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Actuarial risk assessment of expected fatalities attributable to carbon capture and storage in 2050

Minh Ha-Duong¹, Rodica Loisel²

10 February 2011

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 integrating all steps of the CCS chain: additional coal production, coal transportation, 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 baseload coal power plants. The large majority of fatalities are attributable to mining and delivering more coal. These risks compare to today's industrial hazards: technical, knowable and occupational dangers for which there are socially acceptable non-zero risk levels. Some contemporary European societies tolerate about one fatality per thousand year around industrial installations. If storage sites perform like that, then expected fatalities per year due to leakage should have a minor contribution in the total expected fatalities per year: less than one. But to statistically validate such a safety level, reliability theory and the technology roadmap suggest that CO₂ storage demonstration projects over the next 20 years have to cause exactly zero fatality.

Résumé: Nous estimons le coût humain attribuable en 2050 au choix de l'option captage-transport-stockage du carbone (CTSC) pour limiter de 1 GtC les émissions de gaz à effet de serre dans la production d'électricité. L'approche actuarielle utilisée intègre toutes les étapes de la chaîne CTSC: extraction additionnelle et transport du charbon, puis captage, transport, injection et stockage du CO₂. Le nombre de décès attendu dans le monde est estimé à quelques centaines. Les mines de charbon et les transports sont les étapes les plus dangereuses. La plupart des dangers examinés sont des risques professionnels ou des risques familiaux. Le niveau de risque auquel est soumis, dans les sociétés occidentales, la population voisine d'une installation industrielle moyennement dangereuse est évalué à 0.001 décès par an. Si les sites de stockage géologique sont à ce niveau, alors l'étape de stockage serait négligeable dans le total des décès attendus le long de la filière: moins de un décès attendu par an. Toutefois pour démontrer statistiquement ce niveau de fiabilité, les projets de stockage géologique de CO₂ dans 20 prochaines années doivent fonctionner sans aucune défaillance fatale.

Keywords: CCS, risk, analogues, scenario, global, 2050

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1. Introduction

Carbon capture and storage (CCS) involves capturing the CO₂ from industrial installations and storing it underground for geological times instead of releasing it in the atmosphere. According to the International Energy Agency (2008) it is a key carbon abatement option for climate change mitigation. But no technology is risk-free. 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 hazards associated with CCS is that some societies could rely too much on it and that money spent on CCS could divert investments away from sustainable solutions to climate change (Rochon et al., 2008). 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 hazards is leakage, the risk that some of the CO₂ 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, the law of large numbers 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 where ?

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 cradle-to-grave approach used in this paper. Section 3 describes a scenario where CCS is applied at a large-scale in 2050, that is to avoid 1 GtC of CO₂ emissions. Sections 4 and 5 examine available evidence on fatality rates and their extrapolation in space and time. These rates are multiplied by activity levels from the scenario to obtain expected fatality levels. Section 6 sums up the results, discusses their implications for the risks related to leakage, and compares the expected fatalities of CCS with other energy-related risks including those of climate change.

2. The actuarial approach applied to the CCS risk assessment

In the review by Campos et al. (2010), one of us argued that social research on CCS started by looking at acceptability with a particular concern for factors influencing the public perception of the technology. 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

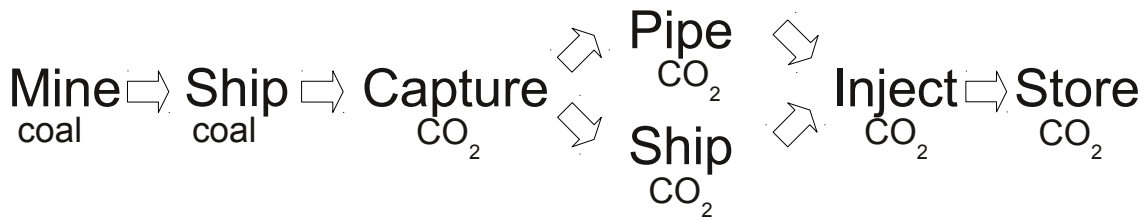


Figure 1: Decomposition of carbon capture and storage in 7 activities.

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., 2009, de Coninck, 2010).

