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Actuarial risk assessment of carbon capture and storage at the global scale in 2050

Minh Ha-Duong
Rodica Loisel

May 2010

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Centre International de Recherches sur l'Environnement et le Développement
UMR 8568 CNRS / EHESS / ENPC / ENGREF
/ CIRAD / METEO FRANCE
45 bis, avenue de la Belle Gabrielle
F-94736 Nogent sur Marne CEDEX
Tel : (33) 1 43 94 73 73 / Fax : (33) 1 43 94 73 70
www.centre-cired.fr

Abstract

This study estimates the human cost of failures in the CCS industry in 2050, using the actuarial approach. The range of expected fatalities is assessed for all steps of the CCS: additional coal production, carbon capture, transport, injection and storage, based on empirical evidence from technical or social analogues. The main finding is that a few hundred fatalities per year should be expected if the technology is used to avoid emitting 1 GtC yr^{-1} in 2050 at 1 500 baseload coal power plants. Implementing the CCS would arguably save several tens of thousands of lives in 2050 by mitigating climate change. Thus, in terms of expected life saved, CCS benefits outweigh its costs. The large majority of fatalities are attributable to mining more coal, next would be shipping casualties. These risks compare to today's industrial hazards: technical, knowable and occupational dangers for which there are socially accepted non-zero risk levels. If storage sites perform at safety levels socially tolerated today in analogue installations, expected fatalities per year due to leakage, while an important concern for the local public, should have a minor contribution in the total expected fatalities per year : less than one. But that condition on storage site performance will be disproved if a single fatality occurs before 2030.

Keywords*: CCS, risk, analogue, storage safety, mortality, actuarial approach.*

Résumé

Dans cette étude on estime les coûts humains des défaillances dans la filière du CSC en 2050, en utilisant l'approche actuarielle. La mortalité prévue est évaluée à tous les stades du CSC : production additionnelle de charbon, captage du carbone, transport, injection et stockage, en se basant sur des données empiriques issues d'analogues techniques et sociaux. La conclusion principale est que quelques centaines de décès par an sont à attendre quand la technologie est employée pour éviter l'émission d'1 GtC an^{-1} en 2050 pour 1500 centrales électriques de base alimentées en charbon. La mise en oeuvre du CSC épargnerait sans doute plusieurs dizaines de milliers de vies en 2050 par l'atténuation du changement climatique. Ainsi, en termes de vies sauvées attendues, les bénéfices du CSC l'emportent sur ses coûts. La grande majorité des décès est attribuable à l'extraction de davantage de charbon, et viennent ensuite les pertes dans l'acheminement maritime. Ces risques sont comparables aux accidents industriels d'aujourd'hui: des dangers techniques, connaissables et professionnels pour lesquels existent des niveaux de risque non zéro socialement acceptés. Si les sites de stockage opèrent aux niveaux de sûreté actuellement tolérés dans des installations analogues, les pertes annuelles attendues liées aux fuites, pourtant une préoccupation importante pour le public local, devraient contribuer de façon mineure à la mortalité annuelle attendue: inférieures à un. Mais cette condition de performance des sites de stockage sera refutée si une seule mort se produit avant 2030.

Mots-clés *: CSC, risque, analogue, sûreté du stockage, mortalité, approche actuarielle.*

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[1] Corresponding author. Research Fellow, CNRS, Centre International de Recherche sur l'Environnement et le Développement (CIRED), Nogent sur Marne, France. haduong@cired.fr.

[2] Post-doctoral Fellow, CNRS, Centre International de Recherche sur l'Environnement et le Développement (CIRED), Nogent sur Marne, France.

1. Introduction

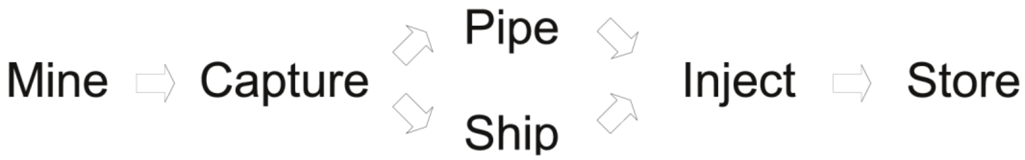
Carbon capture and storage (CCS) is a new technology developed to mitigate the climate impact of large industrial installations. It involves capturing the CO_2 and storing it underground for geological times instead of releasing it in the atmosphere. As every new technology, behind expected benefits it has expected risks. These risks have been discussed in the literature according to diverse points of view, accounting for various technical, economic, environmental, human and social aspects. Politically for example, one of the main moral hazard associated with CCS is that some societies could rely too much on it and invest too little in developing renewable energies. Economically, the key uncertainty is the difference between the value of carbon and the cost of capture. Technically, psychologically and climatically, one of the main hazard is leakage, the risk that some of the CO_2 escapes from where it is stored.

One of the simplest viewpoints on the risks of any activity is: “How many expected deaths?” This issue is as relevant for the layperson as it is for international public policy experts. Here we examine it at the worldwide level. Even if high safety standards are maintained everywhere, large sample laws imply that a non-zero number of failures have to be statistically expected. One example is the case of airlines where fatalities are recorded every year despite of the highest technical security measures. Assuming a large scale use of CCS in 2050, the question is not if it will cause any accidents, but how many can reasonably be expected and with which consequences.

To compute expected fatalities worldwide attributable to the large-scale use of CCS, we decomposed this mitigation option into the six activities described by Figure 1 and used an actuarial approach, based on historical data from analogue industrial activities. The analysis considers both macro evidence, consisting in fatality rates at the industry branch scale, and micro evidence, presenting individual accident reports from historical databases. That data is complemented with more behavioral evidence, the socially accepted standards for similar installations. We find a total number of several hundreds expected fatalities. Contrary to the technical or psychological points of view, the actuarial approach shows that the largest risks are with mining and shipping and not leakage at storage sites.

The paper is structured as follows. Section 2 reviews analysis of the public risks associated with CCS. It examines how the methods and approaches used in the literature relate to the actuarial approach used in this paper. Section 3 describes a scenario where CCS is applied at a large scale in 2050, using the concept of a stabilization wedge. Sections 4 and 5 examine available evidence on fatality rates and their extrapolation to 2050. These rates are multiplied by activity levels from the scenario to obtain expected fatality levels. Section 6 sums up the results, discusses the implications of the objectively smaller leakage risk, and compares the expected fatalities of CCS with other energy-related risks including those of climate change.

Figure 1. *Decomposition of carbon capture and storage in 6 activities*



2. The actuarial approach applied to the CCS risk assessment

Social research on CCS started by looking at acceptability with a particular concern for factors influencing the public perception of the technology (Campos et al., 2008). Various observation tools have been mobilized to understand better the public views about CCS at scales from the individual to the trans-national level. They included informed surveys, focus groups, citizens' panels, media analysis and interviews around existing pilot projects. So far, most of these studies were done in developed countries. They tend to show that most people have low to zero familiarity with CCS, and that there is not a clear rejection or approval of it. Several of those studies conclude that a better understanding of the risks should be one of the main goals of researchers (see e.g. Damen et al., 2006, Stenhouse et al., 2006).

Singleton et al. (2009) argue that a variety of methods should be used to examine the public risks associated with the development of the CCS technology. They classify these methods under two dominant paradigms: Social Constructivism and Realism.

- Social Constructivist methods recognize that the meaning of a risk is determined subjectively by what people think of it. They include psychological approaches, economic approaches, as well as sociological approaches.
- Realist methods are those seeking objectivity by using quantitative methods to measure risk. They include Probabilistic Risk Analysis, which computes a synthesized expected value by using predominantly event and fault tree analysis; the Toxicology/Epidemiology approach, which models an expected value using experiments and population studies; and the Actuarial Approach, which computes an expected value by using extrapolations from analogue cases.

