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GHGT-11 oral communication on"Actuarial assessment of fatalities attributable to CCS in 2050"

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Abstract

We estimated 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 3.67 $GtCO_2$ 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 CO_2 storage demonstration projects over the next 20 years have to cause exactly zero fatality.

1. Introduction

No technology is risk-free. CCS risks have been previously discussed according to diverse points of view, accounting for various technical, economic, environmental, human and social aspects. Economically, the key uncertainty is the difference between the value of carbon and the cost of capture. From the engineering, psychological or climatic point of view, one of the main hazards is leakage, the risk that some of the CO_2 escapes from where it is stored.. Our study [1] takes one of the simplest viewpoints on the risks of any activity: "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 implies 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 some 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 in the technological chain ?

We used an actuarial cradle-to-grave approach (Figure 1), in a scenario where CCS is applied at a large-scale in 2050, that is to avoid 3.67 Gt of CO_2 emissions (1 Gt of carbon). Empirical evidence on fatality rates, extrapolated in space and time, were multiplied by activity levels from the scenario to obtain expected fatality levels.

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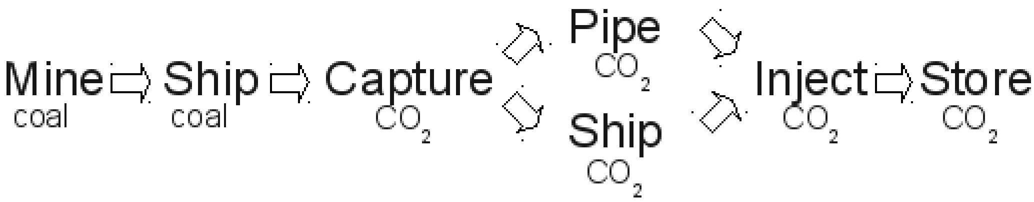

Figure 1. Decomposition of carbon capture and storage in 7 activities.

2. A scenario to avoid 3.67 GtCO2 emissions in 2050 using CCS

Table 1 presents our CCS scenario. The core assumption is that CCS is used to mitigate 3.67 GtCO2 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 [2], the scenario assumes that the capture of 3.67 GtCO2 takes place in coal-fired power plants. Focusing on coal is justified also by its relative abundance compared to conventional oil and gas.

The right column in Table 1 summarizes the scenario's assumptions. The mitigation of 3.67 GtCO2 avoided corresponds to reducing human emissions by 1 Gt of carbon. 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 [9].

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

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 MtCO2 per year (more is captured 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 [3] from 200 sites in 2025 to 3 000 in 2050, and the lower estimates of the G8+3 group, 600 sites in 2030 [4]. This implies that each site captures on average 3 MtCO2 in 2050, in line with values assumed in the IPCC Special Report [5, SPM 19], from 1 to 5 MtCO2/site in 2100, and with the operational specifications of a typical medium-to-large coal-based power plant.

There are two ways to transport large quantities of fluid: pipelining and shipping. Both land and undersea pipelines are used. We expect a negligible number of fatalities directly caused by undersea pipelines. [6] report the need for 26 900 miles (43 000km) of pipelines in the USA in 2050, in a scenario where the carbon value reaches $140/tCO2. In a more conservative CCS scenario, [7] find 17 859 km of pipeline in Europe in 2050, along with 2 515 km of shiping routes. 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 [5] 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 captured 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 MtCO2 in 2025 and 450 MtCO2 in 2050.

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 MtCO2 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 1 MtCO2 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 MtCO2 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 MtCO2 per year, in a 40%CO2 - 60% H2S mix. The quantity injected annualy in the Weyburn and Midale regions of Canada is over 2 MtCO2 per year, using tens of wells for Enhanced Oil Recovery (EOR). [8] reports that the US EOR industry injects 44 MtCO2 per year in 74 fields, operating about 13 000 wells (that is 176 wells per field). The amount injected is 3.38 ktCO2 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 EOR 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 MtCO2 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.

Step		**2010**	**2015**	**2025**	**2050**	**Assumptions**
Coal Mining	Mt coal	0	20	140	2 100	Additional coal allowed by CCS Coal's carbon content 2.38 kg CO_2/kg coal 15% 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
	Mt CO_2	3.1	15	200	4 500	3.67 $GtCO_2$ emissions avoided (= 1 GtC) 20% energy penalty, 90% capture efficiency
Transport by pipeline	km	44	50	100	100	For each capture site.
	Mt CO_2	3.1	15	190	4 050	About 90% of quantity captured.
Transport by ship	miles	0	0	5.000	5 000	Average distance
	Mt CO_2	0	0	10	450	About 10% of quantity captured.
Injection	wells	7	50	667	15 000	Corresponds to 300 $ktCO_2$/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 3.67 GtCO2 emissions in 2050 by using CCS at 1 500 baseload coal-fired power plants.

