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

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Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »
Defines the « wedge of CCS at baseload coal power plants » scenario and summarizes its expected fatalities

Blue cells: Numerical assumptions defining the scenario

Scenario parameters : Coal needed for the wedge of CSC at baseload coal plants

1	Gt C emissions avoided
3,67	Gt CO2 emissions avoided A
4,17	Gt CO2 baseline B =A / a
5,00	Gt CO2 generated G = g B
4,50	Gt CO2 stored S = s B

20%	Energy penalty = p
90%	Capture efficiency = e

2,38	t CO2 generated by t of coal (bituminous grade)

2050	2,101 Gt of coal consumed in 2050
2025	0,879
2015	0,391
2007	

Carbon dioxide emissions and coal types

Source: http://www.ccsd.biz/PSE_Handbook/5/3/

Coal Types	*Specific Energy(a) MJ/kg*	*Carbon Content (b) gC/MJ*	*CO2 emissions* *kgCO2/MJ*	*kgCO2/kg coal*
Lignite	9,3	27,6	0,10	0,93
Sub bituminou	18,1	26,2	0,10	1,72
Bituminous	25,4	25,8	0,09	2,38

a) IEA Coal online b) IPCC 1996

Scenario parameters : Capture

1500		Total number of capture sites in our Wedge scenario.
5	10	Workers exposed to the risk at each capture site. Range representing « a fraction of the workforce of a modern coal power plant ».
7500	15000	Workers on capture sites

Scenario parameters : Shipping

Coal	**CO2**	
15%	10%	Fraction shipped
0,32	0,45	Quantity shipped, Gt in 2050
4500	5000	Average trip, Nm
1,42	2,25	Transport, Tt Nm in 2050

Scenario parameters : Pipeline CO2

90% Fraction pipelined (= not shipped)

Year	km	Mt
2007	1	3
2015	50	15
2025	100	190
2050	100	4050

Scenario parameters : Injection and storage

15000	Injection wells
500	Storage sites
90%	onshore
450	Onshore storage sites
30	Active injection wells at each site
0,30	Mt injected per well

Year	Sites	Wells	Wells/site	Mt Injection	kt CO2/yr Inject/well
2007	3	12	4	3	250
2015	15	50	3,33	15	300
2025	50	667	13,33	200	300
2050	500	15000	30	4500	300

10	30	Full time workers per site for operation, monitoring, development, maintenance...
5000	15000	Workers on injection sites

Scenario parameters : population over storage

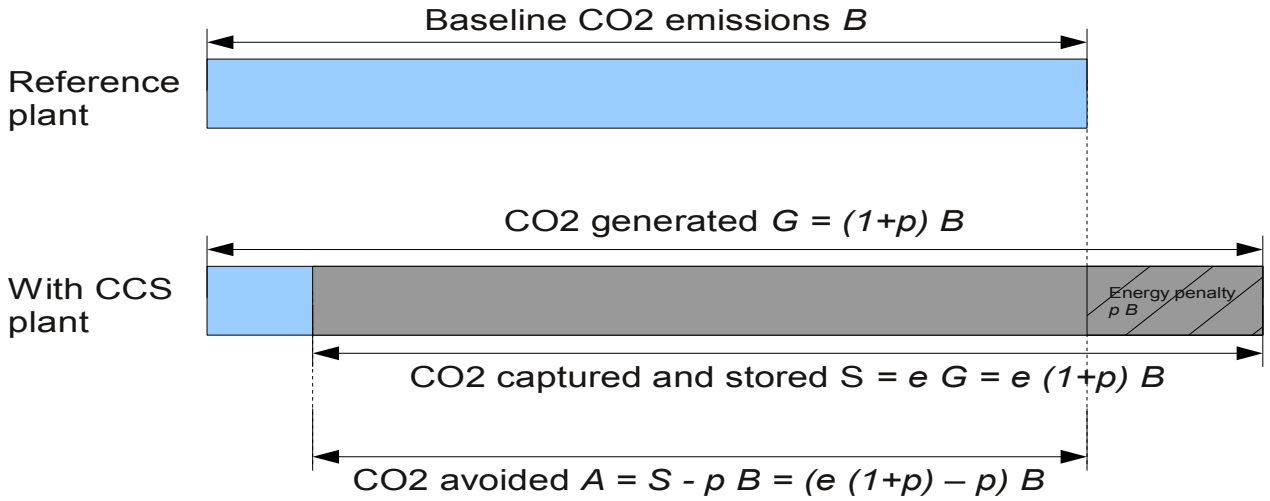
25	100	km² footprint of a storage site
20	20	Inhabitants / km² over storage sites
500	2000	Inhabitants in the footprint zone
225000	900000	Persons exposed to storage sites, worldwide

Mathematical note on CCS and CO2 accounting

Graphically explained by the figure below, based on Figure RID 2 in IPCC SRCCS
The baseline is defined as the nominal capacity of the reference coal plant, without CCS

Knowing e and p, we have:

120% Generation relative to baseline g = 1 + p
108% Fraction captured (and stored) compared to baseline s = e g = e (1 + p)
88% Fraction avoided compared to baseline a = s – p = e (1 + p) – p



Wedge

Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »
This spreadsheet computes global expected fatalities in the mining industry due to the fact that CCS allows the use of coal.