Results presented in this paper draw upon the realist actuarial approach. We assess the total number deaths per year, in 2050, in the whole world, attributable to the choice of CCS as a climate policy option. Expected fatalities numbers are a generally understood measure of risk for a given population. It is clearer and easier to compute than losses of life-years, and correlates well with expected environmental and material damage, often measured in monetary terms, which will not be looked at here. Because of the difficulties to assess the delayed or latent fatalities, numbers will pertain only to immediate fatalities.

Actuarial fatalities are a measure of the social risk globally and say nothing about individual, contextualized risks. Considering key findings from other approaches helps to justify this method and to understand better what are relevant analogues to extrapolate from. These key findings pertain to (a) the presence of large cognitive biases for small probabilities; (b) the qualities that make a risk different from another; and (c) the variability of tolerated risk levels.

(a) Regarding cognitive biases between objective and perceived risks, Slovic (1986) shows that when individuals cannot estimate the uncertainty of consequences, they build the worst potential scenario and tend to have two opposite attitudes: either they deny the potential risk, either they overestimate the importance of risks. Thus, people tend to overestimate the likelihood of low probability risks associated with fatal consequences. These influence decision-making directly or through social processes, potentially leading to indiscriminate calls to the precautionary principle and inefficient allocations of resources.

These biases may be seen as undesirable because the decision to accept CO_2 storage onshore, or to avoid it and incur the costs of offshore CO_2 storage, or to use alternative emission strategies, is a collective choice. There is no pretense that actual climate policy-making is conducted according to rational decision making procedures. The hydrocarbon industry's point of view on CCS has been essential to the formation of its political support. We expect that the industry will remain influential in the near future, but that local community interests will also gain weight. Nevertheless, Renn (2004) argues that science based risk assessment is a beneficial and necessary instrument of pragmatic technology and risk policy, even if it cannot and should not be used as a general guide for public action. Objective evidence for and against major mitigation options should be carefully considered. Actuarial analysis allows to answer rigorously basic questions necessary to reach out to the public: “CCS, how many deaths?” and “Is it worth it?”.

(b) The qualitative nature of risks is critical to define relevant analogues and comparison points. Starr (1969) has shown that the risk acceptability for technologies does not depend only on the expected number of fatalities, but also on the anticipation of benefits or whether the risk is voluntary or imposed. Analogues are more convincing when they are similar along the following three dimensions: natural / technical, voluntary / imposed, familiar / unknown.

Several classes of risks associated with CO_2 today are technical, voluntary and familiar to some extent. These include the dangers of industrial use of CO_2 as a fire suppressant (US EPA, 2000) and those in the agro-alimentary industry (Louis et al., 1999). These risks are accepted because there is a clear direct benefit to the risk bearers and they are mostly voluntary. The benefits of climate change mitigation are not as directly clear, and CCS may also appear imposed to some communities. The strongly technical nature of CCS implies that while there are many natural analogues, volcanism-related CO_2 leaks, they may not appear as valid analogues to CCS risks.

Statistical accident databases generally distinguish between professional and general public fatalities. In principle this would allow the actuarial approach to account for the voluntary / involuntary dimension of the risks analyzed. However, the lack of systematically available data, the scope of the study and the different reporting biases led us to assess only qualitatively the repartition between workers and non-workers fatalities. Thus, our approach allows to answer the question “Who is at risk?” only partially.

(c) Because risks differ qualitatively, and societies are heterogenous, there are many standards against which prevention and mitigation measures are assessed and legitimized. While full stochastic cost-benefit analysis is rarely used, economic rationality cannot be completely ignored, if only because expected costs increase and expected social benefits decrease as a risk goes towards zero. Formal examples abound in civil engineering, healthcare or even finance law and regulations (Marszal et al. 2001). While there is no really satisfying technical analogue to the risks of geological storage, there are generally accepted risk levels around large-scale man-made installation involving industrial quantities of compressed gases.

3. A scenario to avoid 1 Gt of carbon emissions in 2050 using CCS

Pacala and Socolow (2004) introduced the “stabilization wedge” as a useful unit for discussing climate stabilization. A wedge is 1 GtC yr^{-1} of emissions savings attained in 50 years increasing linearly, achieved by a single strategy that will not occur without deliberate attention to global carbon. Implementing about seven wedges composes a “stabilization triangle” that corresponds to the stabilization of the atmospheric CO_2 concentration at about 500±50 ppm. These seven wedges can be picked up from a portfolio of 15 potential wedges, which include energy efficiency and conservation strategies, fuel shift, CCS, nuclear fission, renewable electricity and fuels, and land use strategies. Carbon capture and storage strategies permit three wedges: CCS implemented in baseload power plants, in H_2 plants or in coal-to-synfuel plants. This section builds a scenario for the first of these three options.

This wedge of CCS is not only plausible but also probable, because there is the political will to implement the technology, the technical and geological capacity and an economic optimism as for the carbon value. Politically, the G8+3 in 2008 agreed to setup 20 CCS demonstration projects soon and to deploy the CCS technology at about 600 coal fired plants by 2030 (McKee, 2008). The European Commission wants up to 12 CCS demonstration projects by 2015 already. The technical and geological capacities are large, ranging from 220 to 2 200 Gt CO_2 in different stabilisation scenarios (Metz et al., 2005). As for the economic prospects, it is commonly held that the value of CO_2 will go up while the cost of CCS will go down (Gielen et al., 2004; Torvanger, 2007).

Table 1 presents our CCS scenario. Starting from year 2007, two intermediary steps in 2015 and 2025 are presented to provide an idea of the trajectory. They are not used in the sequel, we only look at additional fatalities in 2050. The narrative definition of this wedge is 1 GtC avoided in 2050 by installing CCS in enough coal-fired power plants. Focusing on coal is justified by its relative abundance compared to oil and gas. Shafiee et al.(2008), for example, argue that coal will be the only fossil fuel remaining after 2042.

The right column in Table 1 summarizes the scenario's assumptions. In the first row, given the 44/12 molecular weight ratio, the mitigation of 1 Gt of C emissions is 3.67 Gt of CO_2 avoided. Assuming a 20% energy penalty and 90% capture efficiency, this amounts to 4.5 Gt CO_2 stored out of 5.00 Gt CO_2 generated in 2050 (see numerical details in the electronic supplementary spreadsheet). We assume that the additional baseload coal-fired power plants would not have been allowed at all without CCS because of climate concerns, as the recent legal developments in Europe suggest. This assumption implies that the whole extra demand for coal is attributed to CCS. We consider that all coal used in the power plants is bituminous grade, which has the carbon dioxide content of 2.38 kg CO_2 / kg coal (Nelson, 2009). The

Step		**2007**	**2015**	**2025**	**2050**	**Assumptions**
Coal Mining	Mt	0	20	140	2 100	The CCS wedge allows the use of coal Coal's carbon content is (2.38 kg CO_2/kg coal) 15% of it shipped for 4 500 Nm
Capture	sites	3	15	100	1 500	Intermediate between G8 and IEA estimations
	Mt	3	15	200	4 500	1 GtC emissions avoided, 20% energy penalty, 90% capture efficiency
Transport by pipeline	km	1	50	100	100	For each capture site.
	Mt	3	15	190	4 050	About 90% of quantity captured.
Transport by ship	miles	0	0	5.000	5 000	Average distance
	Mt	0	0	10	450	About 10% of quantity captured.
Injection	wells	12	60	400	4 000	Corresponds to about 1.1 Mt CO_2/well/yr On average 8 active injection wells/storage site
Storage	sites	3	15	50	500	From ~1 today to ~8.8 Mt CO_2/site in 2050
	offshore	25%	25%	15%	10%	

Table 1. *The scenario: mitigating 1 Gt C emissions in 2050 by using CCS at 1 500 baseload lignite-fired power plants.*

result is a quantity of about 2.1 Gt of coal mined.