3. Fatality rates in coal extraction, CO2 capture and transportation

The scenario described in Table 1 specifies the levels of the seven activities (see Figure 1) associated with avoiding 3.67 GtCO2 emissions by using CCS in coal-based power plants. These activity levels were 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. Our extrapolated fatality rates are summarized in Table 2, column 3. There is no space here to discuss the methods and models, see [1] for a detailed discussion including data sources and the spreadsheet as an electronic supplement.

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 option implies more mining. The assumed 4.5 GtCO2 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, even though the former produced only 2.5 times as much coal than the later in 2006.

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. [9] mentions 11 000 deaths in 2007 worldwide for an overall production of 6.7 Gt mined, an average rate of 1.64 fatalities per Mt of coal. We extrapolated fatality rates for 2050 using the technological progress observed in the USA and other assumptions [1], to a global average rate of 0.038 - 0.094 deaths/Mt coal in 2050. 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.

Carbon Capture

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

Firstly, we consider accidents from the actual industrial use of carbon dioxide. [5] estimated the flux to about 115 MtCO2/year. [10] 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 captured. Wild extrapolation reusing the historical rate suggests to look at 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, from 3 to 14 recorded deaths/year/100 000 workers in developped countries. We assume that on each site, 5 to 10 workers workforce will be exposed to the risks of capture. 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 0.22 and 2.1

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

CO2 pipelines

Based on statistics for various fluids in developed regions such as [11], confidence intervals for pipeline fatalities risks 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 [11]. On the other hand, risks may be higher in developing countries, due to different safety standards and maintenance operations. We assessed that 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.

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. 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 (1 Nm = 1852 m). We estimate that the tanking industry shipped an average of 8 258 Gt Nm of oil (crude+products) per year at a fatality rate is 11.7 deaths Tt^{-1} Nm^{-1} yr^{-1} . 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} . Similar computations based on the all goods trade shipping, rather than just tanking, yields 10.9 fatalities Tt^{-1} Nm^{-1} yr^{-1} . in 2050. 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.

Coal transportation

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 is 0.63 fatalities per million of train km, while the 2001 statistic in the USA was 0.91 fatalities per million of train km. We extrapolate that these levels will be relevant for the world average, in 2050. This implies 56 to 81 expected fatalities per year.

4. 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.

Injection

In our scenario, 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 drilling of more than one new well per year per injection site. In the US Oil and Gas industry it takes 7.7 to 18 workers-year to drill one well. While injection itself is mostly automated, performing real-time monitoring, development, closure and maintenance work would need 10-30 persons per site. Over 500 sites, there would be a total of 5 000 to 15 000 workers.

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 operate a platform or an onshore industrial compound dedicated to CO_2 injection are well known and typical of this industry. The fatality rate in this industry is between 15 to 33 deaths per year per 100 000 workers. At this assumed fatality rate, the expected number of fatalities is between 1 and 4.5 per year.

Engineering estimates of storage risks

We found 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.

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 [1], here we discuss only the Minimum Endogeneous Mortality (MEM).

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? [12] suggest that the answer should be expressed in a new unit, the micromort, which is a one in a million 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. Thus, practically everybody is above 100 micromorts. Therefore, we can argue 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.

The 10 MtCO2 plume at Sleipner is 3.6 km long by 1 km wide, a large CO2 storage may easily impact from 25 to 100 km^2 (5 by 5 to 10 by 10 km),. The worldwide density over land was about 50 persons/km^2 in 2007 and it may grow up to 70 by 2050. But assuming that avoiding populated areas will be a primary criterion for site selection, we assume that the density over storage sites is only 20 persons/km^2. This implies that 500 to 2 000 persons may live near each 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.

Actuarial estimates of risks at social analogues

The Directive 2009/31/EC of the European Parliament and the Council (2009) states that CO2 storage sites shall require a permit to operate, but does not regulate them as strongly as the SEVESO II directive. 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.

In Europe, industrial facilities holding large quantities of dangerous substances are regulated by the directive 2003/105/EC. We observed frequencies of 0.002 fatalities per year in France and 0.001 in Europe. We conjecture that this lower estimate arise because underreporting was lower in France than in Europe on average. For an earlier period, when European Union was smaller and more homogeneous thus less prone to underreporting, [13] find 14 fatal accidents per year with 1 860 sites. Using the average number of 2.3 victims per accident, this suggests 0.017 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 0.01 fatality per year per Seveso site in Europe.