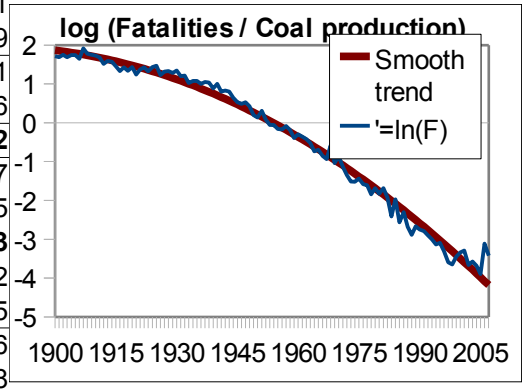
Historical stats for the US coal mining industry

Source (a) http://www.msha.gov/stats/centurystats/coalstats.asp
Source (b) http://www.eia.doe.gov/cneaf/coal/page/fig1_us_historical_production_bar_chart.xls

t	Year	Source (a) Miners	Source (a) Fatalities	Source (b) Coal_Prod_Mt	=D/E FAR_US	'=ln(F) log_FAR_US	Smooth trend a + b t + c t²
1	1900	448,58	1489	268	5,55	1,71	1,86
2	1901	485,54	1574	292	5,40	1,69	1,85
3	1902	518,2	1724	300	5,74	1,75	1,84
4	1903	566,26	1926	356	5,42	1,69	1,82
5	1904	593,69	1995	350	5,70	1,74	1,81
6	1905	626,05	2232	391	5,71	1,74	1,79
34	1933	523,18	1064	383	2,78	1,02	1
35	1934	566,43	1226	417	2,94	1,08	0,96
45	1944	453,94	1298	683	**1,90**	0,64	**0,52**
86	1985	197,05	68	884	0,08	-2,56	-2,17
87	1986	185,17	89	890	0,10	-2,3	-2,25
88	1987	172,78	63	919	**0,0686**	**-2,68**	**-2,33**
89	1988	166,28	53	946	0,06	-2,88	-2,42
90	1989	164,93	68	981	0,07	-2,67	-2,5
93	1992	153,13	55	998	0,06	-2,9	-2,76
106	2005	116,44	23	1131	0,02	-3,9	-3,98
107	2006	122,98	47	1055	0,04	-3,11	-4,08
108	2007	122,94	34	1039	0,03	-3,42	-4,18

OLS estimation of log (fatalities/production)

const	1,8741	a
time	-0,0116	b
timesq	-0,0004	c



The global coal industry in: 2007

Fatalities	11000	Source: Drexler et al. (2008) ICEM report on research, activities and developments, page 20
Production (Mt)	6691,05	Source: http://www.iea.org/Textbase/stats/cealdata.asp?COUNTRY_CODE=29&Submit=Submit
F/C	1,64	This is the global fatality rate today
ln (F/C)	0,497	
time index	45,42	(Positive t solution of ln(F/C) = a + b t +c t²) (the other root is: -73,73)
	1944	Year in which USA was at this fatality rate

Extrapolation of the global average coal mining fatality rate to 2050

Assumption (A): The global coal industry fatality rate per Mt converges to the rate recorded in the USA, averaged over 1990-2007

F/C	**0,0383**	

Assumption (B): The global coal industry fatality rate per Mt declines along the same historical curve as the USA

Target year:	2050	
Years later:	43	
Time index	88,42	
	1987	Year for which we lookup the USA fatality rate
Adjusted value	-2,37	The log fatality rate at this time index, using the smoothed curve
F/C	**0,09351**	The result: global coal mining industry fatality rate for 2050

Summary results table : expected fatalities from coal mining

Coal mined Gt (scenario)	Fatality rate per Mt mined	Expected fatalities In 2050	
2,1	0,0383	81	Convergence to USA 1990-2007
2,1	0,0935	196	Safety progress follows the USA curve

Engineering consistency check about the incremental quantity of coal

According to engineer Nhan T. Nguyen (pers. Com.)
for a future (2021) High Efficiency (45%) IGCC power plant

500	MW coal-based power plant needs	1,08 Mt bituminous coal
	Proportionality suggests that	
800	GW that correspond to one CCS wedge would need	1731,2 Mt bituminous coal
	According to the table above, this would emit	4,12 Gt CO2

Another view	920	kg CO2 / Mwh in 1997, Annex II countries	(source : Marion et al. CONTROLLING POWER PLANT CO2 EMISSIONS: A LONG RANGE VIEW)
	8760	h/yr	
	8059200	kg CO2 / MW / yr for a baseload plant	
	500	MW plant capacity	
	4,03E+006	t CO2/yr (divide by 1000 for kg to t)	A 500MW average plant emits 4 Mt CO2 per year

Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »
This spreadsheet provides evidence to support the coal shipping scenario assumptions (see Shipping CO2 sheet for fatalities estimates).

How much coal is shipped in international trade ?

Total global production (Mt) Source: http://www.worldcoal.org/resources/coal-statistics/

	Hard coal	Brown coal/Lignite
2008e	5848	951
2007	5442	956
2006	5205	914
2005	4934	906
2004	4629	879
2003	4231	893
1996	3734	
1990	3489	
1981	2796	
1980	2805	

Approx. 13% of hard coal production (717 Mt) is used by the steel industry

International Hard Coal Trade (Mt) Source IEA - www.iea.org

	Steam	Coking	Total Trade	Share of trade	By ship
2008	676	262	938	16%	
2007	670	247	917	17%	
2006	593	222	815	16%	15%
2005	548	227	775	16%	14%
2004	541	188	609	13%	15%
2000	421	187	608	14%	
1996	318	196	513		
1995	297	196	494		
1990	299	199	898		

In the scenario, we assume that 15% of coal used will be shipped

How far is coal shipped ?

Development of seaborne trade (Mt) Source SSY - www.ssyonline.com

	Steam coal		Coking coal				
	Atlantic	Pacific	Atlantic	Pacific	Total Mt	billion ton mile	average trip (miles)
2006	240	330	72	129	771	3540	4591
2005	219	289	72	129	709	3113	4391
2004	210	274	67	123	674	2960	4392
2000	157	187	70	98	512	2509	4900
1996	125	139	70	103	437		
1995	120	129	68	103	420		
1994	108	111	66	98	383		
1986	74	59	61	81	275		
1985	76	55	61	83	275		
1984	66	39	56	79	240		

Over 1986-2006, seaborne steam coal trade has increased on average by about 7.5% p.a.