The second row of Table 1 reminds first that in the reference year 2007, that there were 3 CCS projects worldwide operating at the megaton-scale. Admittedly, they were not at baseload coal-fired power plant, but this has no influence on the results. The scenario specifies about 15 capture sites in 2015, 100 in 2030 and 1 500 in 2050. The final target 1 500 is an intermediate number between the high recommendations of IEA (2008) from 200 sites in 2025 to 3 000 in 2050, and the lower estimates of the G8+3 group, 600 sites in 2030 (McKee, 2008). This implies that each site captures on average 3 Mt in 2050, in line with values assumed in the IPCC Special Report (Metz, 2007), from 1 to 5 Mt/site in 2100, and with the operational specifications of a typical medium-to-large coal-based power plant.

There are two main ways to transport bulk hydrocarbons products: pipelining and shipping. Both land and undersea pipelines are used, we expect a negligible number of fatalities directly caused by undersea pipelines. The IPCC Special Report considers configurations where the mean distances from capture to storage vary from 1 to 300 km. Our projection assumes a lower value, from 1 km in 2007 to 100 km in 2050, since networking will reduce the length of pipe per capture plant. As there are 1 500 sites, the overall network length is 150 000 km.

Regarding long distance international trade, assumption for sea shipping is based on the mean distance covered by hydrocarbon tankers today and on a volume of 10% out of the total CO_2 stored in 2050. This percentage is justified because there is a tradition of heavy industry near ports. Big CO_2 emitters cluster in seaside locations. For example in Europe, Le Havre and Rotterdam proactive CCS strategies suggest that carbon management infrastructure is more and more seen as a strategic component of economic attractiveness, just like access to rail, water, power and waste networks. While today CO_2 is mostly shipped by pipeline, the scenario assumes that sea transport will increase reaching 100 Mt in 2025 and 450 Mt in 2050. According to Maersk, one of the larger tanking companies, CO_2 tankers have already been designed. In partnership with TVO and Fortum, this company is willing to start a project to ship 1.2 Mt of CO_2 per year by 2015 for EOR in the North Sea (Iso-Tryykäri et al., 2009).

Table 1's penultimate row is about injection. The number of active injection wells will not be used in our risk computations, based on the number of storage sites. For completeness, we estimate them as follows. IPCC estimates that flows from 1 to 2.2 Mt per year per well can be sustained. As high-injectivity, high-capacity reservoirs are hard to find, we assume 1.1 Mt per year per well in the long run average, or up to 60, 400 and 4 000 active injection wells in 2015, 2025 and 2050 respectively. In addition there will be a constant maintenance and development activity, plus monitoring wells.

Finally, Table 1's last line is about storage sites. Geological, market and regulatory conditions will ultimately determine the number of storage sites and their size distribution in 2050. Our scenario's assumption on the number of storage sites is based on average storage scale increasing from 1 to 8.8 Mt CO_2/yr per site. This implies about 15 sites in 2015, 50 in 2025 and 500 in 2050. The share of offshore sites, starting from 25% in 2007, is assumed to decrease in the long run to 10% because of higher costs. As in the ETP scenario, one can estimate that half of the emissions captured in 2030 will be stored in depleted oil and gas reservoirs and the other half in aquifers, but by 2050 this last option will dominate.

4. Fatality rates in coal extraction, CO_2 capture and transportation

The wedge scenario in Table 1 specifies the levels of the 6 activities of the CCS illustrated in Figure 1 associated with one wedge of CCS in coal-based power plants. In this section, these activity levels are multiplied with projected fatality rates, in order to determine expected fatalities in 2050.

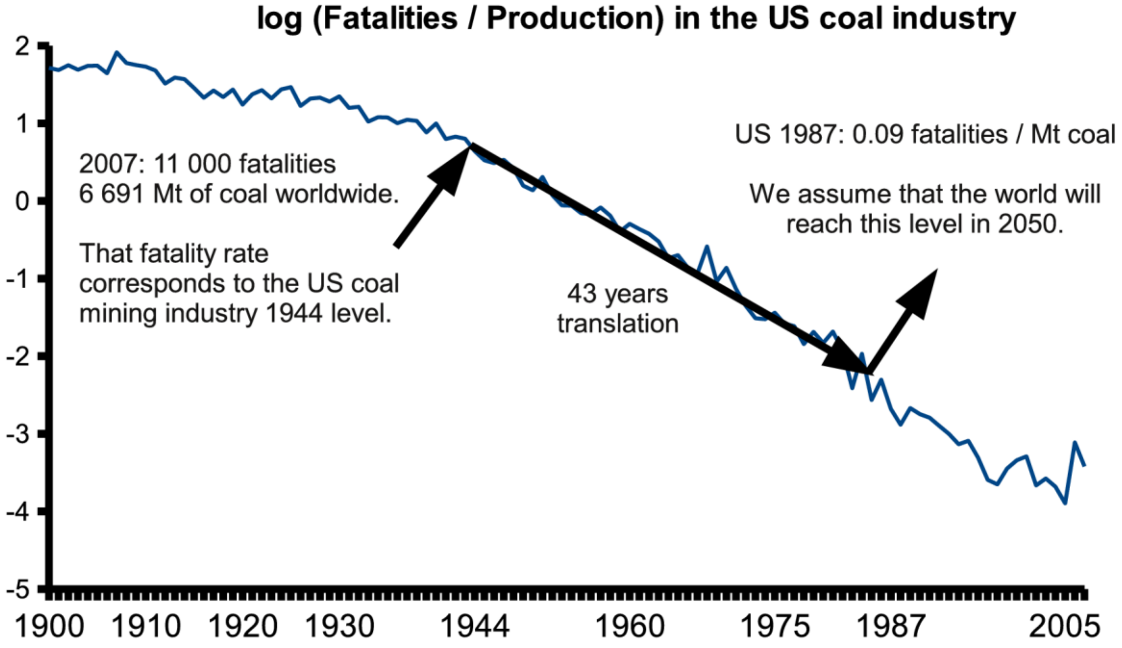
Projected fatality rates are determined by extrapolation from empirically analogue activities. For instance, moving CO_2 around is similar to moving other hydrocarbons, so the statistical risks in hydrocarbon shipping and pipelining are taken as proxies for the unknown CO_2 transportation risks. For robustness, we put together different sources of evidence for each activity. To account for uncertainty, we are not seeking precise numbers, but lower and upper bounds for each parameter, which determine orders of magnitude.

4.1. Coal mining

The wedge scenario means mining about 2.1 Gt of coal that would not be necessary if the CCS option was not included in climate policies. Mining is a dangerous profession. The frequency and gravity of accidents depends not only on the geological characteristics of the mine (depth, hardness, thickness, composition) but also on the technical progress embedded in the mining equipment and operating procedures. This explains why there are thousands of fatalities per year in China, but only dozens in the United States (MSHA, 2008; Hower and Greb, 2005), even though the former produced only 2.5 more coal than the later in 2006.

Drexler (2007) reports that the fatality number in coal mining today is hard to estimate worldwide because there are no official figures on coal mine accidents throughout the world. China's official fatality rate is about 2 people killed for every million ton of coal mined. This is four times higher than in Poland, Russia and South Africa, and Hower and Greb (2005)

Figure 2. *Computation of the world's fatality rate in the coal mining industry in 2050, assuming it follows the same curve as the US coal industry. Sources: MSHA, EIA.*



have estimated that real numbers could be up to four times higher. Worldwide, the ICEM Report (2008) mentions 11 000 deaths in 2007 for an overall production of 6.7 Gt mined, an average rate of 1.64 fatalities per Mt of coal.

To forecast fatality rates for 2050, our key driver is technological progress. We used the data represented Figure 2, the annual fatality rate from the year 1900 to 2007 in the USA, defined as the ratio of the number of deaths over the quantity of coal mined using the MSHA (2008) database. The rate has been declining regularly, but it seems to have hit a floor in the 1990s. We consider two alternative assumptions intended to bracket the results of a more precise assessment which is out of the scope of this paper, as it would require examining geographically the characteristics of coal reserves, seam depths and thickness as well as local social, economic and technical factors.