In France, buildings presenting an environmental risk fall under the Installations Classified for Environmental Protection (ICPE) laws. ICPE includes factories, feedlots, warehouses, mines, dry-cleaning shops and many other facilities. In 2008, France counted about 500 000 of those. Over the last 17 years, [14] 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. Assuming that the average society in 2050 will be less risk averse than Europe now and allow for a risk three times as large as that, for 450 sites this amounts to 1.4 statistical fatalities per year globally.

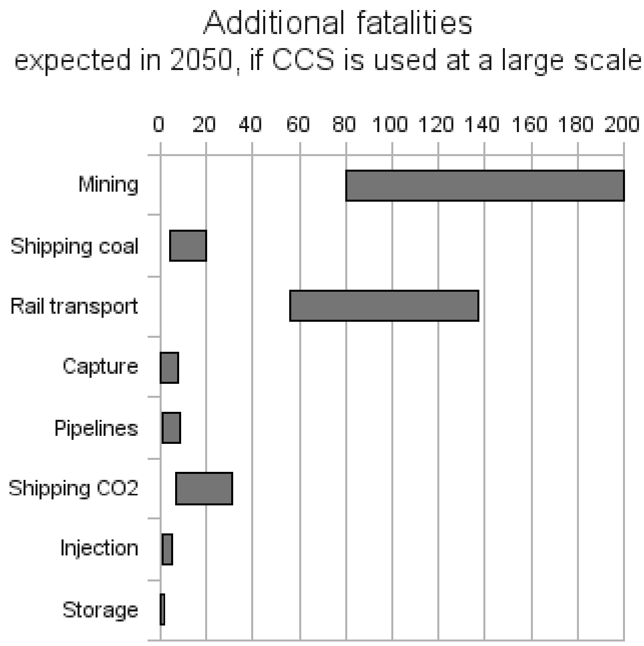

Figure 2: Result summary: Actuarial estimates of the human cost of 3.67 GtCO2 emissions mitigation by using carbon capture and storage at 1500 baseload coal fired power plants.

5. Results summary

Our scenario for CCS at base-load coal-fired power plants in 2050 amounts to 5 $GtCO_2$ generated, 4.5 $GtCO_2$ captured and stored, 1 500 capture sites, 150 000 km of CO_2 pipelines, 2.25 billion ton nautical miles of CO_2 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.

We find that.between 150 and 338 fatalities per year can be expected due to 3.67 $GtCO_2$ 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 CO_2. Miners, sailors and workers are more at risk than the general public.

CCS 2050 scenario definition Additional activities required to avoid 1 GtC of emissions by using CCS at coal-fired power plants. (Unit: activity level for the industry)	Past evidence on analogue risk Annual expected fatalities per activity unit	Extrapolation, 2050 world avg. Annual expected fatalities per activity unit	Expected fatalities in 2050
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, 500 km average trip, that is 89.3 million train-km	0.63 fatalities (european target) to 0.91 (USA, 2011) per million train km excluding trespassers & suicides	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	1 to 4.5
Exposing $2.5{\cdot}10^5$ 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 2. Summary of results: Expected fatalities in 2050 for a 3.67 GtCO2 avoided mitigation scenario. Note: There are two alternative methods for the Capture and for the Storage step (fifth and nineth rows).

6. Conclusion

Site specificity of the leakage risk implies that this part of the uncertainty is not aleatory, but voluntary. Thus, we did not attempt to draw quantitative conclusions from the engineering storage risk assessment literature, but from social analogues. 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 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} fatalities per year par storage site.

The actuarial approach complements most other published engineering or social risk analysis: regarding objectively expected fatalities, the risk of leakage is the least important. However, realist approaches to risk analysis do not account for the public's view and higher order impacts. Actuarially, the expected number of fatalities for storage appears two orders of magnitude lower than corresponding number in mining. Yet psychological effects when comparing risks are known to be as high as three orders of magnitude. This explains why most assessments about the social perception of CCS show that concerns about risks, especially storage leakage risks, are a priority.

Yet managing risk perception is no substitute for rational policy in the decision-making process. 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 will 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 capture, transport and storage is not so exceptional.

The current presumption seems to be that storage implies medium-risk installations, that is one expected fatality in 1000 years of storage. Using quality management statistical models, 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 [15]: 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.

Acknowledgements: see [1]

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