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Final report on the role of Risk Aversion in Accident Risk Assessment and its implications for Energy Security

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Table of Contents

1. Introduction

This Deliverable reports on the activities of Task 3. Allowing for Risk Aversion in Accident Risk Assessment of Work Package (WP) 5.7.

The Task draws upon the methodological developments of WP 1, in particular those related to methodological treatment of risk for energy security analysis (Tasks 2 and 3).

The use of a realistic model for the computation of risk premiums can prove particularly useful in the case of accidents and terrorist threats to energy supply. In these cases the public perception of the risks involved is likely to be reflected in pressure on policymakers through public opinion. In certain circumstances this may cause situations of local or national opposition to energy vectors perceived as particularly risky, precluding the adoption of specific policy option and thus worsening security of supply problems.

Building on the qualitative analysis of Task 1 of WP 5.7, this task applies the methodology developed in WP1 to some selected scenarios of low probability, high consequences accidents and threats in selected major energy chains. The risk premiums thus computed provide a range of additional implicit costs that policymakers should take into considerations when weighting various policy options to tackle security of supply issues.

The risk premium figures are to be taken as merely illustrative of the substantial importance that risk aversion can have in these matters. The risk premium computation exercise is in fact based on very strong assumptions on the value of statistical life (VSL), the accident probabilities, and the way accidents affects expected social utility. However, the accident probabilities are consistent with the frequency curves for fatalities computed in the previous tasks of WP 5.7. Moreover the social utility function specification is consistent with empirical evidence on risk aversion according to Markandya et al. and the value assumed for VSL is the one suggested by Viscousi (2008) for the risk of death in a professional context.

It has been decided to leave out terrorist threats due to the sensitive nature of the related data.

The rest of this Deliverable is organised as follows. The next section recaps the theoretical reasons for taking into account risk aversion in evaluating accident risk for the energy sector. Section 3 discusses briefly the issue of the choice of the functional form for the risk averse utility function. Section 4 describes the methodology applied and the data. Section 5 presents and discusses the results of the risk premium computation, while section 6 illustrates the Monte Carlo sensitivity analysis of these results. Concluding remarks are in Section 7.

2. Risk aversion and the costs of an uncertain threat

As noted in Deliverable 1.2, when probabilities and outcomes are known with reasonable confidence, and when a monetary value can be realistically attached to the outcomes, the related monetary impacts can be quantified using standard procedures. A typical case in which this approach can be applied is the one of technical accidents along the energy chain (nuclear reactor failure, marine transportation accident, pipeline breakage, coal mine accident, dam failure, etc.). However, not taking into account risk aversion and the subjective perception of risk, implies that if the per capita share of the value thus computed was offered to each of the individuals affected by the threat, for accepting the related risk, they would be fully compensated for the cost component of that risk actually taken into account in the assessment.

However, as noted by Markandya and Taylor (1999), the evidence is that people need more money to compensate them for taking risks than the actuarial value of these risks. The reason is simply that people are, in general, averse to taking risks.

Moreover economists have found empirical support for individuals' maximising expected utilities, which we term the ex ante approach, following Hammond (1981). The term "expected utility" is used because individuals are assumed to maximise the expected value of their utility over a state with, and a state without the accident, while accounting for the probability of each state occurring. This may be distinguished from the approach where one estimates the loss in satisfaction from the consequences of an accident if it occurred with certainty and then multiplies this amount by the probability that the accident will occur. This can be termed the "ex post approach", where individuals maximise the expected value of their welfare realised in alternative states (Markandya and Taylor, 1999).

As noted in Deliverable 1.2, in theory, unless these issues are addressed, the sum of money estimated as the damage will not match the amount needed to fully compensate those potentially harmed. The expected utility (EU) approach, that incorporates risk aversion, the ex ante perspective (that is, expected utility maximisation), and can accommodate lay perceptions of risks can tackle these issues.

3. Functional form of the utility function

The degree of risk aversion depends on the concavity of the utility function. There are two main measures of this concavity: the coefficient of absolute risk aversion and the coefficient of relative risk aversion. The terms "absolute risk aversion" and "relative risk aversion" are tied to the nature of the lottery. Absolute risk aversion applies to additive lotteries that are expressed in monetary units while relative risk aversion applies to multiplicative lotteries in rates or fraction. If the individual is risk neutral, the relative risk aversion coefficient is zero and the utility function is: $U(W) = W$. When lotteries are additive the outcome can be expressed in absolute terms as an increase or decrease of current wealth (for instance the outcomes of a simple additive lottery can be *W –A* with probability *p* and *W* with probability *1-p*). When lotteries are multiplicative the outcome can be expressed in relative terms as a percentage increase or decrease of current wealth (for instance the outcomes of a simple multiplicative lottery can be *aW* with probability *p* and *W* with probability *1-p*).