- One assumption is that technology transfers fast enough so that by 2050 the world’s average fatality rate drops to the US post 90's floor. This assumption leads to a rate in 2050 of 0.038 deaths/Mt coal, the average USA fatality rate over 1990-2007.
- Another assumption is to consider that mining safety in the world will follow the US historical trend. The 2007 world average fatality rate 1.64 corresponds to the level recorded in the USA by 1944. We project this rate for 2050 by translating 43 years along the curve. That means a final rate that is the level attained by the USA in 1987, that is 0.094 deaths/Mt coal.

For an additional coal production of 2.1 Gt, expected fatalities in the year 2050 amount to 80.6 with the first assumption and 196.5 with the second.

4.2. Carbon Capture

The carbon capture fatality rate is looked at from two different angles: historical accidents and insurance-based global statistics.

Firstly, we consider accidents from the actual industrial use of carbon dioxide. If a vessel containing pressurized CO_2 is ruptured or overheated, there is a risk of boiling liquid expanding vapor explosion (BLEVE). Even without fireball, this is extremely hazardous as the explosion may destroy the metallic tank and propel shards over a large area. The IPCC Special Report on CCS argues that the design of new plant facilities for CO_2 capture is subject to the guidelines applied to the petrochemical industry and that the CO_2 capture and compression installations are often listed as gas-processing facilities.

Industrial applications of CO_2 include enhanced oil recovery, the production of chemicals such as urea, refrigeration systems, beverages, fire extinguishers and other small-scale applications. The IPCC Special Report on CCS estimates the flux to about 115 Mt CO_2/year. Khan and Abbasi (1999)’s database of the major accidents in chemical industries records two accidents with CO_2 during the period 1926-1997 worldwide, causing 12 deaths. The ratio of the recorded fatalities over quantity times duration is about 0.0017 deaths/yr/Mt CO_2.

The CCS wedge scenario processes industrially 4.5 Gt CO_2 in 2050. Wild extrapolation suggests to look at $4.500 \cdot 0.0017 \approx 7.5$ fatalities/year as a starting order of magnitude.

The second point of view assumes that risks involved in the carbon capture are analogue to occupational hazards in utilities. The extrapolation is that on average considering all countries, the working conditions in the power sector in 2050 will be analogue to the current conditions in the most advanced countries today. International Labor Organization (ILO) statistics provide recorded fatality numbers per 100 000 workers, from 1969 to 2006 in the major economies, for workers in the *Electricity, Gas and Water Supply* sector. While there is a large inter-country and inter-annual variability, most numbers fall in the interval [3, 14] recorded deaths/year/100 000 workers. This range is consistent with the rate of 4 to 17 deaths per 100 000 workers per year in manufacturing industries quoted in Khan and Abbasi (1999).

How many additional workers would be necessary for capture? Based on direct declarations from the generation companies, Beamon and Leckey (1999) estimate that in 1981 an average 300-megawatt coal plant in the US had 75 employees, but by 1997 the average had fallen to 53. This is consistent with the estimates of Virinder and Fehrs (2001) that coal plants employ 0.18 workers per MW, based on financial data. We assume that on each site, only a fraction of the workforce will be exposed to the risks of capture. Modern coal power plants are highly automated, so this is approximated as 5 to 10 workers per site.

Since the scenario has 1 500 capture sites, the additional population at risk is 7 500 to 15 000 workers. This suggests a number of expected fatalities in 2050 between $3 / 100 \cdot 7.5 \approx 0.22$ and $14 / 100 \cdot 15 \approx 2.1$

These two points of view suggest to consider an interval from 0.2 to about 8 expected fatalities in 2050 at the capture stage.

4.3. CO_2 pipelines

Pipelining safety will be discussed in three steps. First, data from the North American CO_2 pipeline network for enhanced oil recovery industry will be discussed statistically. Then, these results will be compared to data on natural gas and hazardous liquids pipeline safety in the USA and Europe. Finally, analogy and extrapolation in time and space will be discussed.

A network of CO_2 transportation pipelines exists in the US oil producing region. This CO_2 is used to enhance the recovery of oil, since flooding the field raises the pressure and may reduce the viscosity, two effects that increase the oil production. Gale and Davison (2004) analyzed this infrastructure of CO_2 transmission for the period 1990-2001 and concluded that such lines do not represent a significant risk in term of potential for release.

Table 2 updates Gale and Davison's numbers with more recent data we queried from the US DoT publicly available databases of pipeline incidents. The risk can be computed as fatalities per Mkm yr of pipelines. The rightmost column shows that no fatalities caused by CO_2 pipelines were recorded over 1990-2009. The average network size over this period is about 6 170 km. Compared to natural gas and hazardous liquids transmission, there is not much experience with CO_2, so the statistical significance of the result should be discussed.

	Natural gas transmission (1986-2009)	**Hazardous liquids (1986-2009)**	**CO_2 (1990-2009)**
No. serious incidents	2 318	4 088	20
No. Fatalities	65	54	0
Avg. network length (1000km)	522	255	6.2
Fatalities/ 10^6 km/ yr	5.2	8.8	0
95% confidence interval	4.0 - 6.6	6.6 - 11.5	0 - 24.3

Table 2. *Statistics of pipeline fatal incidents in the USA. Source: US DoT, Office of Pipeline Safety.*

Evidence for CO_2 pipeline safety comes from $N = 0.123$ M km yr of observations, and the observed number of fatalities is zero. To test how this constrains the risk, we use the simplest model, the Homogenous Poisson Process. Assume that fatal accidents occur at a constant rate λ per million of km-year of pipeline. Then the probability of observing no fatal accident in the CO_2 pipeline system so far is $p = e^{-\lambda * 0.123}$. The larger the rate λ , the smaller the probability p of seeing no failures. If the fatal accident rate was larger than 24.3, then the probability of having no failure would be smaller than 0.05 (= $e^{-24..3 * 0.123}$). Observing events of small probability is unlikely, we should have seen an accident if the rate were that high. In statistical words, the clean record does not allow to reject rates as high as 24.3 fatal accident per M km per year at the 95% confidence level. The number would have even been higher if we had looked at fatality rates, since a fatal accident can cause more than one fatality.

This 24.3 accident rate may seem large considering the natural gas and hazardous liquids columns in Table 2, where the average fatality rates recorded for these two samples are respectively 5.2 and 8.8 fatalities/Mkm/year. And the network sizes and observations period are much larger, so assuming that fatalities occur following the Poisson process (which is a technical simplification, since actually they tend to occur in events involving multiple victims), the 95% confidence interval for these numbers are 4.0-6.6 and 6.6-11.5 respectively.

The distinction between worker and no-worker fatalities for the gas transmission is available only for the period 2002-2008, but show that out of 7 total fatalities during this period, 4 fatalities are among employees and 3 in the general public. For hazardous liquids, about 75% of fatalities were recorded in the general public.

Davis et al. (2009) document incidents from 1971 to 2007 in the European international oil pipelines network (average length 27 000 km). These statistics report 14 fatalities associated with pipeline failure incidents, involving no member of the general public. The corresponding average rate is 14 fatalities/Mkm/yr (95% confidence interval: 7.7-23.5).

Because there is comparatively so little experience from CO_2 pipelines, it is tempting to try to learn from evidence in the natural gas transmission and hazardous liquids pipeline systems. They suggest lower fatality rates, but how valid is the analogy? With only 20 significant incidents on CO_2 pipelines recorded in the US database, we do not have enough observations to compare statistically the lethality of CO_2 pipelines incidents with the lethality of other pipelines incidents. We conjecture that a reason why the gas and oil pipeline transport system presents lower fatal risks in the USA than in Europe may be that transmission pipelines are mostly located in areas of low population density. By contrast, CCS may require a pipeline infrastructure from power plants to storage sites through regions more densely populated than Texas. Enforcing safety zones around capture and injection sites is generally possible, but it will be more difficult to minimize the population in the pipelines potential impact areas.