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, based on historical data from analogue industrial activities. This is in the spirit of Benson (2007), but with an integrated approach, since we follow the fossil carbon used for energy generation along its product chain including extraction, production, use and waste. More precisely, we look at expected fatalities worldwide attributable to the large-scale use of CCS in power generation. To this end, we decomposed the CCS mitigation option into the activities described by Figure 1. Activities for injection include site qualification and extension as well as measurement, monitoring, verification. Storage includes post-closure maintenance activities and remediation if necessary. The perimeter of our analysis does not include construction work or power generation itself, as fatalities in these activities cannot be clearly attributed to the use of CCS specifically.

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 integrated approach shows that the largest risks are with mining and delivering more coal and not leakage at storage sites.

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. This contrasts with Trabucchi et al (2010), who also used an integrated approach to analyse CCS risks, but at the project-scale and monetized. 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 CO₂ storage onshore, or to avoid it and incur the costs of offshore CO₂ storage, or to use alternative emission strategies, is a collective choice. There is no pretence that actual climate policy-making is conducted according to purely rational decision making procedures, the problem at hand is too complex for that. 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 on the following dimensions: natural / technical, voluntary / imposed, familiar / unknown.

Several classes of risks associated with CO₂ today are technical, voluntary and familiar to some extent. These include the dangers of industry using CO₂ for enhanced oil recovery (Gale and Davison, 2004), the risks from the use of CO₂ 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 (Foxon et al., 2010, Malone et al., 2010, Terwel et al., 2010). 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 discussed for example in Holloway et al. (2007), volcanism-related CO₂ leaks may not appear psychologically 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 heterogeneous, 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. There are diminishing returns to risk reduction, so spending money to reduce risks makes sense only up to a certain point. Formal examples of rules to determine that point abound in civil engineering, healthcare or even finance law and regulations (Marszal, 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 installations involving industrial quantities of compressed gases.

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

The plausibility of a scenario describing a wide deployment of CCS by 2050 is supported by evidence of 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 with the goals to set-up 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. The technical and geological capacities are large, ranging from 220 to 2 200 GtCO₂ in different stabilisation scenarios according to Metz et al. (2005). As for the economic prospects, it is commonly held that the value of CO₂ will go up while the cost of CCS will go down (Gielen et al., 2004; Torvanger, 2007).

The IEA Technology Roadmap (2009) argues that CCS technology may be a key option to stabilize CO₂ emission. This roadmap's vision of energy supply trends up to 2050 is based

Step		2010	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 by sea for 4 500 Nm, 85% by rail for 500km
Capture	sites	4	15	100	1 500	Intermediate between G8 and IEA estimations 1 GtC emissions avoided, 20% energy penalty, 90% capture efficiency
	Mt	3.1	15	200	4 500	
Transport by pipeline	km	44	50	100	100	For each capture site.
	Mt	3.1	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	7	50	667	15 000	Corresponds to 300 kt CO ₂ /well/yr
Storage	sites	3	15	50	500	From 3 to 30 active injection wells/storage site
	offshore	25%	25%	15%	10%	

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

on results from the IEA ETP BLUE MAP scenario. In this scenario more than 10 GtCO₂ are captured in 2050; the cumulative storage from 2010 to 2050 is 145 GtCO₂; and the power sector is responsible for about half of the CO₂ captured, about 5.5 Gt in 2050.

Table 1 presents our CCS scenario. The core assumption is that CCS is used to mitigate 1 GtC by 2050 in the power sector. Starting from year 2010, two intermediary steps in 2015 and 2025 are presented to provide an idea of the trajectory. These steps are not used in the sequel, as we only look at fatalities in 2050. As nearly all fossil-based power plants will use CCS by 2040 (IEA, 2009), the scenario assumes that the capture of 1 GtC takes place in coal-fired power plants. Focusing on coal is justified also by its relative abundance compared to oil and gas. Shafiee and Topal (2009), 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 CO₂ avoided. Assuming a 20% energy penalty and 90% capture efficiency, this amounts to 4.5 GtCO₂ stored out of 5.00 GtCO₂ generated in 2050 (see numerical details in the electronic supplementary spreadsheet). This is close to the 5.5 GtCO₂ from IEA's vision.

We assume that the additional baseload coal-fired power plants would not have been allowed at all without CCS because of climate concerns. Recent legal developments in Europe (*e. g.* preamble (10) in the European Industrial Emissions Directive adopted 7/7/2010) imply that member states can now legally forbid new coal power plants without

CCS, and the UK (DECC 23/4/2009 statement) announced its intention do to so already. 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 CO₂ / kg coal (Nelson, 2009), so that 2.1 Gt of coal is needed.