From a theoretical point of view, various functional forms of utility functions have been studied which reflect different attitudes towards risk. Many experimental studies have also been developed to estimate the risk aversion coefficient of individual decision-makers by presenting them lotteries (that is, a set of probabilities associated with different loss of wealth) and by letting them rank these lotteries[1]. These studies usually show that the absolute risk aversion decreases with wealth. As far as relative risk aversion is concerned, they seem to support the idea of a rather constant coefficient of relative risk aversion. As a consequence, the most general way to express suitable potential functional forms of the utility function is a power function (Xie, 2000) defined by:

$$U(W)=\frac{1}{\gamma}\left[1-\exp\left(-\gamma\left(\frac{W^{1-\sigma}-1}{1-\sigma}\right)\right)\right],\ \sigma\geq 0,\ \gamma\geq 0. \qquad (1)$$

When $\gamma=0$ this function boils down to

$$U(W)=\frac{W^{1-\sigma}-1}{1-\sigma} \qquad (2)$$

and exhibits positive and decreasing absolute risk aversion, while the coefficient of relative risk aversion is constant and amounts to σ.

The logarithmic specification *U(W)=ln(W)* (implying that the coefficient of relative risk aversion is equal to unity) can also be derived as a special case of the power function (1) by choosing $\sigma=1, \gamma=0$. The logarithmic specification implies risk aversion levels very close to those empirically observed (Markandya and Taylor, 1999). Risk premiums can be computed following the approach described in Deliverable 1.2.

4. Data and Methods

The main source of data is ENSAD (Energy-related Severe Accident Database) compiled and maintained by the Paul Scherrer Institute (PSI) and described in the previous deliverables of this WP (Burgherr, Eckle and Hirschberg, 2009, 2010). On the basis of that accident data, PSI computed frequency-consequence (F-N) curves for severe (≥5 fatalities) accidents in various energy chains (Burgherr and Hirschberg, 2008a; Burgherr, Hirschberg and Cazzoli, 2008; Hirschberg, Spiekerman and Dones, 1998). The current analysis draws upon F-N curves for coal, oil, natural gas and hydropower chains that were analyzed for three country groups, namely for the EU 27, OECD and non-OECD. F-N curves give the frequency of accidents as a function of

[1] Friend and Blume (1975), Hansen and Singleton (1982), Szpiro (1986), Mehra and Prescott, (1995).

severity, in this case the number of fatalities. The relative frequency is given as a cumulative number, i.e. the function F(N) gives the frequency with which accidents with a maximum number of N fatalities happen.

A comparison of fatal accident risk in the different energy chains is illustrated in Figure 1 below. As shown in the graph, hydropower is, among those considered, the one that can cause, in principle, a very high number of fatalities, but also the one in which catastrophic accidents appear to be the most unlikely, except for non-OECD countries. On the other hand, oil production in non-OECD countries can cause on average a much lower number of accidental deaths, but comparatively much more frequently – and in any case at least in two occasions[2] it has caused several thousands fatalities. From Figure 1 it is clear that the risk of fatal accidents differ substantially across sectors and geographical regions.

The information provided by F-N curves such those just described, although useful to compare the level of accident risk posed by different energy sector, is not directly equivalent to the kind of information provided by probability distribution functions.