In summary, for various fluids and developed regions, confidence intervals based on empirical data yield 4 to 24 fatality per year per million of km of pipeline. To extrapolate to the world in 2050, two effects must be balanced. On the one hand, safety can improve with technical progress. For example the frequency of spillage in European oil pipelines has been divided by 2 over the last 37 years (Davis et al. 2009, figure 5). On the other hand, risks may be higher in developing countries. Beyond the hazards associated with poorer maintenance and due to physical causes such as corrosion or digging accidents, other security issues must be considered, like the vandalisation-induced pipeline explosions in Nigeria discussed by Onuoha (2007).

For these reasons, it would seem over-optimistic to assume that the world's average in 2050 is safer than Europe and USA today. If the system is perfectly safe in 80% of the world, the remaining 20% will determine the average fatality rate. In front of the variability of economic, physical and cultural conditions, we considered that up to 50 fatalities/Mkm/yr as an upper bound, and 5 as a lower bound.

The scenario has 0.15 Mkm of CO_2 pipelines. Applying these rates suggest an interval from 0.75 to 7.5 deaths in 2050.

4.4. Shipping CO_2 and coal

While shipping is comparatively a safe mode of transportation, moving large quantities of CO_2 will increase the traffic at sea, and therefore accidents. Tanker accidents with fishing boats with fatal consequences happen every year. Collisions with ferries causing even more dramatic consequences have occurred. Complete sinking due to rough sea, collision, grounding, mechanical problems or structural failure are rare, but a few of the thousands merchant ships go missing each year.

Risks in the shipping business are better known statistically than most others. Skjong (2005) even argues that the industry is one of the first where formal risk assessments are used for making regulation at the UN level. Since the usual unit for measuring shipping activity is the ton-mile, risks in what follows are computed in terms of fatalities Tt^{-1} Nm^{-1} yr^{-1}, that is per year per tera (10^{12}) tons nautical miles of cargo. Projections of casualties attributable to shipping are based on two analogues, the first related to risks in oil tankers and the second to risks in all goods maritime trade.

Citing the LMIS database, Ranheim (2002) from Intertanko wrote that there were 2 322 fatalities in oil tanker accidents over the period 1978-2001. During that period, based on Fearnleys Review (2004) data cited in IMO (2005, p. 6), we estimate that the tanking industry shipped an average of 8 258 Gt-miles of oil (crude+products) per year. The corresponding fatality rate is 11.7 deaths Tt^{-1} Nm^{-1} yr^{-1}. According to the same sources, the trend in fatalities is declining: 1617 over 1978-1989, 775 over 1990-2001 and 229 over 2002-2007. Comparing one period with the next, average annual fatalities improved by a factor 2 over 1978-1989, then by 1.7 over 1990-2001. We extrapolate that future technical progress will continue to improve navigation safety, up to a factor 4 in 2050, that is 2.9 deaths Tt^{-1} Nm^{-1} yr^{-1}.

Regarding all goods trade, for the period 1989-2004 the IMO (2006) FSI circular reports a total of 9 724 lives lost as the consequence of the total loss of ships of 100 Gt and above. According to Fearnresearch (2005), the total seaborne world trade on the same period is about 340 Tt Nm. This yields an empirical fatality rate of 28.6 deaths Tt^{-1} Nm^{-1} yr^{-1} in average. Since these data sources provide annual data, we were able to fit a logarithmic tendency to the decline of fatality rate over time. Extrapolation to 2050 yields 10.9 fatalities Tt^{-1} Nm^{-1} yr^{-1}.

The wedge scenario ships about 2.2 Tt Nm of CO_2 in 2050. Using the extrapolated rates to account for the progress of safety over time, the expected fatalities numbers are 6.6 and 24.6 respectively.

The scenario also provides for the production of 2.1 Gt of coal. Based on current international coal trade numbers, we assume that 15% of the world's coal production is shipped for an average of 4 500 Nm. This amounts to 1.42 Tt Nm per year of sea transportation. We assume that the other 85% of coal is transported at a negligible fatality risk.

Like for mining, we assume that this additional coal shipping business only permitted by the use of CCS as a climate policy option, so the expected fatalities can be attributed to it. If the extrapolated fatality rate in all goods trade is applied for all goods trade, one can expect 15.5 fatalities per year. The number is only 4.2 if we use the rate based on statistics for tankers.

5. Expected fatalities at CO_2 injection and storage sites

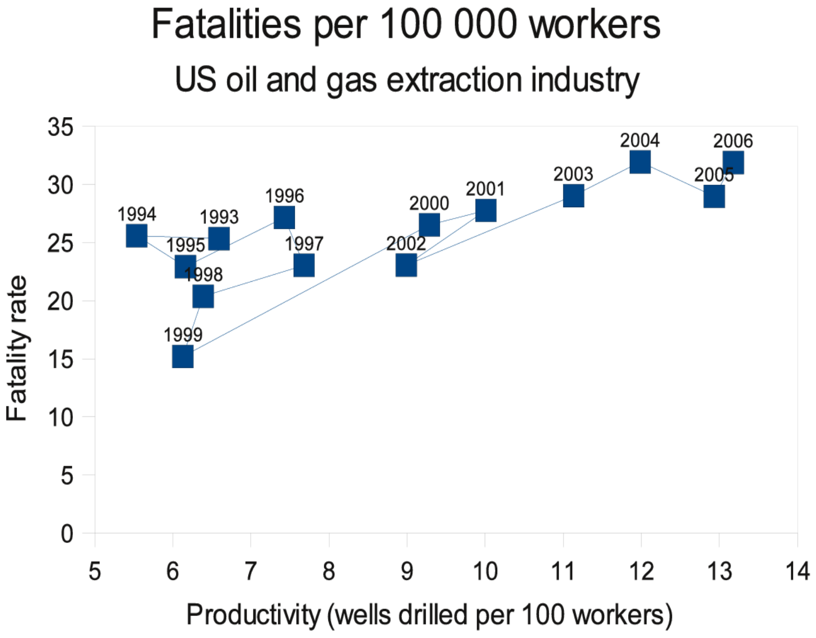
After discussing injection, fatalities rates associated with CO_2 storage will be examined from three points of view: bottom-up engineering, social regulations, and actuarial statistics.

5.1. Injection

Damen et al. (2006) argue that the major risk associated with injection is well failure and report that the frequency of blowout for oil or gas wells are 10^{-4} to $3\cdot10^{-4}$ per well year (Duncan et al., 2009). However, hazards at injection facilities also involve many other causes like fires, falls and accidents with moving machinery. From an expected fatalities point of view, we assumed that the risks at the CO_2 injection step are analogue to the average risks in the oil and gas industry as a whole, because the techniques to drill wells and inject CO_2 underground are well known and typical of this industry.

As Figure 3 shows, fatality rate in this industry is between 15 to 33 deaths per year per 100 000 workers. Over the observation period 1993-2007, this number increased along with the sector’s productivity, measured in drilled wells per 100 workers. We do not take this as a

Figure 3. *The fatality rate in US oil and gas industry and the sector's productivity both increased from 1993 to 2007. The regression line is FAR = 13.2 +147 Wells/ Workers. Source: Centers for Disease Control and Prevention. 2008. Fatalities Among Oil and Gas Extraction Workers --- United States, 2003--2006. MMWR 57:429-431. U.S. Energy Information Administration 2009. Annual Energy Review 2008. Report DOE/EIA-0364(2008).*



long-term trend, but assume that the global average fatality rate in 2050 will be like the US rate at the end of the twentieth century. This is about 20 to 30 fatalities per year per 100 000 workers.

In the wedge scenario, there are 500 storage sites operating in 2050, each storing for 3 capture sources on average, about 8.8 Mt CO_2 per year. While injection itself is mostly automated, real-time monitoring, development and maintenance work will need to be performed. Assuming that each site has 10 to 30 full time employees, for a total of 5 000 to 15 000 workers, the expected number of fatalities is between 1 and 4.5 per year.