In Table 1, the column for the reference year 2010 is based on four existing large-scale CCS operations: the gas processing plants at In Salah, Sleipner, Snøhvit and Shutte Creek. Together they inject 3.1 Mt per CO₂ year (more is capture at Shutte Creek, but sold for EOR), have 7 injection wells and the Snøhvit operation uses a 160km pipeline. These numbers allows to setup the orders of magnitude, but have has no influence on the final results which is solely based on 2050 assumptions.

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 MtCO₂ in 2050, in line with values assumed in the IPCC Special Report (Metz et al., 2005, SPM 19), 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 large quantities of fluids: pipelining and shipping. Both land and undersea pipelines are used. We expect a negligible number of fatalities directly caused by undersea pipelines. Dooley et al. (2009) report the need for 26 900 miles (43 000km) of pipelines in the USA in 2050, in a scenario where the cabon value reaches \$140 tCO₂. In a more conservative CCS scenario, Morbee et al (2010) find 17 859 km of pipeline in Europe in 2050, along with 2 515 km of shiping routes. Neele et al. (2009) find between 21 800 and 32 000 km of backbone CO₂ pipelines may be required in Europe in 2050, depending upon the scenario. In our scenario the network length for the whole world is 150 000 km. Since capture occurs at 1 500 power plants, this amounts to assume that pipeline length per capture plant goes from 44 km in 2010 to 100 km in 2050. This is consistent with what the IPCC Special Report (Metz et al., 2005, TS 2) regarded as a reasonable maximum distance between potential sources and sedimentary basins, 300 km.

Regarding long distance international trade, assumption for sea shipping is based on the mean distance covered by oil tankers today and on a volume of 10% out of the total CO₂ stored in 2050. This percentage is justified because there is a tradition of heavy industry near ports. Big CO₂ 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 CO₂ 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 Schulze (2010), the leading tanking company Maersk already designed CO₂ tankers and, in partnership with TVO and Fortum, is willing to start a project to ship 1.2 Mt of CO₂ 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. Indeed in the Sleipner area of the North Sea, Statoil has been injecting CO₂ in the Utsira formation at about 1Mt per year since 1996 using a single, horizontal well under the sea floor. In the Krechba field under the Algerian desert, In Salah Gas has been injecting about 1 Mt of CO₂ per year since 2004 using three state of the art horizontal wells. The gas processing facility at Shutte Creek, Wyoming uses two injection wells to inject 0.4 Mt of CO₂ per year, in a 40%CO₂ - 60% H₂S mix. The quantity injected annually in the Weyburn and Midale regions of Canada is over 2 Mt per year, using tens of wells for Enhanced Oil Recovery (EOR). Meyer (2007) reports that the US EOR industry injects 0.044 10⁹ t of CO₂ per year in 74 fields, operating about 13.000 wells (about 176 wells per field). The amount injected is 3.38 t per well per year, way below the IPCC estimates. This can be understood because high-injectivity, high-capacity reservoirs like Utsira and Krechba are exceptional, and the economics often favor many simpler vertical wells rather than a few horizontal ones. For these reasons, we consider the sustained injection rates given by IPCC optimistic. In our 2050 scenario we assume that 0.3 Mt of CO₂ per year can be injected in the average well. This corresponds to 15 000 active injection wells in the world, or about 30 wells per site. Even if injection lines are mostly automated, there will be a non negligible amount of activity for maintenance, monitoring, closing and development.

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 MtCO₂/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 2010, is assumed to decrease in the long run to 10% because higher CO₂ prices will favor on-shore sites which were less competitive in the first place. 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, CO₂ capture and transportation

The scenario described in Table 1 specifies the levels of the seven activities illustrated Figure 1 associated with avoiding 1GtC equivalent of CO₂ emissions by using 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 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.