In the scenario, we assume that average trip will be 4500 miles

World seaborne trade in ton-miles, selected years (billions of ton-m Source: Table 5 in UNCTAD. Review of Maritime Transport 2009. (link)

	Oil								
Year	Crude	Products	Crude plus products	Iron ore	Coal	Grain	5 main dry bulks	Other dry cargoes	World total
1970	5597	890	6487	1093	481	475	2049	2118	10654
1980	8385	1020	9405	1613	952	1087	3652	3720	16777
1990	6261	1029	7290	1978	1849	1073	5259	3891	16440
2000	8180	1319	9499	2545	2509	1244	6638	6790	22927
2001	8074	1345	9419	2575	2552	1322	6782	6930	23131
2002	7848	1394	9898	2731	2549	1241	6879	7395	23516
2003	8390	1460	9850	3035	2810	1273	7118	7810	25124
2004	8795	1545	10340	3444	2960	1350	9521	8335	26814
2005	8875	1652	10527	3918	3113	1686	9119	8730	28376
2006	8983	1758	10741	4192	3540	1822	9976	9341	30058
2007	9214	1870	11084	4544	3778	1927	10676	9665	31425
2008	9300	1992	11292	4849	3905	2029	11209	10245	32746

Summary table : expected fatalities for shipping coal

Activity level	Fatality rate	Fatalities	
Tt Nm in 2050			
1,42	2,9	4,2	Extrapolated from tanking
1,42	10,9	15,5	Extrapolated from all goods trade

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This spreadsheet provides evidence to support the coal railr transport scenario assumptions

How much railroad activity to transport the coal in the scenario ?

2,101 Gt of coal (lignite) consumed in 2050
85% Fraction transported by train
1,79 Gt transported by train
10000 t of coal per unit train
178 571 number of train trips
500 km, average trip

In USA, a typical unit train is 100 to 120 cars long, each holding 100 to 115 (short) tons of coal. http://www.wsgs.uwyo.edu/coalweb/trains/unit.aspx

119 train trips per power plant per year

In USA, average distance shipped per ton of coal, grew from about 430 miles in 1979 to about 700 miles in 1997.

Reference: Energy Information Administration. http://www.eia.doe.gov/cneaf/coal/ctrdb/tab34.html Accessed 2011-02-03

In China, average coal transportation distance increased from about 400 km in 1978 to about 600 km in 2008.

Reference: Tu (2010) http://www.glenbradford.com/files/Stocks/Summary_China_Coal_Value_Chain_J.Tu_Draft.pdf, figure 2 page v

8,93E+07 Train km
5,55E+07 Train miles

Railroad accident statistics in the US

http://safetydata.fra.dot.gov/OfficeofSafety/publicsite/Query/tenyr1a.aspx

Class I RAILROADS Accident/Incident overview

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
ACCIDENTS/ INCIDENT	9502	8435	8345	8585	8336	7888	7573	6940	5482	5390
Total fatalities	629	639	590	613	577	622	546	505	412	460
Employee on duty deaths	15	15	13	18	18	8	10	15	12	9
Trespasser deaths, not at HRC	327	356	345	318	300	362	305	291	250	275
Highway-rail Xing incidents deaths	277	251	223	264	241	246	220	195	140	171
	44%	39%	38%	43%	42%	40%	40%	39%	34%	37%
Train miles	5,4E+8	5,5E+8	5,6E+8	5,8E+8	6,0E+8	6,1E+8	5,9E+8	5,8E+8	4,8E+8	5,1E+8
a/i rate	17,7	15,3	14,8	14,7	13,9	12,8	12,8	12,0	11,5	10,5
Fatality rate (per million train miles)	0,56	0,51	0,44	0,51	0,46	0,42	0,41	0,37	0,34	0,36
Fatality rate (per million train km)	0,91	0,83	0,7	0,81	0,74	0,68	0,65	0,59	0,55	0,58

Previous decades had higher rates.

http://www.drsc.org/Research/AAR_Info+Publications/PETER_FRENCH_RAIL_SAFETY_STATS_011706.pdf

Railroad accident statistics in Europe

In 2004, EU-25

The number of fatalities per million train-kilometers
(excluding suicides) varied from ~0 (Ireland & Luxembourg) to ~2.8 (Portugal). Six countries were above 1.

The average was 0.92 in 2004, and 1.13 in 2005.

Simo Pasi (2006) Rail transport accidents in the European Union in 2004, Eurosta Transport, “Statistics in Focus”

http://www.eds-destatis.de/en/downloads/sif/nz_06_06.pdf , FR version http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-NZ-06-006/FR/KS-NZ-06-006-FR.PDF

Piazza, Mihm and Cassir (2006) Developing CSTs for the European Railway System

IRSC 2006, Dublin http://www.intlrailsafety.com/Dublin/presentations_AM_23_Oct/03_R_Piazza_P_Mihm_C.Cassir.pps

In France

EPSF (2010) Rapport sur la sécurité du réseau ferré national http://www.securite-ferroviaire.fr/fr/modules/cms/fichiers/403/rapport_securite_2009.pdf

2006	2007	2008	2008	
0,197	0,141	0,118	0,119	Serious injuries
0,193	0,173	0,163	0,159	Fatalities per million train-km (excl. Suicides)
0,024	0,020	0,020	0,018	Travelers
0,075	0,073	0,072	0,072	Level crossings users
0,087	0,062	0,068	0,066	Trespassers
0,008	0,006	0,005	0,004	Workers
0,000	0,013	0,008	0,007	Others

Normative european targets (FWSI / million train-km / year)

European Railway Agency (2009) Common Safety Targets

http://www.era.europa.eu/Core-Activities/Safety/Pages/common-safety-targets.aspx

ERA recommendation on the first set of Common Safety Targets as referred to in Artilce 7 of Directive 2004/49/EC

http://www.era.europa.eu/Document-Register/Pages/recommendation-first-set-common-safety-targets.aspx

0,08	Employees
0,74	Level crossing users
0,02	Others
2,3	Trespassers
2,51	Whole society