5.2. Engineering estimates of storage risks

Saripalli et al. (2003) decompose the risk of geological storage in six hazard events: three involving well-head failure and three involving cap rock failure, and then estimated the probabilities and consequences shown Table 3. For our purposes, we interpreted their magnitude of consequences scale in terms of expected fatalities.

The consequences defined as “Severe” correspond to a CO_2 concentration >10% in the air or 5% indoors. We linked this with the base case studied by Saripalli et al, a complete blowout of a 30 cm diameter well, in the first few years after injection. It was estimated that the amount released, $8.36 \cdot 10^6$ m^3, or 4.2 kt of CO_2 per day, had lethal consequences in an aerial extend of 11.6 km^2. As a comparison, the Lake Nyos event involved 240 kt of CO_2, a quantity 57 times larger released over a much smaller duration. Based on that, we interpreted the “Major” case as 1 expected fatality, and then proceeded logarithmically. The “Moderate consequence”, defined as concentration >5% outside or 2% indoors, is interpreted as a 0.1 expected fatality, and the “Low consequence” as 0.01 expected fatality.

With this scale, total risk amounts to $6.9 \cdot 10^{-4}$ expected fatality per year per storage site. Since there are 450 onshore sites in the scenario, this is 0.31 expected fatality in the world in 2050.

But the robustness of these frequency/consequence levels can be questioned. Saripalli et al.

Hazard event	**Saripalli's Frequency estimates**	**Saripalli’s Consequences index**	**Expected fatalities per event***	**Expected fatalities per 100 000 storage year col 1 * col 3 * 10^5**
1. Well-head failure				
1A. Major wellhead failure	0.00002	1	1	2
1B. Moderate, sustained leak	0.0001	0.5	0.1	1
1C. Minor leaks of joints	0.001	0.1	0.01	1
2. Cap rock failure				
2A. Fractured cap rock	0.01	0.3	0.05	50
2B. High permeability zones	0.01	0.1	0.01	10
2C. Seismic induced failure	0.0001	0.8	0.5	5
TOTAL				**69**

Table 3: *Saripalli et al. (2003) frequency and consequence estimates of CO_2 storage risks, with *our reinterpretation of the consequences index in terms of expected fatalities.*

suggested that the risk of leakage trough existing wells is small in front of the risk of leakage through the caprock, but the IEA (2008, p.125, chap. 5) wrote that the most prevalent risk is the migration of CO_2 within well bores. Saripalli et al.'s argument that no serious incident occurred in the US and Canadian natural gas storage industry should be reconsidered. In Chemery, France, technical work on an existing well caused high pressure natural gas stored underground leakage during 2 days in 1989. In Novare, Italia, drilling a new well in an existing underground storage caused oil, water and gas leakage during 3 days in 2000.

Benson et al. (2002, p. 7) note that while underground natural gas storage has been used safely and effectively, there have been a number of documented cases where leakage has occurred. According to Damen (2006), nine natural gas storage reservoirs out of 900 operated in US, Canada and Europe have experienced leakage: five due to defective wells, three due to cap rock failure and one due to inaccurate reservoir selection. Dramatic accidents occurred at Brenham, Texas (3 fatalities, 07/04/1992), at Hutchinson, Kansas (2 fatalities, 17/01/2001) and in China at Baohe, Heilongjian (70 fatalities, 11/10/1993).

Jordan and Benson (2008) examined blowouts in oil fields undergoing thermally enhanced recovery (via steam injection) and their implications for geological storage of CO_2 in California Oil and Gas District 4 from 1991 to 2005. Blowout rates were on the order of 1 per 1 000 well construction operations, 1 per 10 000 active wells per year, and 1 per 100 000 shut-in/idle and plugged/abandoned wells per year. The frequency of blowouts in District 4 decreased significantly during the study period, most likely because of increased experience, improved technology, and/or changes in the safety culture in the oil and gas industry. Any of these explanations suggests that blowout risks can also be minimized in CO_2-storage fields.

Over 1991-2005, the 102 blowouts for 4 053 injection wells caused one worker fatality, but regarding our analysis the circumstances of this fatal accident pertain more to the injection step than to the storage step. There was no public injury, which is explained in part by the low population density over most fields, less than 4 persons/km².

Based on a SWIFT review of storage systems, Vendrig (2004) estimates the frequency of significant leaks (>10 t/d) during operation as 10^{-3} per reservoir-year (confidence interval: $5 \cdot 10^{-4}$ to $2.5 \cdot 10^{-3}$). The estimated probability-weighted release quantity was 92 000 t (CI: 1 600 to 960 000) during the reservoir lifetime, that is 0.2% of the amount stored (CI: 0.004 to 2.4%). He concluded that it is currently difficult to quantify with any confidence the likelihood of accidental releases from CO_2 storage reservoirs because of the lack of detailed research and field trials, and the difficulty of assigning generic risks to what in reality would be extremely site-specific risks.

Overall, this review suggests that engineering estimates in this field are not robust yet. We argue that this does not prevent us from making estimates for our scenario, because the risk will be determined socially. For the system under consideration, uncertainties related to human volition are more important than aleatory chance. To derive global fatality estimates from blowout frequencies, one needs assumptions on the population and abandoned wells in exposed areas. This implies to make assumptions on where CO_2 storage will be allowed.

5.3. Normative approaches for storage risks

Assuming that storage occurs necessarily assumes that the regulators will authorize a non-zero level of risk. There are various approaches for societies to determine the risk level at which CO_2 storage systems will be allowed to perform.

Some industrial norms (e.g. CENELEC standard EN 50126) suggest that a technical risk is acceptable if it does not increase significantly the death rate for any age group. How much is a negligible increase of the risk of dying? Fishbeck et al. (2010) suggest that the answer should be expressed in a new unit, the *micromort*, which is a one in a million (10^{-6}) probability of dying next year. According to data they compiled, the probability of dying for Females, aged 5-9 is 97 micromort in Western Europe, 106 in New England. We checked that this is the minimum across genders, region and age groups. Since practically everybody is above 100 micromorts, we can say that 1 micromort is a negligible increase. In other words, the endogenous mortality criterion says that is acceptable to increase individuals' risk of dying by no more than 10^{-6} per year. There is an implicit caveat to this condition, which is that the increase has to be for a good reason, that is to provide direct essential services to the risk bearers. Access to cleaner electricity is such a service.

A large CO_2 storage may easily impact from 25 to 100 km² (5 by 5 to 10 by 10 km). For example, according to seismic imagery shown by Chadwick et al. (2009) the 10 Mt CO_2 plume at Sleipner is 3.6 km long by 1 km wide.

Worldwide density over land was about 50 persons/km² in 2007 and it may grow up to 70 by 2050. But assuming that avoiding populated areas will remain a primary criterion for site selection, we assume in our scenario that the density over storage sites is only 20 persons/km². This implies that 500 to 2 000 persons may live above a typical storage site. If there are 450 onshore sites, and the individual risk is increased by 10^{-6} per year, the expected number of fatalities is 0.2 to 0.9 per year.

In the context of industrial installations with dangerous compressed gases, Schjølberg and Østdahl (2008) define "tolerable risk" as risk that is accepted in a given context based on the current values of society, meaning what society thinks is reasonable regarding the frequency and consequences of hazardous events. The French regulations on industrial risks (MEDDAD, 2009; annex 6, p. 130, table 40) provides an explicit (probability, consequence) table stating when an installation may be seen as "compatible with its environment". It says, for example, that for a risk of gas emission with a probability lower than 10^{-3} per year (class C), there should be less than 10 persons exposed to lethal effects, defined as the 1% lethal concentration level (MEDDAD 2009; p. 60, table 11 and 12). This level is generally understood as the level causing a 1% fatality frequency in an exposed population. In other words, the guidelines in France can be seen as defining a tolerable risk level around an industrial installation, e.g. 10^{-4} fatality per year is tolerable. Bowden et al. (2004) quote the same number as relevant for storage safety in Australia, as guidelines for the dams industry.