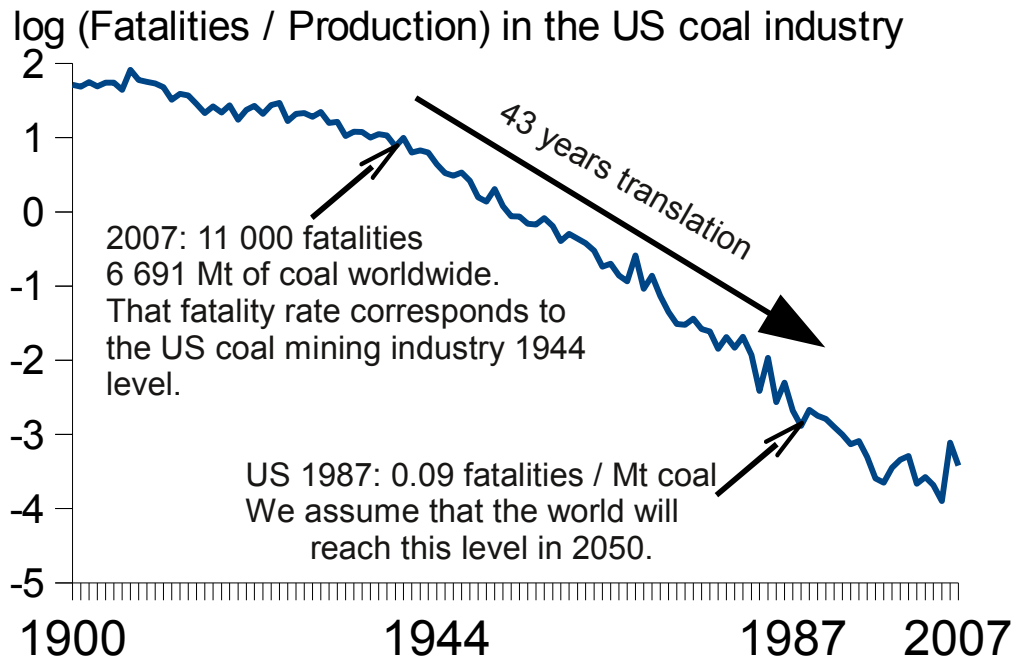


Figure 2: Computation of the world's fatality rate in the coal mining industry in 2050, assuming it follows the same curve as the US coal industry. Sources: [MSHA](#), [EIA](#).

4.1. Coal mining

The scenario analyses the CCS risk in coal-based power plants, that wouldn't be allowed to run without a CCS system. This means that the CCS policy implies more mining. The assumed 1 GtC captured translates into about 2.1 Gt of coal. Mining is a dangerous profession. The frequency and gravity of accidents depend 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 times as much 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) 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 (2010) 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. That 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 progress occurs 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 CO₂ is ruptured or overheated, there is a risk of boiling liquid expanding vapour 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 CO₂ capture is subject to the guidelines applied to the petrochemical industry and that the CO₂ capture and compression installations are often listed as gas-processing facilities.

Industrial applications of CO₂ 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 MtCO₂/year. Khan and Abbasi (1999)'s database of the major accidents in chemical industries records two accidents with CO₂ 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/MtCO₂.

To avoid emitting one gigaton of carbon in 2050, this scenario assumes that 4.5 GtCO₂ will have to be handled by capture processes. 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. At the scenario's 1 500 capture sites, the additional population at risk is 7 500 to 15 000 workers. This suggests between $3 / 100 \cdot 7.5 \approx 0.22$ and $14 / 100 \cdot 15 \approx 2.1$ expected fatalities in 2050.

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. CO₂ pipelines

Pipelining safety will be discussed in three steps. First, data from the North American CO₂ 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 USA and Europe. Finally, analogy and extrapolation in time and space will be discussed.

A network of CO₂ transportation pipelines exists in the US oil producing region. This CO₂ 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 CO₂ 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 (2004)'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 year per million km of pipelines. The rightmost column shows that no fatalities caused by CO₂ 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 CO₂, 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 CO₂ 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 Homogeneous Poisson Process (NIST/Sematech e-handbook, 2010). Assume that fatal accidents occur at a constant rate λ per year per million km of pipeline. Then the probability of observing no fatal accident in the CO₂ 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 year per million km 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 per year per million km. And the network sizes and observations period are much larger, so assuming that fatalities occur following the Poisson process, the 95% confidence interval for these numbers are 4.0-6.6 and 6.6-11.5 respectively. This is however a technical simplification, since actually fatalities tend to occur in events involving multiple victims.

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 per year per million km (95% confidence interval: 7.7-23.5).

Because there is comparatively so little experience from CO₂ 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 CO₂ pipelines recorded in the US database, we do not have enough observations to compare statistically the lethality of CO₂ 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. Creating safety zones may be possible in theory around new capture and injection sites. This is more difficult for pipelines, which extend for kilometres. Demonstration projects in Lacq (France), Le Havre (France) and Barendrecht (The Netherlands) highlight the practical relevance of the population density parameter in the old continent.