Share of fatalities in FWSI (fatalities and weighted serious injuries)

10 serious injury statistically equivalent to 1 fatality http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:150:0011:0019:EN:PDF

In UK WSI < F for the main risks (trespass & level crossing) http://www.rssb.co.uk/SiteCollectionDocuments/pdf/reports/strategic%20safety%20%20plan%20%2009-14.pdf

See also data above for France

75% Share of F in FWSI

Trespassing is a crime, we don’t attribute these fatalities to CCS but to alcohol, stupidity and depression

0,84 FWSI per million train-km European common target « Employees + level crossing users + other »

0,63 Fatalities per million train-km, excluding trespassers and suicides, European Common Safety target

Summary table : expected fatalities from coal on railroads

Mkm	Fatality rate	Fatalities	
89,3	0,63	56	2009 ECS target are realised
89,3	0,91	81	The 2001 USA risk rate applies

Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »
This spreadsheet computes global expected fatalities to capture the CO2

Method 1: Industrial carbon dioxide use

120 100 Mt CO2/year Sources (a) (b) Source (c)
12 Fatalities from the two chemical accidents record Source (d)
1926 1997 Period 72 Years

Source (a) IPCC (2005) SRCCS main report says 115 in 7.3.4. Numbers on table 7.2 add up to 152.6 with a large uncertainty and include artificial CO2.
Source (b) IPCC (2005) SRCCS Technical Summary says 120 in section 7.
Source (c) Conclusion of Aresta & Tommasi (1997) Carbon dioxide utilisation in the chemical industry, Energy Convers. Mgmt, v 38:S373-S378
Source (d) Khan & Abbasi (1999) Major accidents in process industries and an analysis of causes and consequences
Journal of Loss Prevention in the Process Industry 12:361-378

Summary table : expected fatalities in 2050 to capture the CO2

Qty captured	Risk rate	Expected	
Gt CO2	$Gt^{-1}\ a^{-1}$	Fatalities	
4,5	1,4	6,3	Accident record, low case
4,5	1,7	7,5	Accident record, high case

Method 2: Fatalities from utilities in large economies

In industrialized countries, 3 to 14 fatalities per year, per 100,000 workers can reasonably be expected.
This range is a guesstimate based on the table below, which is a descriptive statistics summary of the data to the right --->

	n	Min	Average	Max
UK	25	0	2,1	4,4
USA	4	4	5,0	6
France	31	1,7	13,0	31,9
Canada	14	10,5	14,2	19,7
Italy	16	1	3,6	7
Japan	38	0	2,8	16
China	18	6,1	16,8	27,3

Summary table : expected fatalities in 2050 to capture the CO2

Workers	Fatality rate	Fatalities	
7500	3	0,23	Worker's safety, low case
15000	14	2,1	Worker's safety, high case

Rates of fatal injuries (Raw data)

Source: International Labor Organisation, LABORSTA database. http://laborsta.ilo.org/data_topic_E.html (accessed 2009-02-06)
Query: By Topic / Occupational injuries - 8B. Rates of occupational injuries, by economic activity.
1969-present, for the 10 largest economies.
Row selected: Economic activity code 4 (in ISIC revision 2) or E (in ISIC revision 3), meaning Electricity, gas and water
Note: Data for Germany, India and Russia were not available or useable.

		1969	1970	1971	2004	2005	2006	2007
UK	4							
	E				0	1	,,,	,,,
USA*	E				6	4	6	,,,
France**	4	*0,136*	*0,231*	*0,207*				
	E				,,,,	,,,	,,,	,,,
Canada*	E				12,8	18,4	19,7	
Italy*	E				2	2	3	,,,
Japan***	4	0,06	0,06	0,08				
	E			-	0	0	0	0
China*	4				17,7	14,2	,,,	
Brazil*	E				,,,	,,,	,,,	,,,

* Per 100.000 workers employed.

** Per 1000 workers employed, excluding agents of public gas and electricity services.

*** Per 1.000.000 hours worked. According to http://en.wikipedia.org/wiki/Japanese_work_environment, the average number of hours worked in Japan was 2150/yr in 1986, and 1889 in 1995. Therefore 200 Is the conversion factor to 100.000 workers employed: Assuming that 1 worker does 2000 hours, then a million hours is 500 workers employed.

Rates of fatal injury (all rows per 100.000 workers)

	1969	1970	1971	2004	2005	2006
UK				0,0	1,0	
USA				6,0	4,0	6,0
France	13,6	23,1	20,7			
Canada				12,8	18,4	19,7
Italy				2,0	2,0	3,0
Japan	12,0	12,0	16,0	0,0	0,0	0,0
China				17,7	14,2	
Brazil						

Summary table

n	Min	Max	Average
25	0	4,4	**2,12**
4	4	6	**5**
31	1,7	31,9	**13,03**
14	10,5	19,7	**14,21**
16	1	7	**3,63**
38	0	16	**2,84**
18	6,1	27,3	**16,75**
1	18,6	18,6	**18,6**

Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »
This spreadsheets analyzes the risk of pipelines

Following IPCC (2005), we consider the yearly incident rate as Number/km, not Number / Mt / km

Evidence from the US pipelines networks

Updated statistics of pipeline incident in the USA

	Natural gas Transmission	Hasardous liquids	CO2
Start	1986	1986	1990
End	2009	2009	2009
Duration (years)	24	24	20
# significant incidents	2 318	4 088	20
# fatalities	65	54	0
Network length (1000km)	522	255	6,2
Observation basis (Mkm yr)	12,532	6,113	0,123
Incidents /Mkm / yr	184,97	668,73	162,09
Fatalities / Mkm / yr	5,2	8,8	0,0

Homogenous Poisson Process statistics

Fail free duration	Desired confidence	MTBF at this conf. Level	Upper rate of failure
0,123	95%	0,0412	24,3

Assumptions from the 2050 scenario

Sites	Distance km	Total network size Mkm
1500	100	0,15

Summary table : expected 2050 fatalities from pipelines

Mkm	Fatality rate	Fatalities	
0,15	5	0,75	Lower expectation
0,15	50	7,5	Upper expectation

Table data sources:

US Department of Transportation, Office of Pipeline Safety. Natural Gas Pipeline Operators Incident Summary Statistics by Year 1/1/1986 – 12/31/2008 (accessed 2010-02-18) (link)

Hazardous liquid pipeline operators accident summary statistics by year (accessed 2010-02-18) (link)

The 20 significant incidents, 0 fatalities for CO2 pipes were obtained by looking up the PHMSA data files directly, see table to the right.

