lower magnitude and occurring not only in nuclear power stations, but also in nuclear enrichment or recycling facilities. These statistical analyses tackle a different question, e.g. the assessment of the risks of nuclear catastrophes over the whole industry. Likewise, we do not consider the results obtained by D'Haeseleer (2013) and Rangel and Lévêque (2014) as they use bayesian methods to combine PRAs with observations of nuclear accidents. These methods thus seem inadapted to answer our research question.

3.2 Attitude towards risk and model-uncertainty

In order to capture the attitude of individuals regarding risk and model-uncertainty, and to derive a numerical assessment of the expected social costs of nuclear accidents, we parametrically specify functions u and v.

Following the empirical evidence proposed by Berger and Bosetti (2016), we propose to specify both functions u and v as constant relative risk aversion (CRRA) functions. We then use the respective coefficients of relative aversion to risk and model uncertainty experimentally derived by these authors, e.g. $r_u = \frac{-xu''}{u'} = 0.28$ and $r_v = \frac{-xv''}{v'} = 0.72$. To remain coherent with the empirical finding that people exhibit stronger aversion towards model uncertainty than towards risk, we study the sensitivity of our results with respect to the values of r_u and r_v while keeping r_v larger than r_u.[14]

[14] Another way of using the experimental results of Berger and Bosetti (2016) would be to specify the function ϕ as a constant relative ambiguity aversion function (CRAA) with its constant relative aversion coefficient r_ϕ set at 0.53.

Formally, we can write:

$$\forall x \in \mathbb{R},\ u(x) = \frac{x^{1-\beta}}{1-\beta} \text{ and } v(x) = \frac{x^{1-\eta}}{1-\eta}. \tag{17}$$

This parametric specification is in line with some of the related literature. Eeckhoudt et al. (2000) use a similar CRRA utility function in his study of the external cost of nuclear accidents, and uses a coefficient of relative risk aversion of 2. Treich (2010) uses the same utility function for a numerical application regarding the effect of ambiguity and ambiguity aversion on the value of a statistical life. In an application of their asset-pricing model, Ju and Miao (2012) use the same parametric specification of the utility and model-uncertainty functions. Moreover, when η is superior to β, our specification is consistent with the empirical finding that ϕ exhibits decreasing absolute ambiguity aversion (Berger and Bosetti, 2016).

Given this specification, the individual willingness to pay to avoid any lottery l_i is given by:

$$C_{A,i}(l_i) = W - \left[\sum_{m \in M} \mu(m) \left(\sum_{s} m(s)(W - l_i(s))^{1-\beta}\right)^{\frac{1-\eta}{1-\beta}}\right]^{\frac{1}{1-\eta}} \tag{18}$$

3.3 The nuclear lottery

As was presented in the first section above, a nuclear lottery is an N-tuple of individual lotteries, each of which describing the consequences faced by a given individual due to the likelihood of occurrence of nuclear accidents. For tractability, and in order to avoid the complexities of having to consider multiple reactors, we further assume that the nuclear lottery faced here consists in the potential consequences of operating one nuclear power reactor in a country like France. In the following, we assume that 65 million French live in a territory similar to France, but only endowed with one nuclear reactor.

Using the central damage estimation performed by Rabl and Rabl (2013), we account for the following six types of costs induced by a nuclear accident: relocation cots, agricultural costs, health costs, clean-up costs, the cost of lost electricity production, and the cost of lost reactors. The total cost of the nuclear accident considered is €354.5 billion. The details of each cost item are provided in table 2.

Table 2: Total costs of a nuclear accident according to Rabl and Rabl (2013)

Types of costs	Costs (in b€$_{2013}$)
Relocation costs	250
Agricultural costs	7,5
Cancer costs	19
Cost of clean up	30
Cost of lost power	18
Cost of lost reactors	30
Total cost	354,5

s

We separate the population in three distinct groups defined according to their exposure to the nuclear accident. All members of a given group face the same lottery. The first group is constituted of local residents that require relocation in case of a nuclear accident. The second group gathers the local residents that do not need relocation in the wake of the accident. Both the members of the first and second group bear the agricultural and health costs of the accidents. The third group is composed of individuals living far enough from the power station. The global economic consequences of the accident, e.g. the clean-up cost and the costs of lost reactor and lost electricity generation, are homogeneously sorted among the members of all three groups.