On average, CCS may require a pipeline infrastructure from power plants to storage sites through regions more densely populated than Texas. An indicative map of a possible trans-European CO₂ network in European Union can be seen in Morbee et al. (2010). Based on an optimization tool minimizing the transport cost, they stand that by 2030, about 16 European Union Member States would be involved in cross-border CO₂ transport where countries do not have adequate CO₂ storage potential. In our scenario, we stress out the specificity of the CO₂ pipeline network compared to gas and oil, since several emitting source would store the carbon in the same sink. Thus industrial and power plants would use the same storage location, even if they are not located in the same area.

In summary, for various fluids and developed regions, confidence intervals based on empirical data yield 4 to 24 fatalities per year per million 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, due to different safety standards and maintenance operations. For a comparative analysis between OCDE and non-OCDE countries, see Burgherr and Hirschberg (2008).

For these reasons, it would seem over-optimistic to assume that the world's average in 2050 will be 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 per year per million km as an upper bound, and 5 as a lower bound.

The scenario has 150 000 km of CO₂ pipelines. Applying these rates suggest an interval from 0.75 to 7.5 deaths in 2050.

4.4. Shipping CO₂

While shipping is comparatively a safe mode of transportation, moving large quantities of CO₂ 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 $\text{Tt}^{-1} \text{Nm}^{-1} \text{yr}^{-1}$, that is per year per tera (10^{12}) tons nautical miles of cargo (1 Nm = 1852 m). 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 (2005a, 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 $\text{Tt}^{-1} \text{Nm}^{-1} \text{yr}^{-1}$. 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 $\text{Tt}^{-1} \text{Nm}^{-1} \text{yr}^{-1}$.

Regarding all goods trade, for the period 1989-2004 the IMO (2005b, p. 29) 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 $\text{Tt}^{-1} \text{Nm}^{-1} \text{yr}^{-1}$ 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 $\text{Tt}^{-1} \text{Nm}^{-1} \text{yr}^{-1}$.

The scenario ships about 2.2 Tt Nm of CO₂ in 2050. Using the extrapolated rates to account for the progress of safety over time, the expected fatality numbers are 6.6 and 24.6 respectively.

4.5. Coal transportation

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. 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.

We assume that 85% of the coal mined, that is 1.79 Gt, is transported by railroad. With a unit train capacity in the order of 10 000 t, this amounts to 179 000 train trips, or 119 per power plant per year. Assuming that the average trip is 500 km, the total level of railroad activity is 89 millions of train km in our scenario.

Excluding suicides and trespassers who legally bear the responsibility of their demise, fatal accidents with railroad most frequently occur at level crossings. Risk rates are usually measured by million of train-km. The Common Safety Targets of the European Railway Agency (2009) are 0.63 fatalities per million of train km, while the 2001 statistic in the USA was 0.91 fatalities per million of train km (Federal Railroad Administration, 2011). We extrapolate that these levels will be relevant for the world average, in 2050. This implies 56 to 81 expected fatalities per year.

5. Expected fatalities at CO₂ injection and storage sites

After discussing injection, fatalities rates associated with CO₂ 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 $3 \cdot 10^{-4}$ per well year (Duncan et al., 2009). Aines et al. (2009) lists six CO₂ blowouts in the oil and energy extraction industries. Holloway et al (2007, section 4) describe two cases of well blowout involving respectively a CO₂ production well in Sheep Mountain, USA and a CO₂-rich mineral water production well in Florina, Greece. Meyer (2007) found that when current technologies and practices are used, EOR operators injecting CO₂ can expect well-bore integrity equivalent to those seen for conventional oil and gas wells. Additionally, there is no indication from available information that geologic integrity of the receiving formations are at risk. 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 CO₂ injection step are analogue to the average risks in the oil and gas industry as a whole, because the techniques to operate a platform or an onshore industrial compound dedicated to CO₂ injection are well known and typical of this industry.