For average network length computations, see tables to the right

References interesting but not used

Dooley JJ, Dahowski RT, Davidson CL, 2008, «Comparing existing pipeline networks with the potential scale of future U.S. CO2 pipeline networks», doi:10.1016/j.egypro.2009.01.209

The ENSAD database at PSI. http://gabe.web.psi.ch/research/ra/

John Gale and John Davison (2004) Transmission of CO2—safety and economic considerations. *Energy* 29:1319-1328 (link)

Jo Y.D., Crowl D.A., 2008, « Individual risk analysis of high-pressure natural gas pipelines », Journal of Loss Prevention in the Process Industries, 21: 589-595.

Note: in UK CO2 pipeline are designed similarly to natural gas transportation http://www.hse.gov.uk/pipelines/resources/designcodes.htm

In the US, are CO2 incidents more or less likely to cause fatalities ?

	Natural gas Transmission	Hasardous liquids	CO2		
Fatalities / incident	0,0280	0,0132	0,0000		
Incidents without fatalities (at least)	2253	4034	20		
The probability that an serious incident has no victim is larger than	97,20%	98,68%	100,00%	90,00%	86,00%
Probability that the number of incidents in E37 all have No fatalities			100,00%	12,16%	4,90%

We have a run of 20 incidents without fatality.
But even if a significant CO2 incident has 10% probability of causing at least one fatality,
there is more than 10% probability that the observed run of 20 incidents without victims is just luck.
If we want the 95% confidence level, we can only say that the probability that a serious incident with a CO2 pipeline causes a fatality is less than 14%.
In other words, we do not have enough observations to compare statistically
the lethality of CO2 pipelines incidents with the lethality of other pipelines accidents.

Evidence from European networks

Ancien (a) Concawe Oil Pipelines Management Group's Special Task Force on oil pipeline spillages (OP/STF-1), 2007, "Performance of European crosscountry oil pipelines, . Statistical summary of reported spillages in 2005 and since 1971", Brussels.

Source (a) Concawe Report No. 7/08. Performance of European cross-country oil pipelines - statistical summary of reported spillages in 2006 and since 1971

27	Oil Pipeline in Western Europe (average from Figure 1 page 3, thousand km)		
37	Period	1971	2006
14	Total Fatalities, section 3.1 page 7, all « Workers »		
0,0140	Fatalities per 1000 km per year		

Imperial-metric distance unit conversion factor

1,61 km 1 mile

Natural gas transmission pipeline annual mileage *Unit: 1000 miles*

Year	N° of records	Onshore	Offshore	Total transmiss	onshore	offshore	total gathering	total pipe	(in Km)
1984	885	277,6	7,35	284,95	33,29	3,67	36,96	321,92	518,07
1985	952	282,75	7,72	290,46	33,73	1,74	35,47	325,93	524,54
1986	1,01	280,67	9,29	289,96	29,74	1,96	31,7	321,65	517,65
1987	963	284,24	7,62	291,86	29,65	2,48	32,13	323,99	521,41
1988	1,02	280,25	7,91	288,16	28,94	3,1	32,04	320,2	515,32
1989	1,03	279,73	8,2	287,93	29,6	2,55	32,14	320,07	515,1
1990	1,11	283,88	8,11	291,99	29,27	3,15	32,42	324,41	522,09
1991	1,21	285,3	8,57	293,86	29,01	3,7	32,71	326,58	525,57
1992	1,18	283,07	8,4	291,47	28,91	3,72	32,63	324,1	521,58
1993	1,13	285,04	8,22	293,26	28,43	3,63	32,06	325,32	523,55
1994	1,23	293,44	8,11	301,55	27,4	3,91	31,32	332,86	535,69
1995	1,27	288,85	8,1	296,95	26,67	4,26	30,93	327,88	527,67
1996	1,25	285,34	6,85	292,19	24,86	4,76	29,62	321,8	517,89
1997	1,35	287,75	6,63	294,37	28,3	6,16	34,46	328,83	529,21
1998	1,17	295,61	7,11	302,71	23,49	5,67	29,17	331,88	534,11
1999	1,18	290,1	6,02	296,11	26,36	5,92	32,28	328,39	528,49
2000	1,17	293,72	5,24	298,96	21,88	5,68	27,56	326,52	525,48
2001	1,35	284,91	5,54	290,46	17,73	3,88	21,61	312,07	502,23
2002	1,47	297,21	6,33	303,54	16,98	5,58	22,56	326,1	524,81
2003	1,47	295,55	6,28	301,83	16,43	6,33	22,76	324,59	522,37
2004	1,43	296,86	6,24	303,22	17,27	7,41	24,73	327,95	527,78
2005	1,48	294,68	5,86	300,66	16,03	7,37	23,4	324,06	521,53
2006	1,49	293,61	6,7	300,46	13,1	7,33	20,43	320,89	516,42
2007	1,45	294,73	6,2	301,17	12,57	7,12	19,7	320,86	516,38
2008	1,48	295,22	6	301,22	12,99	7,23	20,22	321,44	517,31
									522,16

Average 1986-2007

Carbon dioxide systems, jan 12, 2010

	No of records	Onshore	Offshore	Total pipe (mi)	Total pipe (1000 km)
2004	21	3408	0	3408	5,48
2005	27	3718	127	3846	6,19
2006	29	3827	0	3827	6,16
2007	31	3884	0	3884	6,25
2008	30	4202	0	4202	6,76
			Average, 2004-2008		**6,169**