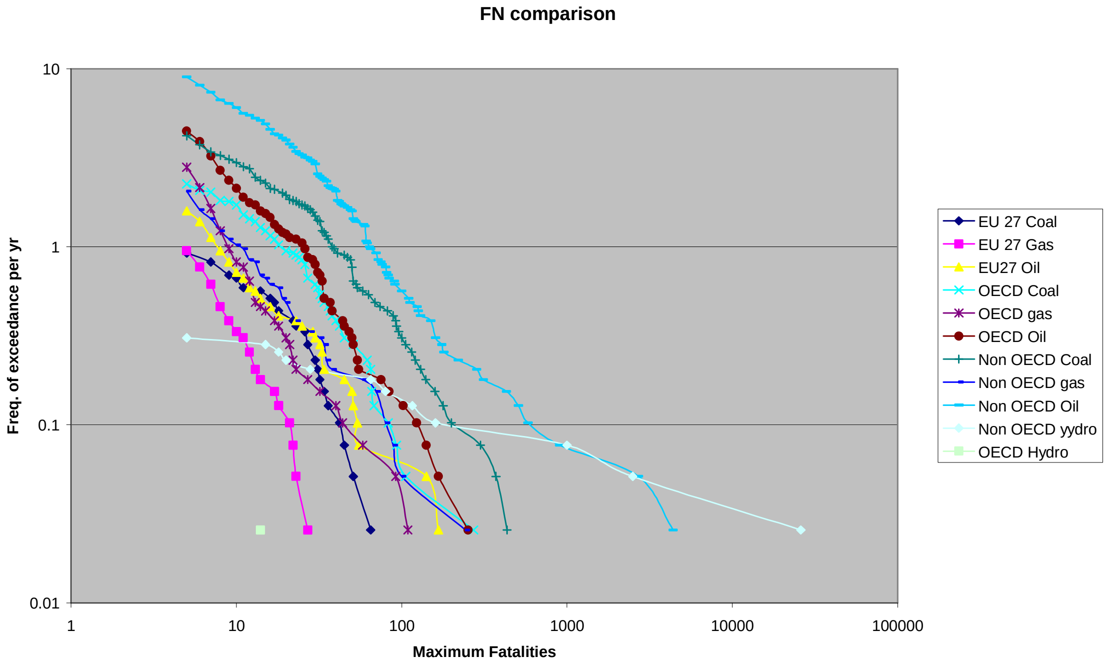

Figure 1 Frequency-consequence (F-N) curves, for severe (≥5 fatalities) accidents for selected energy sectors in EU 27, OECD and non-OECD countries, based on ENSAD (Burgherr, Eckle and Hirschberg, 2010).

For the analysis described in this report, the raw data on accidents were divided by energy sector and geographical region as shown in Figure 1 above. Each entry of the original dataset records an accident, reporting the year of occurrence and the number of fatalities. Probabilities can then be derived by defining classes of accidents in terms of fatalities occurred (e.g. accidents with less than 10 fatalities, 11-20, 21-30 fatalities etc.) and by computing the frequency of occurrence of each class in each geographical region

[2] Accidents in Afghanistan and Philippines.

and energy chain, respectively, e.g. the frequency of accidents causing from 11 to 20 victims in the coal sector in OECD countries.

	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	more
Oil non OECD	0.699	0.099	0.065	0.040	0.021	0.019	0.012	0.007	0.005	0.005	0.027
Oil EU 27	0.837	0.066	0.030	0.024	0.012	0.018	0	0	0	0	0.012
Oil OECD	0.877	0.051	0.026	0.021	0.007	0.007	0.002	0.002	0.008	0	0
Hydro OECD	0.75	0.25	0	0	0	0	0	0	0	0	0
Hydro non-OECD	0.214	0.214	0.071	0	0	0	0.071	0.071	0	0	0.357
Gas OECD	0.907	0.059	0.016	0.006	0.003	0.003	0	0	0	0.003	0.003
Gas EU 27	0.838	0.108	0.054	0	0	0	0	0	0	0	0
Coal OECD	0.845	0.061	0.035	0.024	0.008	0.005	0.011	0	0.003	0.003	0.005
Coal non -OECD	0.536	0.162	0.072	0.077	0.047	0.017	0.013	0.004	0.009	0.017	0.047
Coal EU 27	0.537	0.164	0.119	0.075	0.060	0.030	0.015	0	0	0	0
Gas non-OECD	0.839	0.097	0.013	0.021	0	0.004	0.008	0.004	0.004	0.004	0.004

Table 1. Frequency of occurrence per class of accident based on ENSAD data (Burgherr, Eckle and Hirschberg, 2010).

This yields a frequency table such as Table 1. These frequencies cannot be regarded as probabilities as such. However, assuming that, given the long time series on which they are based they represent the typical pattern of occurrence of the accidents of each class in the various sectors and geographical region, they can be considered as *conditional* probability of accident occurrence, the conditionality being on the fact that an accident of any class occurs in that given sector and geographical region, in any given year (since the entries in the original database are associated to the year in which the accident took place).