Multiplying this order of magnitude by 450 storage sites would suggest 0.45 tolerable fatality per year worldwide. But tolerable risk is a normative concept. It should be increased if communities using CCS in 2050 are assumed to be more risk tolerant than France or Australia today, to account for the gap between law requirements and real behaviors. The tolerated risk also depends on the nature of installation, how many jobs it brings.

According to the UK Health and Safety Executive guidelines (Berry, 2006), in those situations where the work activity is unusual (i.e. good practice is not yet established), dutyholders should demonstrate that the risk has been reduced 'as low as reasonably practicable (ALARP)'. The ALARP criterion is satisfied when all reasonable measures have been taken to reduce the risk until the cost of further reduction is disproportionate with the benefit. At the global scale, this implies that annual average leakage rates should be smaller than 10^{-4}, because above this level the climate benefits of storage start to be questionable. If the wedge means having a total of 100 Gt of CO_2 stored by 2050, this leakage rate is a flow of

10 Mt per year back to the atmosphere. Averaged over 500 sites, this is 20 kt per year per site. Since injecting 8.8 Mt per year means approximately 1 kt of CO_2 injected every hour, this is about 20 hours of injection leaked in the atmosphere every year. As CO_2 density is about 2 kg/m^3, 20 kt is also about 10^7 m^3. This corresponds to the complete blowout Saripalli et al. (2003)'s base case discussed previously, but with an annual frequency 1 instead of 0.00002. This confirms Ha-Duong et al. (2003)'s conclusion that to determine socially appropriate risks of leakage, the global scale cost-benefit analysis is less strict than local scale risk constraints.

5.4. Actuarial estimates of risks at social analogues

In Europe, CO_2 storage requires a permit to operate, but are not regulated by the SEVESO II directive. This suggest that on the one hand, an underground CO_2 storage is considered less risky than an industrial facility holding large amount of dangerous chemicals. And on the other hand, an underground storage is more than a simple installation that may have an impact on the environment. Estimates of the fatality rates for these two extreme cases thus provide upper and lower bounds to the risk of storage, as currently viewed by the legal authorities.

In Europe, industrial facilities holding large quantities of dangerous substances are regulated by the directive 2003/105/EC. According to the F-SEVESO study (Salvi et al., 2008, Table 8 p. 72) there were 1 076 such establishments in France, and 8 558 in Europe in 2007. According to Michel (2009, p. 13), over the last 17 years accidents in these facilities caused 38 victims in France, and 153 victims in 67 accidents in Europe. The observed frequencies are $2 \cdot 10^{-3}$ fatalities per year in France and 10^{-3} in Europe. Regarding this lower estimate, thr source notes that it is likely that Member States are not homogeneous in reporting accidents which means that underreporting is an issue. Haastrup et al. (1995) found out that these kinds of databases typically recorded only 20 to 45% of the fatal accidents.

For an earlier period, when European Union was smaller and more homogenous, Haastrup et al. (1995) find 14 fatal accidents per year with 1 860 sites. Using the average number of 2.3 victims per accident, this suggests $17 \cdot 10^{-3}$ fatalities per year per establishment. This number is based on a much more thorough analysis of most accidents databases available. Considering these estimates, a realistic order of magnitude is 10^{-2} fatality per year per site in Europe.

In 2008, France counted about 500 000 installations classified for environmental protection (ICPE). This is a broad category which includes factories, feedlots, warehouses, mines, dry-cleaning shops and many other facilities. Over the last 17 years, Michel (2009) cites 403 recorded fatalities implying these installations (62% workers, 28% public and 3% rescuers), including 14 cases of death by CO_2. The observed frequency is thus $4.7 \cdot 10^{-5}$ fatalities per year per establishment. We suspect that the underestimation is significant since there are only 1 400 inspectors, there is an obligation but no incentive to report accidents especially for the earlier segments of the time period. Thus we double the estimate and consider 10^{-4} to be closer to the reality.

We argued that current regulations place CCS below Seveso II but above ICPE. It means that implicitly, regulators estimate a risk level greater than 10^{-4} but lower than 10^{-2}. That is around 10^{-3} fatality per year per site.

6. Summary and discussion of results

6.1. Summary of results

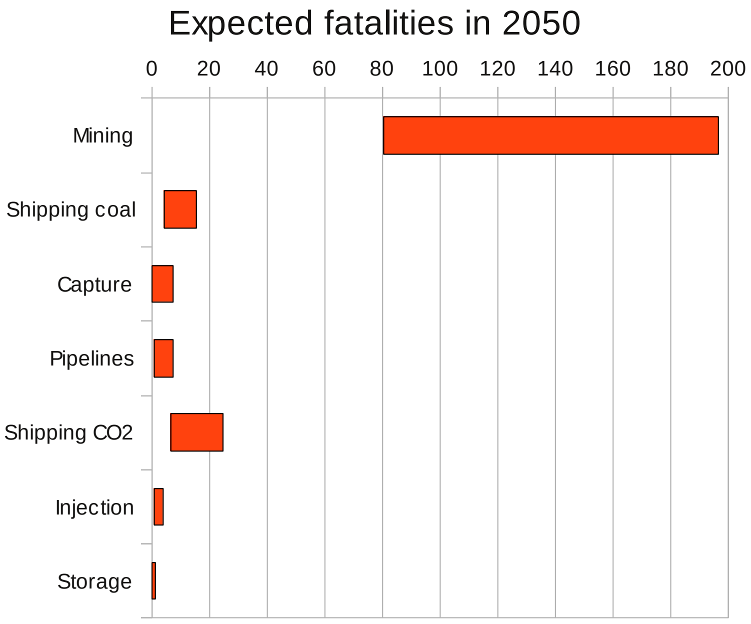
As Table 1 shows, our CCS at baseload coal-fired power plants wedge scenario in 2050 is about 5 Gt CO_2 generated, 4.5 Gt captured and stored, 1 500 capture sites, 150 000 km of CO_2 pipelines, 2.25 billion ton nautical miles of CO_2 shipped, 4 000 active injection wells and 500 storage sites, with only 50 offshore. Fatalities attributable to CCS also include those related to the production of 2.1 Gt of coal in 2050, also requiring 1.42 billion ton nautical miles of coal shipping.

Table 4 and Figure 4 sums up the results. Between 93 and 257 fatalities per year can be expected due to one wedge of CCS mitigation in 2050. Expected fatalities vary by two orders of magnitude for the different steps. The most dangerous activity is mining more coal. Next is shipping coal and CO_2 . Miners, sailors and workers are more at risk than the general public.

We did not attempt to draw quantitative conclusions from the engineering risk assessment literature. Site specificity of the leakage risk implies that this part of the uncertainty is not aleatory, but voluntary.

Increasing the risk of dying of an individual by 10^{-6} per year (1 micromort) is negligible, but storage sites have a large footprint since CO_2 in geological formations spreads wide and thin. Thus, even if the risk increase is kept negligible for each individual, allowing storage in populated areas may lead to 0.25 to 1 fatality per year in the world. In postmodern societies, planning a large human activity installation at a level of 10^{-4} fatality per year seems tolerable. Actual records show that dangerous industrial establishments have a much higher risk level, 10^{-2} fatalities per year per site. The current legal status of storage in Europe places it in between these two levels, around 10^{-3}. Assuming that the average society in 2050 will allow for a risk one to three times as large as that, for 450 sites, this amounts to 0.45 to 1.35 statistical fatalities per year globally.