Among these costs, health costs are borne by locals, e.g. both individuals from the first and second group. Rabl and Rabl (2013) assume that a nuclear accident will lead to 10.000 deaths due to radio-induced cancers. In order to associate health costs with individuals from group 1 and 2, we assume that these deaths will occur homogeneously within groups 1 and 2. Thus, for each model m in M, if the probability of a nuclear accident is m_{acc}, then the associated probability of contracting cancer is given by $m_{cancer} = m_{acc} * \frac{1}{N_1+N_2}$ in which N_1 and N_2 refer to the respective population within groups 1 and 2. This way of distributing health costs across the population is very schematic, and neglects the complexity of the analysis of the health effects caused by the exposure to radioactivity. Yet, this source of uncertainty is beyond the scope of this paper. Agricultural costs are distributed equally across members of groups 1 and 2.

Following Rabl and Rabl (2013), we assume that approximately 500.000 people will be relocated after a nuclear accident. This is approximately equivalent to saying that the population living within 50 kilometres from the plant will be relocated. Indeed, 11 million French people live within 50 kilometres of the 19 French nuclear stations, which roughly means that on average, 578.000 people live within 50 kilometres of each nuclear station. Next, we assume that all the population living within 100 kilometres of the nuclear power plant will be affected by the local consequences of the accident (health and agricultural costs). In France, approximately 40 million people live within 100 km of the 19 power station, which means that on average, 2.1 million people live within 100 km of each nuclear power station. Rounding this figure to 2 millions, and accounting for the members of group 1, we thus assume that group 2 counts 1.5 million individuals. Group 3 is constituted of the rest of the French population, e.g. 63 million individuals. These estimations were performed using publicly available French demographic data from INSEE.

On the other hand, clean-up costs and the costs associated with the loss of nuclear reactors and their future generation of electricity are assumed to be borne by all individuals. Indeed, these three cost items are not necessarily external costs, as they may be paid for by the nuclear operator, if they do not exceed its limited liability. As we aim to calculate an expected social cost, we will assume that the nuclear operator is state-owned, and that these costs will be financed by the entire society through either taxation or future sales of electricity. This is coherent with the French organization of the nuclear industry. [15] For all of these cost items, we use the valuation proposed by Rabl and Rabl (2013), which is summarized in detail in table 2.

[15] A caveat of this assumption is that these costs would be asymmetrically paid for by large and small electricity consumers, but as we have assumed that our society is constituted of homogeneous individuals, our assumption remains somehow coherent.

3.4 Results

3.4.1 The expected social cost of nuclear accidents

We can now derive the various lotteries faced by individuals from groups 1 to 3. These lotteries and their associated probabilities for each probability distribution in M are summarized in table 3.

Table 3: Individual nuclear lotteries by population group

Group	**Population** (million)	**State of the world**	**Damage** (€)	m_{PRA}	m_{SA}
Group 1 Relocated	0,5	No accident	0	$1-1.10^{-7}$	$1-1.10^{-4}$
		Relocation	504950	$9{,}95.10^{-8}$	$9{,}95.10^{-5}$
		Relocation, cancer	2404950	$5{,}00.10^{-10}$	$5{,}00.10^{-7}$
Group 2 Other locals	1,5	No accident	0	$1-1.10^{-7}$	$1-1.10^{-4}$
		No cancer	4950	$9{,}95.10^{-8}$	$9{,}95.10^{-5}$
		Cancer	1904950	$5{,}00.10^{-10}$	$5{,}00.10^{-7}$
Group 3 Remote	63	No accident	0	$1-1.10^{-7}$	$1-1.10^{-4}$
		Accident	1200	$1{,}00.10^{-7}$	$1{,}00.10^{-4}$

Then, using the definitions presented in section 2, we can first compute the expected costs associated with this nuclear lotteries. In order to present this cost in a manner coherent with the literature, we express it in €/MWh. To do so, we divide the results obtained from equation (8) by the total production of electricity expected from a new build reactor. This estimated production is rounded to 10 TWh per year, after assuming a nominal power of 1500 MW and a load factor of 75%. In the following, all costs are reported in €/MWh, using this normalizing factor.

Following equation (8), we find a compound expected cost of 1.35€/MWh. This compound expected cost is the exact mean of the two expected costs that would have been obtained by computing the expected sum of the monetary consequences of the lottery presented on table 3 using respectively model m_{PRA} and m_{SA}. According to model m_{SA}, the "worst-case" expected cost amounts to 2,70€/MWh. This figure is coherent with the findings of Rabl and Rabl (2013). Likewise, according to model m_{PRA}, the "best-case" expected cost amounts to $2.70.10^{-3}$ €/MWh.