We need now a reasonable conjecture to derive the probability that a generic accident takes place in any given year. The crucial assumption we make is that it is very unlikely that more than one accident per day occurs in a given sector and in a given geographical aggregate. Given the broad definition of these concepts in this study, this is not necessarily the case, but we take it as a first, plausible approximation of the reality, that such joint probability of accident occurrence is negligible.

Assuming thus a maximum of one accident per day in any given region-sector set, we take the average number of accident over the whole time span of the original series in the database, independent of its fatality class, and we divide it by 365.25[3] to get the probability that a generic accident occurs in any given year. To fix ideas, consider what happens in the EU 27 oil sector, as illustrated in Table 2.

The database spans over 39 years, thus, on average, 4.26 =166/39 fatal accidents occur in this sector in the EU 27. Assuming that not more than one such accident per day can occur, we have that the probability that a generic accident occurs in any given year is 0.012= 4.26/365.25.

By applying this procedure to all sector-region aggregates we can derive the generic occurrence probabilities and by complementarity, the probability that no fatal accident occurs. These probabilities are listed in Table 3. As shown by the last column of Table 3

[3] To take into account bissextile years.

the experience of the last 4 decades indicates that these are very low probability accidents.

Fatalities	Accidents
0-10	139
11_20	11
21-30	5
31-40	4
41-50	2
51-60	3
61+	2
TOTAL	166

Table 2. Number of fatal accidents in the EU 27 oil sector, based on ENSAD data (Burgherr, Eckle and Hirschberg, 2010).

We are now able to compute the final probabilities of each possible state of the world related to fatal accidents in the energy sector considered. This is accomplished simply by multiplying the probabilities of occurrence of a generic accident of Table 3 with the conditional probabilities listed in Table 1. This yields the probabilities listed in Table 4. Note that, by construction, since for certain classes no accidents with number of deaths in the corresponding range occurred, a zero probability is imputed.

	Average number of accidents per year	Probability of occurrence of a generic accident	Probability of no accident
Oil non-OECD	18.667	0.0511	0.9489
Oil EU 27	4.256	0.0117	0.9883
Oil OECD	15.692	0.0430	0.9570
Hydro OECD	0.103	0.0003	0.9997
Hydro non-OECD	0.359	0.0010	0.9990
Gas OECD	8.256	0.0226	0.9774
Gas EU 27	1.897	0.0052	0.9948
Coal OECD	9.590	0.0263	0.9737
Coal non-OECD	6.026	0.0165	0.9835
Coal EU 27	1.718	0.0047	0.9953

Table 3. Probability of occurrence and non-occurrence of a generic accident. Source: authors' computations based on ENSAD data (Burgherr, Eckle and Hirschberg, 2010)..

In the next step of our framework, the *consequences* of these accidents are analyzed. How to put a value on the fatalities implied by each accident is a complex theoretical issue that has been much debated in the past couple of decades both in the academic and in the policy arenas. For a synthesis of the debate, see Viscousi (2008), who also points to a consensus average value on the value of life for professional accidents of 7 million 2008 US$, or using the yearly average US$/Euro exchange rate for 2008, about 4.6 million €. As a first approximation, we will use this value as a reference for our computations. A word of caution is in order here: ours is but an illustrative exercise of the importance of accounting for risk aversion, and thus our results must be taken with a pinch of salt.

Final probabilities	**Fatalities**											
	1-10	**11-20**	**21-30**	**31-40**	**41-50**	**51-60**	**61-70**	**71-80**	**81-90**	**91-100**	**101 +**	**no accident**
Oil non-OECD	3.6E-02	5.1E-03	3.3E-03	2.0E-03	1.1E-03	1.0E-03	6.0E-04	4.0E-04	3.0E-04	3.0E-04	1.4E-03	0.9489
Oil EU 27	9.8E-03	8.0E-04	4.0E-04	3.0E-04	1.0E-04	2.0E-04	0	0	0	0	1.0E-04	0.9883
Oil OECD	3.8E-02	2.2E-03	1.1E-03	9.0E-04	3.0E-04	3.0E-04	1.0E-04	1.0E-04	4.0E-04	0	0	0.957
Hydro OECD	2.0E-04	1.0E-04	0	0	0	0	0	0	0	0	0	0.9997
Hydro non-OECD	2.0E-04	2.0E-04	1.0E-04	0	0	0	1.0E-04	1.0E-04	0	0	4.0E-04	0.999
Gas OECD	2.1E-02	1.3E-03	4.0E-04	1.0E-04	1.0E-04	1.0E-04	0	0	0	7.0E-05	7.0E-05	0.9774
Gas EU 27	4.4E-03	6.0E-04	3.0E-04	0	0	0	0	0	0	0	0	0.9948
Coal OECD	2.2E-02	1.6E-03	9.0E-04	6.0E-04	2.0E-04	1.0E-04	3.0E-04	0	1.0E-04	1.0E-04	1.0E-04	0.9737
Coal non-OECD	8.8E-03	2.7E-03	1.2E-03	1.3E-03	8.0E-04	3.0E-04	2.0E-04	1.0E-04	1.0E-04	3.0E-04	8.0E-04	0.9835
Coal EU 27	2.5E-03	8.0E-04	6.0E-04	4.0E-04	3.0E-04	1.0E-04	1.0E-04	0	0	0	0	0.9953
Gas non-OECD	1.4E-02	1.6E-03	2.0E-04	4.0E-04	0	1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04	0.9834