Fatalities per 100 000 workers US oil and gas extraction industry

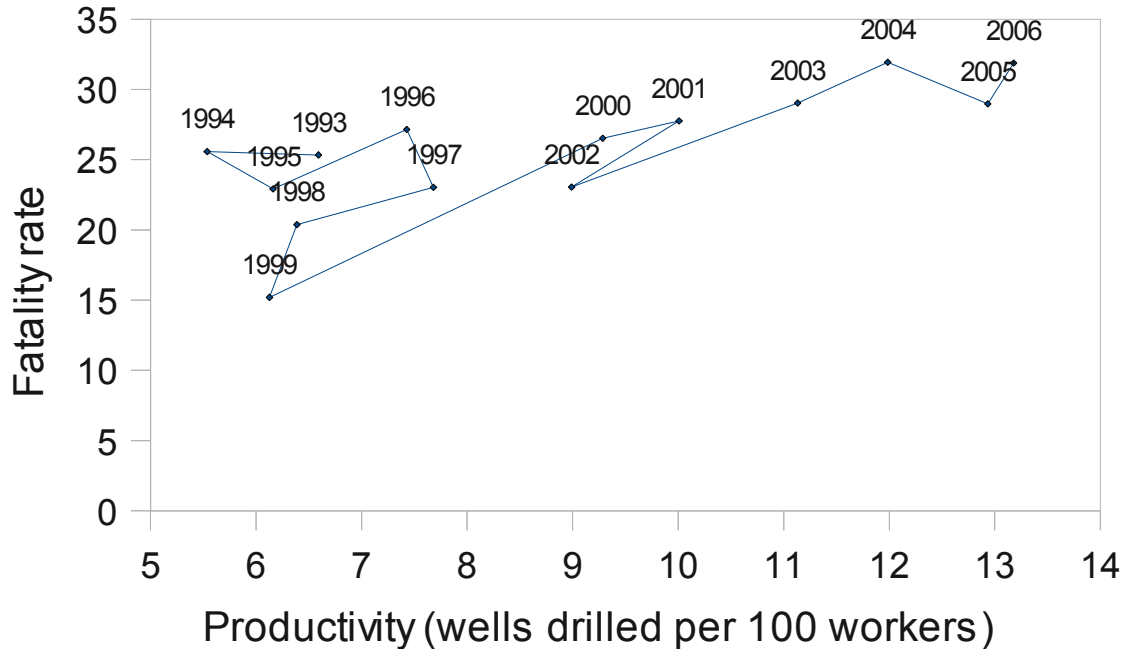


Figure 3: The fatality rate in US oil and gas industry and the sector's productivity both increased from 1993 to 2007. The regression line is $FAR = 13.2 + 147 \text{ Wells/Workers}$. Source: Centers for Disease Control and Prevention. 2008. *Fatalities Among Oil and Gas Extraction Workers --- United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

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 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 our scenario, there are 500 storage sites operating in 2050. To compute the number of workers in the injection industry, we assume that each site has 10 to 30 full time employees and multiply. This assumption can be empirically justified from two points of view.

First, each site stores for 3 capture sources on average, about 8.8 MtCO₂ per year using 30 wells. Since most storage sites are developed over the 2025 to 2050 time period, that is 25

years, there is more than one new injection well per year. Figure 2 shows that in the US Oil and Gas industry it takes 7.7 to 18 workers-year to drill one well. This justifies why while injection itself is mostly automated, performing real-time monitoring, development, closure and maintenance work would need 10-30 persons per site.

Second, according to their respective annual reports top-tier oilfield services companies (Schlumberger, Haliburton, Baker Hughes, Weatherford International, CGGVeritas) generated in 2009 an operating revenue per employee in the 156 000 - 352 000 USD range. If one assumes that the injection fee charged for operating a CO₂ field is 50 cents per ton, then the revenue generated from an 8.8 Mt yr⁻¹ injection field is 4.4 millions of USD, which corresponds to 13 - 28 employees.

Over 500 sites, there would be a total of 5 000 to 15 000 workers. At the assumed fatality rate, 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 CO₂ 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, $8.36 \cdot 10^6$ m³, or 4.2 kt of CO₂ per day, had lethal consequences in an aerial extend of 11.6 km². This extend is larger than the results of Aines et al. (2009) plume dispersion simulations, who found that in a worst case scenario (low wind day, maximal release of 225 kg/sec) the maximum extent for TEEL level 2 (serious harm) is 374 meters from the well head. On the other hand, Saripalli's result is smaller than the Lake Nyos event, that involved 1 240 kt of CO₂ (Holloway et al, 2007), a quantity 295 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. suggested that the risk of leakage through existing wells is small in front of the risk of leakage through the cap rock, but the IEA (2008, p.125, chap. 5) wrote that the most prevalent risk is the migration of CO₂ within well bores. Saripalli et al. argue that no serious incident occurred in the US and Canadian natural gas storage industry. But in Chemery,

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 CO₂ storage risks, with *our reinterpretation of the consequences index in terms of expected fatalities.