3.4.2 Social costs and the uncertainty premium

Second, we turn to the calculation of the certainty equivalents of each individual lottery for group 1, 2 and 3. Results are gathered in table 3.4.2, in which we present both the social cost of nuclear accident obtained using our framework, and the compound social cost of nuclear accident, obtained under ambiguity neutrality. Using equations (7) and (9), the expected social cost of the nuclear lottery is defined as the sum over individuals of the $C_{A,i}(l_i)$, whereas the compound social cost is defined as the sum of the $C_{R,i,m^\star}(l_i)$. The compound social cost matches the definition proposed by Eeckhoudt et al. (2000), but uses the compound distribution $m^\star$, rather than the PRA model.

We present our results for several values of the parameters r_u and r_v. For each result, we keep the ratio between r_u and r_v experimentally determined by Berger and Bosetti (2016), rounding both parameters to the nearest integer.

r_u	r_v	Compound social cost (€/MWh)	Social cost (€/MWh)
0,28	0,72	1,800106	1,800108
2	5	1,98753	1,98754
3	8	2,12856	2,12858
4	10	2,30665	2,30669

Table 4: The expected social cost of facing the nuclear lottery.

The main takeaway from table 3.4.2 is the numerical value obtained for the expected social cost of an accident. Our values vary between 1.8 and 2.3 €/MWh, which is larger but consistent with most of the recent estimations listed in D'Haeseleer (2013) and Matsuo (2016). This figure can be compared with the social costs of other means of production of electricity. For instance, when comparing our figures with those presented by Rabl and Rabl (2013) concerning conventional fossil fuels and wind technologies, it appears that the expected social cost of nuclear accidents remains lower than these other social costs.

Another takeaway from table 3.4.2 is that accounting for aversion to model uncertainty does not significantly modify the estimation of the expected social cost of a nuclear accident from the value calculated using Eeckhoudt et al. (2000), provided one uses the compound distribution $m^\star$ obtained by mixing probabilistic risk assessments with statistical analyses of past events. This result is somehow satisfying, as it provides an additional rationale for the method designed by Eeckhoudt and coauthors, but using the compound probability distribution $m^\star$ instead of the PRA-based model. Thus, we provide a simple heuristic for the calculation of the social cost of nuclear accidents: their cost should be calculated as if these accidents were classical risky lotteries, associated with a compound probability distribution capturing the various models that can be used to describe their potential consequences.

3.4.3 The egalitarian cost of nuclear accidents

Finally, using the definition of the egalitarian social cost of a nuclear lottery presented in equation (15), and noting that individuals from group 1 are the worst off in each state of the world, the expression of $C_{eq}(L)$ boils down to:

$$C_{eq}(L) = W - u^{-1}\left(\sum_{s\in\mathcal{S}} m_{SA} u(W - l_1(s))\right) \tag{19}$$

which, by equation (3), is equal to the certainty equivalent of lottery l_1 for any individual in group 1, and when preferences presented in equation (1) are represented by MEU preferences.

In this case, and using a coefficient of relative risk aversion of 0.28, the egalitarian certainty equivalent of lottery L is as high as €52.3, which can be compared to the certainty equivalents of the same nuclear lottery for members of group 2 and 3, which respectively amount to €1.5 and €0.12.

For a policy-maker abiding by the criterion proposed by Fleurbaey and Zuber (2017) and presented in equation (15), the meaning of a €52.3 egalitarian certainty equivalent is the following. The policy-maker should be willing to require every individuals to forego up to €52.3 in order to avoid facing a nuclear accident. Equivalently, this would amount to spending up to €3.4 billion per reactor and per year in a country such as France to avoid facing nuclear accidents, or to an expected social cost of 340€/MWh.

This very high figure cannot be compared with the other figures derived in previous paragraphs and previous references, as this calculation aims to capture both the specificities associated with the uncertainties characterizing nuclear accidents, but also the very high inequalities that exists between the prospects faced by individuals in group 1, 2 and 3. Hence, as our simple set up presents nuclear accidents as extremely non-egalitarian events, it is normal that this welfare criterion associates them with a very high costs. Indeed, as we stressed it in the previous section, uncertainty-aversion does not drive the results of our simple numerical case to such extreme values. For instance, when aggregating the certainty equivalents obtained under MEU preferences, we obtain an expected social cost of only 3.6€/MWh.