Figure 4: *Result summary: Actuarial estimates of the human cost of 1 GtC of CO2 emissions mitigation by using carbon capture and storage at 1500 baseload coal fired power plants.*



6.2. On the relatively smaller size of the storage risks

The actuarial approach complements radically most other published engineering or social risk analysis: regarding objectively expected fatalities, the risk of leakage is the least important. Admittedly, this is based on limited statistics on analogue accidents, expected values are uncorrected for reporting biases and globally extrapolated to 2050. But since these limitations apply to all the steps along of the CCS chain, they do not invalidate the result that the storage risk is relatively smaller. It is critical, however, to remind that realist approaches to risk analysis, as we defined above section 2, do not account for the public's view and higher order impacts.

Objectively, the expected number of fatalities for storage appears two orders of magnitude lower than corresponding number in mining. However, psychological effects when comparing risks may be stronger than that: individuals routinely show more concern for small but involuntary and unknown risks than for voluntary, familiar risks 1 000 times greater. Indeed, most assessments about the social perception of CCS show that concerns about risks, especially storage leakages risks, are a priority.

Renn (2004) warns that managing risk perception is no substitute for rational policy in the decision-making process. This means that to regulate the development of CCS at a large scale,

Additional activities required to not emit 1 GtC by using CCS at power plants	**Fatality rate per year** extrapolated 2050 world average	**Expected fatalities** in 2050
Mining 2.1 Gt of coal	0.04 to 0.09 per Mt	80.6 to 196.5
Shipping 1.42 billion tons nautical miles of coal	2.9 to 10.9 per Tt Nm	14.2 - 15.5
Processing 4.5 Gt of CO_2	1.7 per Gt (historical accidents)	7.5
Employing 7 500 to 15 000 workers for capture at 1 500 sites	3 to 14 per 10^5 workers (utilities industry)	0.2 to 2.1
Operating 0.15 Mkm of CO_2 pipelines	5 per Mkm (lowest achieved today in analogue)	0.8
	50 per Mkm (worst case assumption)	7.5
Shipping 2.2 billion tons nautical miles of CO_2	2.9 per Tt Nm (based on oil tankers)	6.6
	10.9 per Tt Nm (based on all goods trade)	24.6
Employing 5 000 to 15 000 workers to maintain, develop and monitor 2 000 wells	20 to 30 per 10^5 workers (US oil & gas industry)	0.9 to 4.1
Exposing $2.5 \cdot 10^5$ to 10^6 persons to a diffuse environmental risk	10^{-6} per individual (negligible risk level)	0.2 to 0.9
Operating 450 man-made big installations	10^{-3} per site (accepted risk, European analogues)	0.5
	$3\ 10^{-3}$ per site (worst case assumption)	1.4
Total		**93 to 257**

Table 4. *Summary of results: Expected fatalities in 2050 for a CCS stabilisation wedge scenario. Note: Different lines within the same cell do not add up, they are alternative approaches for the same quantity. The total is the sum of extremes within each cell above.*

policy-makers should consider the public opinion, but also objective risks levels. In the long run, over large number of storage installations, fatal accidents happen. Our analysis helps to relativize this concern by pointing out that handling all forms of energy and compressed gases is intrinsically a dangerous activity, and CO_2 storage is not so exceptional.

Our results may contribute to make the risks of CCS easier to understand. This may make them more acceptable, as less unknown risks are less threatening psychologically. However, the results on storage risks are contingent on successful regulation. Storage sites seem to be regulated today in Europe as medium-risk installations, those at the level of about 10^{-3} fatalities per site per year. Decisions on where to allow storage should be based on site-specific safety analysis. To keep the risk at an accepted level, the number of people exposed to it should be inversely proportional to the probability and gravity of accidents. It is not obvious that more off-shore storage would decrease the total expected fatalities. The human risk over storage sites would decline, but the difficulty of injection would increase.

Keith (2004) argued that we do not need to do a risk assessment for the storage risk at the gigaton scale today. Current risk assessment may enable a suite of power-plant scale of 10 Mt/yr projects that will start over the next decade or two. The results of these will provide our children with data that will allow them to make choices about the gigaton scale. Thus, there is an extra value to avoid accidents in the early stages of the technology.

The current presumption seems to be that storage implies medium-risk installations, that is one expected fatality in 1000 years of storage. Using the same statistical model as in the section 4.3 on pipelines, to check at the usual 95% confidence level that a system has a mean time between failure of 1000 time units (MTBF), one has to see it working without failure for 3000 time units (-log[0.05] is approximately 3). In our scenario, it is not before 2039 that the world has seen 3000 years of storage, cumulated across all sites. A single fatality occurring in the next 30 years would be sufficient to disprove the currently assumed safety level and make storage areas more comparable to high-risk industrial facilities. This would imply storing in very low human density areas, in the deserts or offshore only. The learning effect explains the paradox pointed out in Ha-Duong and Loisel (2009): all parties involved with CCS demonstration look for a zero risk, admitting at the same time that the technological risk cannot be zero because of existing natural and human hazards.

6.3. CCS risks versus nuclear, large hydro and climate risks

Even though there is no global policy-maker choosing between mitigation wedges, climate change mitigation and energy security policies involve choices between different technologies. The risks of the CCS option have to be balanced against the risks associated with other energy technologies like nuclear, large hydro, other fossil fuels and climate change.

Felder (2009) exposed the methodological limits of energy risk analysis using accident databases. The expected value of the risk is determined by a few, rare but large events: for nuclear, Chernobyl 1987 (which caused thousands of additional fatal cancer cases), and for hydro, the Shimantan dam failure in China in 1975 (which caused well over 100 000 deaths). In these kinds of statistical situations, robust mathematical inference from finite samples and time series is difficult. This is compounded by the incompleteness of databases, which are mostly based on English sources, not publicly peer-reviewed or continuously updated.

Hundreds of fatalities are recorded in the energy sector every year. For fossil fuels only, Burgherr and Hirschberg (2008) document energy accidents over the period 1969-2000 and found about 2 259 fatalities in the coal industry, 3 713 in oil sector, 1 043 for the gas and

1 905 for LPG. That gives an average of about 300 recorded deaths per year. Our results are in the same order of magnitude as these numbers. However, including also nuclear and large hydroelectric power leads to higher figures, as shown in Sovacool (2008), about 1 800 deaths on average per year during the period 1907-2007. The main qualitative conclusion is that CCS is typical of fossil fuels technologies, which seem to have a lower record of extremely large (> 10.000 casualties) accidents than nuclear and large hydro.

The number of fatalities from CCS can also be compared with the number of lives that it is meant to protect. IPCC (2006) estimated that by 2100, global average surface temperature could rise by 1.4 to 5.8°C relative to the 1990 level, well above 2°C which is already recognized as a dangerous level. OCDE (2008) finds about 3.9 billions of people could be affected by climate change in 2050, mainly through hydric stress because of the temperature increase and to a unsustainable water management.

A report of the World Health Organization (2002) argues that climate change was responsible in 2000 for about 154 000 deaths, mostly from malaria, diarrhea and dengue. In industrialized countries, 7% of dengue fever was attributable to the climate change. The review by McMichael et al. (2006) did not provide specific expected values, but nevertheless wrote “we could infer that approximately half of excess deaths during the 2003 heatwave were due to that underlying anthropogenic contribution”. More decisively, the UCL Lancet Commission (Watts, 2009) wrote that “Climate change could be the biggest global health threat of the 21st century. Effects on health of climate change will be felt by most populations in the next decades and put the lives and wellbeing of billions of people at increased risk.”

In addition to the benefits of lower climate change, CCS may provide co-benefits in terms of local air quality. Haines et al. (2009) examined the potential benefits of climate policies in terms of reduced burden of diseases, concluding that in some case, the potential benefits seem to be substantial.

The above numbers mean that the stakes of climate policy are high, and are reasons to believe that implementing the stabilization triangle would save several tens of thousands of lives in 2050. Being one-seventh of the triangle, each wedge can thus be seen as saving thousands of lives. Under this kind of very rough cost-benefit analysis, the expected costs of CCS appear an order of magnitude lower than its benefits.

7. Acknowledgements

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