Source: PHMSA Office of Pipeline Safety Natural Gas Transmission Pipeline Annual Mileage (link)

Liquid Pipeline Operator Total National Mileage

Year	Miles	1000 km
1984	153404	246,88
1985	152859	246
1986	152489	245,41
1987	152376	245,23
1988	148910	239,65
1989	150158	241,66
1990	152089	244,76
1991	165689	266,65
1992	155113	249,63
1993	153444	246,94
1994	154731	249,02
1995	154933	249,34
1996	163422	263
1997	156638	252,08
1998	154528	248,69
1999	158248	254,68
2000	160900	258,94
2001	159648	256,93
2002	161670	260,18
2003	159512	256,71
2004	166798	268,44
2005	166349	267,71
2006	166283	267,61
2007	168036	270,43
Average 1986-2007:		**254,71**

Database report on CO2 pipeline spills in the US.

Source: PHMSA Significant Incident Data Assess database (link)

RPTID	SIGNIFICA	TFAT	COMM	
20020028	YES	0	CARBON DIOXIDE	Significant incidents
20000144	YES	0	CARBON DIOXIDE	6
19970029	YES	0	CARBON DIOXIDE	
19960133	YES	0	CARBON DIOXIDE	
19960132	YES	0	CARBON DIOXIDE	
19960016	YES	0	CARBON DIOXIDE	
20010030	NO	0	CARBON DIOXIDE	
19950092	NO	0	CARBON DIOXIDE	
19940149	NO	0	CARBON DIOXIDE	
19940082	NO	0	CARBON DIOXIDE	
19940025	NO	0	CARBON DIOXIDE	
RPTID	SIGNIFICA	FATAL	COMM	Significant incidents
20090248	YES	0	CO2	14
20090243	YES	0	CO2	
20090204	YES	0	CARBON DIOXIDE	
20070207	YES	0	DRY CO2	
20070122	YES	0	CO2	
20070030	YES	0	CARBON DIOXIDE	
20070063	YES	0	CARBON DIOXIDE	
20070100	YES	0	CARBON DIOXIDE	
20060217	YES	0	CARBON DIXOIDE	
20050026	YES	0	CARBON DIOXIDE	
20040283	YES	0	CARBON DIOXIDE	
20040271	YES	0	CARBON DIOXIDE	
20040243	YES	0	SOUR CARBON DIOXIDE	

Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »
This spreadsheet computes global expected fatalities attributable to shipping CO2 in the wedge scenario

Method 1. Oil tanking statistics: we consider the average FAR/ Mt-miles in oil trade by tankers for 1978-2001

2322 Fatalities on the period 1978-2001 from oil tanker incidents (Ranheim 2002)
24 Period duration
8258 Gt miles of oil (crude+products) shipped by tankers – average 1978-2001 (see table below)
11,7 fatality per Tt-miles-yr

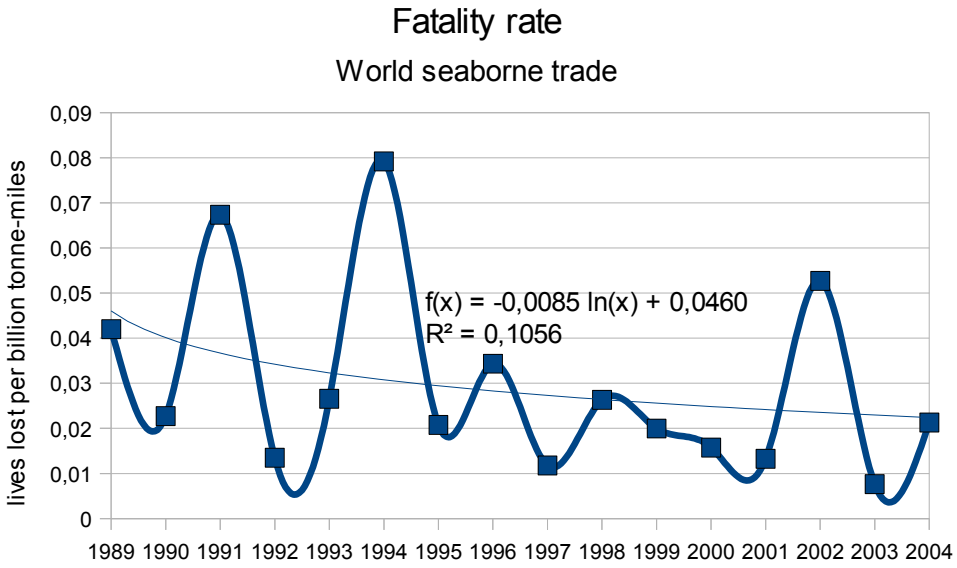
Oil (crude+products)	
1970	6487
1975	9727
1980	9405
1985	5157
1990	7821
2000	10265
2001	10179
2002	9898

World seaborne trade in Gt-miles (Table reproduced from IMO 2005 Facts and figures p. 6, citing data from Fearnleys Review, 2004)

Weigted average	
75-80	9566
80-85	7281
85-90	6489
90-00	9043
00-01	10222
78-01	**8258**

Method 2. Shipping/ World Trade statistics

	Year	Fatalities*	Total trade**	Fatality rate	Log. Tendency
1	1989	688	16385	0,0420	0,0460
2	1990	389	17121	0,0227	0,0401
3	1991	1204	17873	0,0674	0,0367
4	1992	246	18228	0,0135	0,0342
5	1993	504	18994	0,0265	0,0323
6	1994	1552	19600	0,0792	0,0308
7	1995	419	20188	0,0208	0,0295
8	1996	710	20678	0,0343	0,0283
9	1997	257	21825	0,0118	0,0273
10	1998	566	21492	0,0263	0,0264
11	1999	439	21990	0,0200	0,0256
12	2000	373	23693	0,0157	0,0249
13	2001	317	23891	0,0133	0,0242
14	2002	1274	24172	0,0527	0,0236
15	2003	197	25844	0,0076	0,0230
16	2004	589	27635	0,0213	0,0224
	Total	**9724**	**339609**	**0,0286**	
62	2050				**0,0109** E