4 Discussion and policy implications

This paper develops a method for the calculation of the expected-costs of rare and catastrophic nuclear accidents, that takes into account the uncertainty that characterizes their probabilities of occurrence, and the aversion of individual preferences regarding these uncertainties. To do so, our method proposes a theoretical framework adapted from the literature dedicated to decision-making under model-uncertainty, which generalizes the methods previously used to assess the cost of nuclear accidents. The expected-cost provided by this method is no longer the expected sum of the monetary valuations of the damage undergone by society in the aftermath of an accident, but the sum of the individual willingness-to-pay to avoid facing this type of lottery. This definition is relevant as it allows social-planners to account for individual preferences towards both risk and model-uncertainty. We apply this method in order to derive the expected-cost of nuclear accidents in France, in new-builds. This expected-cost is evaluated at approximately 2 €/MWh when accounting for relocation, agricultural and health costs at the local level; and for lost reactors, lost electricity production and clean-up costs at the level of the whole country.

We can now focus on the policy implications of these figures. First, from a methodological standpoint, the figures we derive are well suited to be used in order to compare different energy alternatives involving nuclear power. For instance, using our framework, one could compare the social acceptability of various future nuclear energy scenarios in countries that use this technology. Likewise, our results can be compared to the social costs of other energy-generation technologies, such as those derived by Rabl and Rabl (2013). It appears that when accounting for uncertainty-aversion, the social cost of nuclear power remains lower than the social cost of other conventional fuels.

Moreover, when comparing nuclear power with technologies that may also be subject to catastrophic risks, such as dams or fossil fuels, it could be interesting to use the method developed in this paper to compare the expected social costs of nuclear accidents with the expected social costs associated with these other rare energy disasters. Global warming, oil spills or dam failures are good examples of such rare disasters, that may lead to an increase in the social cost of other conventional technologies when accounting for individual attitudes towards risk and uncertainties.

Likewise, when setting safety standards for firms subject to ambiguous risks, our method provides a tractable way to measure the marginal expected-costs and benefits of modifying existing safety standards, as long as these modifications can be associated with changes in the multiple probabilistic models characterizing accidents, or with their associated damage.

Our approach provides information regarding the individual willingness to pay to avoid facing the risk of a nuclear accident. We discuss the implications of considering this as a measure of welfare. We find that the social choices implied by this measure are consistently inegalitarian, which may at first be coherent with intuition, as catastrophic risks are usually located in areas characterized by low population densities. Nevertheless, this result casts doubts on the normative scope of the measurement of the cost of nuclear accidents, and suggests that social choices involving nuclear power may have to rely on other measurements of welfare.

Another key takeaway of this paper is the necessity to combine technical engineering expertise with the available information derived from past failures and accidents when providing guidelines for policies characterized by rare but catastrophic outcomes. Indeed, the Fukushima-Daiichi and the Chernobyl accidents have shown that nuclear accidents can be caused by human errors or "beyond-design-basis" failures, such as major geological events. As these risks are not accounted for in PRAs, learning from these past failures is essential if we want to make good decisions for the future. This implies to include this alternative source of information when providing policy guidelines in the form of risk and cost assessments.

To conclude this paper, it is possible to point out some shortcomings of this framework. First, the numerous parametric assumptions required to perform our numerical application may cast some doubt on the plausibility of our numerical results, and undermine even more their normative scope. Therefore, it may be important in the future to try and assess the extent of uncertainty-aversion shown by individuals when making energy-related decisions. Efforts in this direction have already been exerted by Barham et al. (2014), who showed that farmers exhibit ambiguity-averse behaviours when adopting new seed technologies. It could be interesting in the future to assess whether these uncertainty-averse preferences can also be observed in energy-related decisions.

Second, in our framework, decisions are optimal *ex ante*. Hence, the decision criterion we use does not consider the possibility of learning new relevant information in the future. With a dynamic setting in which information could evolve over time, as is for instance the case regarding nuclear waste management and storage technologies, one could argue that it might be better *ex ante* to choose energy alternatives that allow to adapt decisions after the acquisition of new information in the future. Such preferences have been studied by Kreps (1979), who modelled the behaviour of individuals characterized by preferences for flexibility: being uncertain about their future preferences, they would rather keep a combination of options than choose among them right away. Other dynamic frameworks have been proposed by Epstein and Schneider (2003) and Klibanoff et al. (2009). This refinement is left for future research.

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