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 et al. (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 CO₂ 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 well 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 CO₂-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, CI: $5 \cdot 10^{-4}$ 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 CO₂ 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 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 CO₂ storage will be allowed.

5.3. Normative approaches for storage risks

Assuming that storage occurs necessarily implies that the regulators will authorize a non-zero level of risk. There are various approaches for societies to determine the risk level at which CO₂ storage systems will be allowed to perform.

According to the UK Health and Safety Executive guidelines (Berry, 2006), in situations where the work activity is unusual (i.e. good practice is not yet established), duty-holders 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.

We argue that the ALARP criterion could apply at the local scale, but does not constrain risk at the global scale. Consider the situation where each of the 500 sites has one accident per year as large as Saripalli et al.’s (2003) complete blowout case: a release of 20 kt of CO₂ or about 10^7 m³. This would obviously not be ALARP at the local scale. Yet globally, this would be only 10 Mt of CO₂ per year back to the atmosphere. In the scenario the cumulative quantity of CO₂ stored by 2050 is about 100 Gt, so the leakage fraction would be about 10^{-4} . Ha-Duong and Keith (2003) has shown that cost-benefit analysis offers little support for further reduction of the average leakage ratio below this 10^{-4} , because of time discounting. So the situation would be ALARP from a global point of view. This suggests that only local risk constraints have to be looked at.

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 and Gerard (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, in the 5 to 9 years age group 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 CO₂ 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 MtCO₂ 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 near 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 regulation on industrial risks provides an explicit (probability, consequence) table stating when an installation may be seen as “compatible with its environment”. For example, given 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 and annex 6, p. 130, table 40). 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 and Rigg (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 0.045 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.

5.4. Actuarial estimates of risks at social analogues

CO₂ storage requires a permit to operate, but sites are not regulated by the SEVESO II directive in Europe. This suggests that on the one hand, an underground CO₂ storage is considered less risky than an industrial facility holding large amount of dangerous chemicals by European regulations. 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.

European 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, the source notes that it is likely that Member States are not homogeneous in reporting accidents which means that underreporting is an issue. Haastrup and Romer (1995) found out that this kind of databases typically recorded only 20 to 45% of the fatal accidents.

For an earlier period, when European Union was smaller and more homogeneous, Haastrup and Romer (1995) find 14 fatal accidents per year with 1 860 sites. Using the average of 2.3 victims per accident, this suggests $17 \cdot 10^{-3}$ fatalities per year per establishment. This 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 CO₂. 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 base-load coal-fired power plants scenario in 2050 is about 5 GtCO₂ generated, 4.5 Gt captured and stored, 1 500 capture sites, 150 000 km of CO₂ pipelines, 2.25 billion ton nautical miles of CO₂ shipped, 15 000 active injection wells and 500 storage sites, with only 50 offshore. Fatalities attributable to CCS also include those

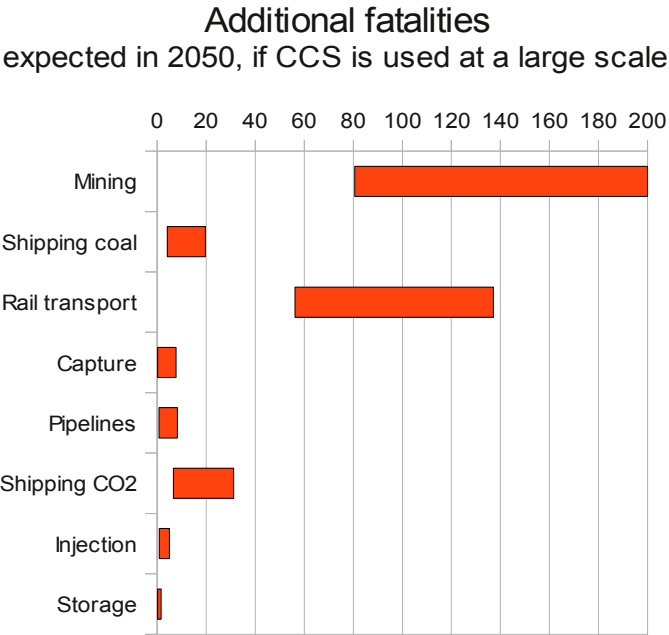
related to mining 2.1 Gt of coal in 2050, and its transportation to the power plants, sea shipping for 1.42 billion ton nautical miles and rail-road transport for 89 million train-km.