Table 4. Final accident probabilities

Thus, assuming that losing a life in a professional accident brings about a loss for the society of about 7 millions US$, irrespective to where it takes place[4], we still need to make further assumptions to determine the point of reference from which the variation in welfare is computed.

In fact, as discussed in Deliverable 1.2, risk premiums are evaluated as the difference between two different measures of welfare variation as a consequence of a probabilistic event: the welfare change when individuals are risk neutral, or the **cost of accident without risk (aversion),**

$$CA_{RN} = W_0 - E(W), \quad (3)$$

where $E(W)$ is the expected value of the individual's wealth, and the welfare change when individuals are risk averse, or **cost of accident with risk (aversion),**

$$CA_{RA} = W_0 - U^{-1}\left[E\left(U^*\right)\right] \quad (4)$$

where $U^{-1}\left[E\left(U^*\right)\right]$ is the *"certainty equivalent"*, that is that value of wealth that yields the same level of "satisfaction" to the (risk averse) individual as being exposed to risky situation.

The risk premium for each sector *i* in region *k* is then computed by looking at the difference between the two welfare changes:

$$RP_{ik} = CA_{RA_{ik}} - CA_{RN_{ik}}. \quad (5)$$

[4] As subsistence costs and average wages differ widely across the globe, this assumption is debatable in strictly statistical terms. However, it has a clear merit in policy terms, as it avoids equity concerns about making the implicit value judgment that a human being might be worth more in some countries (typically, high income countries) than in others. For this reason, a common value is generally adopted in policy-relevant analyses.

It is then crucial to define our W_0 in this case. In principle this is the value of life of all those potentially exposed to accidents like those under scrutiny. Obviously this is a very difficult number to determine with a reasonable degree of precision, and some arbitrariness is unavoidable. A reasonable shortcut could be to assume that the worst has already happened and the worst accident recorded affected the maximum number of potential victims in any given year. Thus we assume that $W_{0ik} = N_{ik} \times 4.6 Mio\, EUR$, where N_{ik} is the highest number of fatalities ever recorded in sector *i* in region *k*.

To determine the expected damage *E(W)*, we multiply the average number of fatalities $\overline{n}_{ikm}$ in each class *m* by their final occurrence probability p_{ikm} as given in Table 4 and by the value of life for professional accidents. Thus the cost of accident without risk aversion equals:

$$CA_{RN_{ik}} = W_{0ik} - E(W_{ik}) = \left[N_{ik} - \sum_{1}^{m} \overline{n}_{ikm} p_{ikm} \right] \times 4.6 Mio\, EUR . \qquad (6)$$

In order to determine our **cost of accident with risk (aversion**), we use a similar procedure, but we incorporate risk aversion by “filtering” the risk-neutral payoff in the state of the world in which an accident may occur through a strictly concave utility function; in this case, by taking the natural logarithm of the damages in each state of the world in which a damage occurs, multiplying it by the attached final probability, summing these values over the accident classes *m*, and then taking the exponential of this summation in order to derive the *certainty equivalent*. To do this we use an original numerical procedure developed in FEEM to assess the role of risk aversion in the assessment of crude oil spills probabilistic externalities (Bigano et al., 2009, 2010).

5. Results

We can now compute the values of the risk premiums for each energy sector and region as described above. These values are collected in absolute terms in Table 5 and in per capita terms in Table 6 below. These tables highlight that allowing for an inherent dislike for risk in the exposed individuals may lead to very diversified values of the willingness to pay to avoid that risk according to the different situation of the various sectors and geographical region. Consider the case of hydropower: based on the evidence of the last 4 decades, in OECD countries, it is highly unlikely that an accident causing fatalities takes place, as very few such accidents have been recorded, none of which with more than 20 victims[5]. On the other hand, in non-OECD countries there have been accidents with more than 60 victims and the probability that an accident with more than 100 victims takes place is actually two thirds higher than the probability that an accident with 10 victims or less takes place[6]. In fact, the maximum number of causalities recorded in non-OECD countries for hydropower accidents is 26000, and only 14 for OECD countries. This implies that comparatively much less is at stake in the hydro sector in the latter geographical region, and the difference between being

[5] Going back to the 1960s this picture would change, e.g. Vajont accident in Italy and others in France and Switzerland .

[6] This could also be due to underreporting of accidents with 5-10 fatalities in non-OECD countries, but unfortunately there is not enough systematic empirical evidence to support this explanation.

exposed to accident risk and not being exposed is very small, while it is substantially higher in non-OECD countries. The (strictly concave) logarithmic functional form of the social utility function emphasizes this difference in utility terms, hence leading to the large difference in the risk premium.

	Cost of accidents without risk (aversion) (M€)	Cost of accident (M€)	Risk Premium (M€)	Risk premium/Cost of accident without risk (aversion)
OECD				
Oil	1.660	1.747	0.086	5.2%
Gas	0.731	0.822	0.090	12.3%
Hydro	0.005	0.007	0.001	22.5%
Coal	1.177	1.266	0.089	7.6%
Non.OECD				
Oil	17.640	23.299	5.659	32.1%
Gas	0.717	0.775	0.058	8.1%
Hydro	21.791	30.176	8.385	38.5%
Coal	2.064	2.433	0.369	17.9%
EU 27				
Oil	1.660	1.747	0.086	5.2%
Gas	0.177	0.267	0.090	50.6%
Hydro				
Coal	0.359	0.627	0.267	74.5%

Table 5. The impact of risk aversion on accident damages evaluation in selected energy sectors.

Table 5 displays moderate absolute values for the risk premiums in selected energy sectors. Consider that these are aggregate values, summed over all those regarded as potentially affected by the accidents under scrutiny.
Table 6 provides the same values in per capita terms, and shows that, indeed, they are quite small: the highest value (accidents in the oil sector in non –OECD countries,) for the risk premium corresponds to about 0.06% of the VSL), while for the majority of the other cases are much lower.

	Cost of accidents without risk (€)	Cost of accident (€)	Risk Premium (€)	Risk premium / Cost of accident W/o risk	Risk premium/VSL
OECD					
Oil	6589.0	6930.8	341.8	5.2%	0.005%
Gas	6710.9	7538.5	827.5	12.3%	0.012%
Hydro	381.8	467.6	85.8	22.5%	0.001%
Coal	4326.0	4654.3	328.3	7.6%	0.005%
Non-OECD					
Oil	4021.9	5312.1	1290.2	32.1%	0.018%
Gas	2951.1	3190.5	239.4	8.1%	0.003%
Hydro	838.1	1160.6	322.5	38.5%	0.005%
Coal	4755.0	5606.1	851.1	17.9%	0.012%
EU 27					
Oil	9942.7	10458.5	515.8	5.2%	0.007%
Gas	6558.1	9877.3	3319.2	50.6%	0.047%
Hydro	n.a.	n.a.	n.a.	n.a.	
Coal	5525.0	9640.0	4114.9	74.5%	0.059%

Table 6. The impact of risk aversion on accident damages evaluation in selected energy sectors (per capita).

6. Sensitivity Analysis

As noted in the previous sections, we are aware of the illustrative purpose of our risk premium estimation and their limited validity as indicators of the true value of the willingness to pay of individuals to avoid the accident risk embedded in the operation of the energy sectors under scrutiny. Notwithstanding these limitations, our analysis has been able to pinpoint interesting differences in the risk premiums across sectors and regions, differences due to the inherent variety of risk structures in the various sectors and regions that has been captured in the PSI database.

The main reason for this limited validity lays in the strong assumptions on which we based our risk premium computations. In order to check the importance of some of these assumptions for the final results, a Monte Carlo sensitivity analysis has been performed on the impact of W_0, of the VSL, and the impact of the damage of the highest tier accident (to evaluate the impact of extreme accidents) using Oracle Crystal Ball™.