Table 4 and Figure 4 sum up the results. Between 150 and 338 fatalities per year can be expected due to one GtC 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 delivering it to the power plants by train or boat, then shipping CO₂. 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 CO₂ 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 many developed 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

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.

CCS 2050 scenario definition	Past evidence on analogue risk	Extrapolation, 2050 world avg.	Expected fatalities in 2050
Additional activities required to avoid 1 GtC of emissions by using CCS at coal-fired power plants. (Unit: activity level for the industry)	Annual expected fatalities per activity unit	Annual expected fatalities per activity unit	
Mine coal, 2.1 Gt	11,000 fatalities for 6.7 Gt mined that is 1.6 fatalities Mt-1	0.04 to 0.09 per Mt (catching up US safety levels)	81 to 196
Ship coal, 15% of the production for 4,500 Nm average trip, that is 1.42 billion tons nautical miles	11.4 fatality Tt-1 Nm-1 (oil tanking) 28.6 fatality T-1 Nm-1 (all goods trade)	2.9 to 10.9 per Tt Nm (assuming safety improvement slows down)	4.2 to 15
Transport coal by rail, 85% of production, 500km average trip, that is 89.3 million train-km	excluding trespassers & suicides, 0.63 fatalities (european target) to 0.91 (USA, 2001) per million train km	0.63 to 0.91 (same as today)	56 to 81
Workers for CO ₂ capture, 7 500 to 15 000 (at 1 500 sites)	3 to 14 per 10 ⁵ workers (utilities industry, rich countries)	3 to 14 per 10 ⁵ workers (same as historical rate)	0.2 to 2.1
Industrial processes for CO ₂ capture, 4.5 G (20% energy penalty, 90% capture efficiency)	12 deaths in 2 accidents over 1926-1997, that is 1.7 fatalities Gt-1	1.7 per Gt (same as historical rate)	7.5
Operate CO ₂ pipelines, 0.15 Mkm	7.7-23.5 (European oil pipelines) 4.0-6.6 (US nat. gas transmission) 6.6-11.5 (US hasardous liquids) less than 24 (US CO ₂ pipelines)	5 per Mkm (safest analogue today) 50 per Mkm (worst case assumption)	0.8 7.5
Ship CO ₂ , 2.2 billion tons nautical miles (10% of total captured)	same as coal shipping	same as coal shipping	6.6 to 25
Workers for injection, 5 000 to 15 000 to maintain, develop and monitor 500 sites	15 to 33 per 10 ⁵ workers (US oil & gas, 1993-2007)	20 to 30 per 10 ⁵ workers	0.9 to 4.1
Exposing 2.5 · 10 ⁵ to 10 ⁶ persons to a diffuse environmental risk	Minimum individual risk of dying is 10 ⁻⁴ per year (Females aged 5-10, western Europe)	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)	3 · 10 ⁻³ per site	1.4
Total			150 to 338

Table 4: Summary of results: Expected fatalities in 2050 for a 1 GtC of CO₂ emissions avoided scenario. Note: There are two alternative methods for the Capture and for the Storage step (fifth and ninth rows).

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.

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 leakage 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, 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 CO₂ 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 (Slovic, 1986; Singleton et al., 2009). 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, 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, well under 20 persons / km² on average. 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 options, 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 (Murray et Lopez ed., 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 mitigation technologies would save several tens of thousands of lives in 2050. Being an important part of these abatement options --one fifth of the lowest-cost reduction solutions in 2050 according to IEA (2009)-- the CCS technology 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.

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Highlights

- We expect a few hundred fatalities / year could be attributed to CCS in 2050.
- Most of these fatalities would come from mining more coal and delivering it.
- CCS dangers would be mostly technical, knowable and occupational.
- We look at socially acceptable risk levels today for industrial hazards.
- A perfect record of early storage demonstration projects is statistically critical.

Additional fatalities
expected in 2050, if CCS is used at a large scale