The analysis was performed under two alternative assumptions concerning the probability distribution underlying the uncertainty concerning the parameters under scrutiny: namely we assumed that the last two parameters above could vary according to a Normal distribution function (with mean 4.76 and standard deviation 0.48 in the VSL case, 1 and 0.1 for the extreme accidents parameter), or according to a uniform distribution (with possible values ranging from 4.28 to 5.23 for VSL and from 0.9 to 1.1 for the extreme accidents parameter). We were constrained to keep the minimum value above 1 in order to allow the logarithmic utility function to be defined, and thus we chose a gamma distribution for the sensitivity coefficient of W_0. The rationale of considering alternative distributions is to evaluate the impact of letting extreme values have the same probability as original values as opposed to have the probability mass mostly concentrated around the original values and gradually and symmetrically fading towards the extremes.

As

Table 7 below illustrates, the three parameters have very different impacts on our risk premium computations. In OECD and EU 27 countries, the most relevant role is played by the sensitivity of the computation to W_0; lower but still important role is played by the choice of VSL, while the impact of extreme accidents is almost non existent. In the non-OECD, the impact of extreme accidents and of W_0 switch their ranking and the former plays a more relevant role than the latter.

It is quite reassuring that the choice of VSL is confirmed as a moderately relevant driver, as it is reassuring that catastrophic accidents have in general a negligible impact on the main picture. In the case of VSL, the figure chosen is the outcome of a long scientific and policy debate and represents a well established consensus and a point of convergence of many studies. Thus, yes, choosing an alternative value of VSL *would* make a difference, but, standing on the shoulders of giants, we have picked the most recommended option already.

We would have preferred that extreme accidents could not influence risk premium in a noticeable way in all three geographic regions, because we treated, rather arbitrarily, the accidents with more than 100 fatalities as a single accident class, which however may contain events with much direr consequences than those of the other classes. Monte Carlo sensitivity analysis indicates that setting the threshold for residual higher consequence accidents to 100 or to 1000 is of little consequence for our analysis in the

OECD and in the EU 27, but we must be more careful about the interpretation of the results in the non-OECD countries. This makes sense, as the accidents with the direst consequences in terms of human lives lost were recorded in non OECD countries, as we discussed above for the hydropower case in the previous section. More relevant however is the result that the way we determine W0 plays a crucial role. Consistently with the theoretical properties of the utility function chosen, the risk premium is inversely proportional to the initial wealth, due to the decreasing risk aversion characteristic of the logarithmic utility function. In the uniform distribution case, the picture is similar, but the predominance of the role of W0 in OECD and EU 27 and of extreme damages in non OECD countries is more pronounced, as Table 8 illustrates.

	W_0 sensitivity coefficient	VSL (M€)	Extreme damage sensitivity coefficient
	OECD		
Oil	56.70%	43.10%	0.10%
Gas	75.50%	24.00%	0.50%
Hydro	61.50%	38.40%	0.10%
Coal	46.00%	29.10%	24.90%
	non-OECD		
Oil	19.30%	8.90%	71.80%
Gas	53.70%	34.00%	12.30%
Hydro	19.20%	8.90%	71.90%
Coal	24.30%	12.40%	63.30%
	EU 27		
Oil	46.10%	28.20%	25.70%
Gas	86.50%	13.10%	0.40%
Coal	86.40%	13.60%	0.00%

Table 7. Contribution of key methodological assumptions to the variance of Montecarlo simulations, (normal distribution case).

	W_0 sensitivity coefficient	VSL (M€)	Extreme damage sensitivity coefficient
	OECD		
Oil	80.40%	19.60%	0.00%
Gas	90.90%	8.80%	0.40%
Hydro	83.40%	16.60%	0.00%
Coal	73.90%	13.10%	13.00%
	non-OECD		
Oil	47.10%	5.20%	47.70%
Gas	79.10%	14.50%	6.40%
Hydro	47.00%	5.20%	47.70%
Coal	53.50%	6.80%	39.70%
	EU 27		
Oil	74.00%	12.60%	13.40%
Gas	94.50%	5.50%	0.00%
Coal	93.20%	6.70%	0.10%

Table 8. Contribution of key methodological assumptions to the variance of Monte Carlo simulations, (uniform distribution case).

Finally, Table 9 summarises the main robustness indicators. Overall, the estimates appear quite robust, although this varies with the sector and the geographical region.

The mean standard error is always a small fraction of our risk premium estimates, and the very low mean standard errors indicates that the Monte Carlo forecasts are accurate, and by comparison with the last but one column in Table 5, in general close to our risk premium estimates in the normal distribution case. If we believe that the normal distribution correctly portraits the underlying distribution of the parameters under scrutiny, the last column of Table 9 can thus be regarded as a probabilistic refinement of our initial risk premium estimates.

	Uniform distribution			**Normal distribution**		
	Mean	**Standard Deviation**	**Mean Std. Error**	**Mean**	**Standard Deviation**	**Mean Std. Error**
			OECD			
Oil	0.070	0.0098	0.0003	0.088	0.0123	0.0004
Gas	0.065	0.0124	0.0004	0.098	0.0233	0.0007
Hydro	0.0010	0.0001	0.0000	0.001	0.0002	0.0000
Coal	0.072	0.0114	0.0004	0.092	0.0171	0.0005
			non-OECD			
Oil	4.42	0.97	0.03	5.94	1.90	0.06
Gas	0.0468	0.0072	0.0002	0.0597	0.0100	0.0003
Hydro	6.55	1.44	0.05	8.80	2.82	0.09
Coal	0.291	0.058	0.002	0.385	0.108	0.003
			EU 27			
Oil	0.043	0.007	0.0002	0.055	0.010	0.0003
Gas	0.056	0.014	0.0004	0.057	0.014	0.0004
Hydro						
Coal	0.130	0.032	0.0010	0.131	0.033	0.0010

Table 9. Main robustness indicators for Monte Carlo sensitivity analysis of risk premiums.

7. Concluding Remarks

This Deliverable has reported on the activities of Task 3. Allowing for Risk Aversion in Accident Risk Assessment of WP 5.7.
Drawing on a database of fatal accidents in the energy sector developed and maintained by PSI, we applied an original methodology developed by FEEM to assess the impact of risk aversion on the damages implied by those accidents. We were thus able to arrive to some *illustrative* figures for risk premium for fatal accidents in the coal, oil, natural gas and hydro sectors in the EU 27, OECD, and non-OECD geographical regions.

The theoretical motivation for this exercise, discussed in Deliverable 1.2, is that not taking into account risk aversion implies that if the per capita share of the expected damage was offered to each of the individuals affected by the threat, for accepting the related risk, they would be fully compensated for the cost component of that risk actually taken into account in the assessment. The evidence on the contrary points to the fact that that people, being *risk averse*, need more money to be compensated for taking risks than the actuarial value of these risks. As noted in Deliverable 1.2, in theory, unless these issues are addressed, the sum of money estimated as the damage will not match the amount needed to make whole those potentially harmed.

Our computations show that indeed, people would need from 5% to 75% more money than the actuarial value of the damages, depending on the sector and the geographical region. Interestingly, the range of risk premium estimates is quite broad, and we argue that this depends upon the intrinsic risk characteristics of each sector in the different regional aggregates. A Monte Carlo sensitivity analysis fairly supports the robustness of our results and points to a pivotal role played by the assumptions concerning the initial level of wealth.
As said at the outset, notwithstanding its relative robustness, this analysis merely responds to illustrative purposes concerning the potential role of risk aversion in the analysis of these threats and needs further refinement and validation. We thus do not make any claim of absolute validity of the figures presented here and we explicitly discourage their use for policy purposes[7]. All the conjectures made in order to construct our computations can be further refined, for instance by means of an extensive real world survey of the people actually exposed to such risks in each country. This would substantiate much more the crucial assumptions concerning the initial level of wealth of those at risk of losing everything.
The other limitation of this analysis is its partial coverage of the possible threats. This is partly our choice and partly due to data limitations. We intentionally left out terrorist attacks, in order to avoid disclosing sensitive information and keep this deliverable publicly available. On the other hand, we had no data on some sectors: the most noticeable is probably the nuclear sector. Fortunately however, the number of accidents to nuclear installations with at least five fatalities in civil nuclear power installations boils down to one (the Chernobyl accident). However large hydropower, analysed in this Deliverable, is not the only renewable energy sources prone to potential fatal accidents. Since the '70s, 60 wind turbine accidents have claimed about 66 human lives,

[7] At most one could take the relative ranking of the various energy sources as a rough indication of their perceived riskiness.

according to Caithness Windfarm Information Forum (2010). The majority of these events are small accidents with one fatality, and few resulting in two fatalities. Therefore they could not be classified as severe accidents according to the ENSAD definition and were not included in the accident database, and thus could not be used for our computations.

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