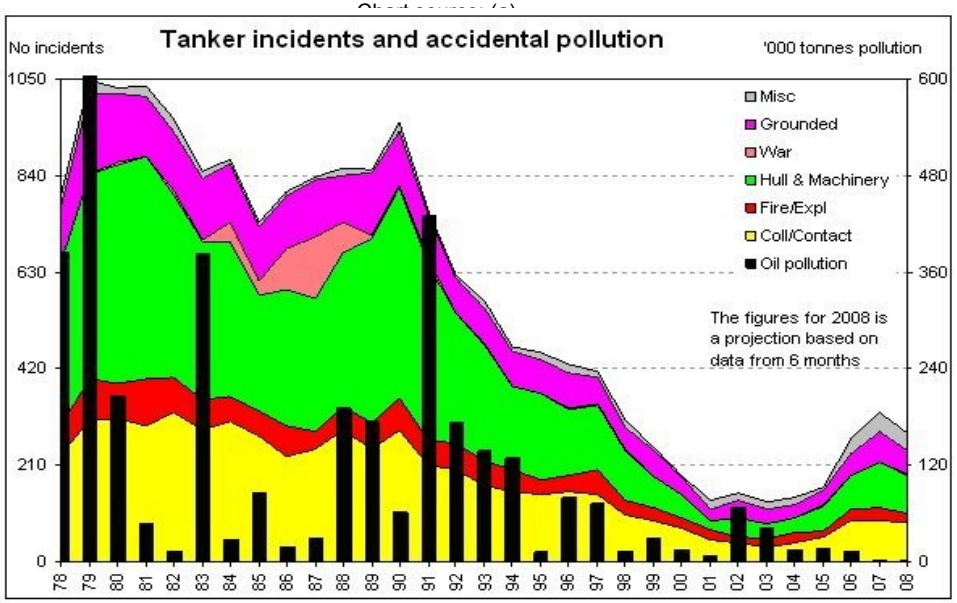
Source: * Fatalities: IMO 2005 FSI.3/Circ.6. ** Total world seaborne trade (billion tonne-miles): Fearnley annual Review 2004, p.49

Analysis of the trend, for extrapolation

According to Ranheim (2002), the trend in fatalities is declining. 775 in the second 12 year half of the series, versus 1617 in the previous 12 years.

However the number of tanker incidents increased again during 2002-2007, see chart, source (a).

And over 2002-2007, the table below sums up to 229 fatalities.



Recent data (include descriptions)

Fatalities in recorded tanker incidents – all types and sizes

2008->27/5	33
2007	61
2006	40
2005	26
2004	65
2003	21
2002	16

Sources: Compiled by E. Ranheim at Intertanko, based on reports from LMIU, published at:

(a) http://www.themaritimefoundation.com/templates/Page.aspx?id=44456

(b) http://www.themaritimefoundation.com/templates/Page.aspx?id=43302

(c) http://www.themaritimefoundation.com/templates/Page.aspx?id=44172

(d) http://www.themaritimefoundation.com/templates/Page.aspx?id=42406

Period	Fatalities*	Annual average	
1978-1989	1617	134,75	
1990-2001	775	64,58	2,09
2002-2007	229	38,17	1,69

*Ranheim (2002)

The table suggests that safety improved by a factor 2 over 78-89, then by 1.7 over 90-01. We extrapolate a factor 4 over 2002-2050.

Summary table : expected fatalities for shipping CO2

Shipping CO2 Tt Nm	Fatality rate Fat/Tt Nm	Fatalities 2050 expected	
2,25	2,9	7	Tanking, extrapolated
2,25	11	25	All goods, extrapolated

References and data sources on shipping

Ranheim E (2002) dans "Sécurité Maritime et protection de l'environnement" Evolution et Perspectives (Brest), p 68-77.

IMO (International Maritime Organization) Library Services (2005) International Shipping and World Trade. Facts and figures

IMO (2005) Casualty statistics and investigation. Very serious and serious casualties for the year 2003. FSI.3/Circ.6 – 17/3/2005.

The IMO database on marine casualty and incidents (not very useful)

Fearnley annual Review 2004

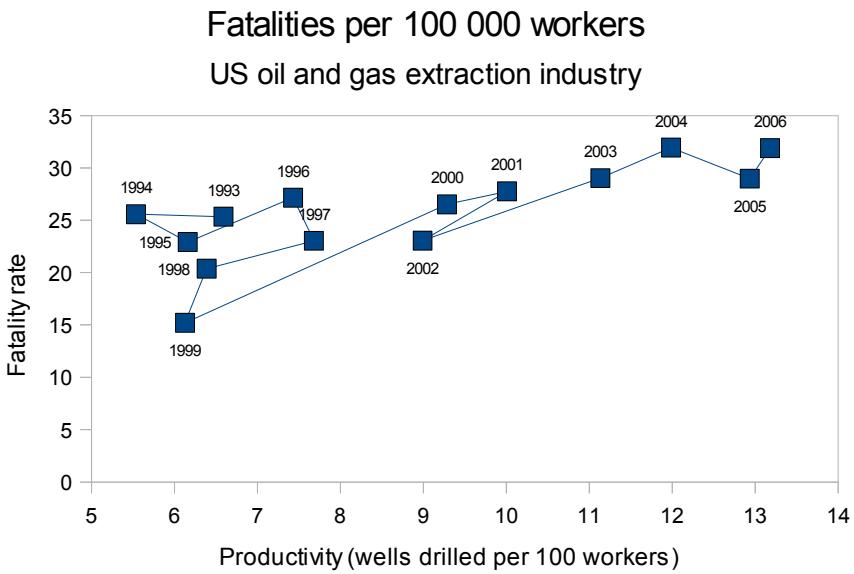
For global production and productivity, see UNCTAD « Review of maritime transport »

Casualties topic page on Seasearcher, Lloyd's database.

Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »
This spreadsheet computes global expected fatalities attributable to the injection of CO2 in the wedge scenario

Source:	(a)	(a)	(a)	(b)	
Year	No of fatalities	No of workers	Rate per 100.000 workers	Drilled wells	Drilled wells/100 workers
1993	94	371 000	25,3	24 452	6,6
1994	99	387 000	25,6	21 427	5,5
1995	77	336 000	22,9	20 698	6,2
1996	82	302 000	27,2	22 432	7,4
1997	85	369 000	23,0	28 341	7,7
1998	76	373 000	20,4	23 825	6,4
1999	50	329 000	15,2	20 158	6,1
2000	83	313 000	26,5	29 063	9,3
2001	98	353 000	27,8	35 331	10,0
2002	71	308 000	23,1	27 689	9,0
2003	85	292 846	29,0	32 599	11,1
2004	98	306 863	31,9	36 777	12,0
2005	98	338 234	29,0	43 747	12,9
2006	123	385 803	31,9	50 842	13,2
2007				50825	
2008				55670	

Figure 3 in the paper



Sources

(a) Centers for Disease Control and Prevention. 2008. Fatalities Among Oil and Gas Extraction Workers --- United States, 2003--2006. MMWR 57(16):429-431.
Table 1, Available at http://www.cdc.gov/mmwr/preview/mmwrhtml/mm5716a3.htm

(b) U.S. Energy Information Administration 2009. Annual Energy Review 2008. Report DOE/EIA-0364(2008)
Table 4.5 Crude Oil and Natural Gas Exploratory and Development Wells, 1949-2008. Column Total, Wells drilled. Available at http://www.eia.doe.gov/emeu/aer/txt/ptb0405.html

Assumptions from the 2050 scenario

5000 15000 Workers on injection sites

Summary table : expected fatalities from injection

Workers	Fatality rate	Fatalities	
5000	20	1	Lower expectation
15000	30	4,5	Upper expectation

	31/12/10			31/12/09			
	Revenue (million $)	Employees	R/E $	Revenue (million $)	Employees	R/E $	Source : annual reports available at
Schlumberger	27 447	108 000	$254 139	22 702	77 000	$294 831	http://investorcenter.slb.com/phoenix.
Halliburton	17 973	58 000	$309 879	14 675	51 000	$287 745	http://ir.halliburton.com/phoenix.zhtm
Baker Hugues	14 414	53 100	$271 450	9 664	34 400	$280 930	http://investor.shareholder.com/bhi/ar
Weatherford International	10 221	55 000	$185 836	8 833	52 000	$169 865	http://annualreport.weatherford.com/
CGGVeritas	2 904	7 264	$399 780	3 109	7 500	$414 533	http://www.cggveritas.com/default.asp
Minimum			$185 836			$169 865	
Maximum			$399 780			$414 533	

Injection per site	8,8	million ton per year
Assumed injection fee	0,50 USD	per ton of CO2
Revenue	4,40 USD	million per year

Employees per site	R/E 2010	R/E 2009
Maximum	24	26
Minimum	11	11

Number of sites	500

Total workers	R/E 2010	R/E 2009
Maximum	11 838	12 951
Minimum	5 503	5 307

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l?c=67605&p=irol-reportsAnnual
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Electronic supplement to the manuscript « Expected fatalities foone wedge of CCS in 2050 »
This spreadsheet computes global expected fatalities attributable to the storage of CO2 in the wedge scenario

Method 1: Minimum endogenous mortality risk increase

Negligible level of individual risk increase in MicroMort units: 1

1 micromort is defined as a one in a million probability of dying next year. This is a negligible level because:
According to P. Fishbeck and D. Gerard « Death Risk Rankings » database, accessed at http://www.deathriskrankings.com/ 2001-02-23,
the probability of dying for Females, aged 5-9 is 97 MicroMort in Western Europe, 106 in New England
This is the minimum across genders, region and age groups. So practically everybody is above 100 micromorts.

Summary table : expected fatalities in 2050 from storage, method 1

Exposed population	Risk level	Expected fatalities in 2050	
225000	1E-06	0,23	MEM, small footprint
900000	1E-06	0,90	MEM, large footprint

Method 2: Storage sites as artificial installations

Analogue with a risk level apparently greater than CO2 storage: Risk around dangerous installations (Seveso)

France	Europe			Europe (former period)	
1076	8558	Sites	Source (a)	1860 Sites	Source (c)
38	153	Fatalities	Source (b)	14 Accidents per year	Source (c)
17	17	Years	Source (b)	2,3 Fatalities per accidents	Source (c)
2,08E-003	1,05E-003	Fatalities per site per year		1,73E-002 Fatalities per site per year	

Analogue with a risk level apparently smaller than CO2 storage: Risk around common installations in France

500000	Sites	403 Fatalities	17 Years	Source (b)
4,74E-005	Fatalities per site per year			

The above rates should be increased to account for underreporting (except those from source c), so the range is 0.01 – 0.0001
Because CO2 storage is regulated in-between these analogues, we assume that the accepted risk will be 0.001, in the (geometric) middle.
But we extrapolate a worst case 3 times as high, because EU societies are more risk averse than our 2050 world

Summary table : expected fatalities in 2050 from storage, method 2

Onshore sites	Risk per site	Expected fatalities	
450	0,001	0,45	Analogue, low risk
450	0,003	1,35	Analogue, high risk

Sources for method 2

(a) Salvi, O., A. Jovanovic, C. Bolvin, C. Dupuis, C. Vaquero, D. Balos, et A-M. Villamizar. 2008. F-SEVESO. Study of the effectiveness of the Seveso II Directive. Final report. Contract nº070307/2007/476000/MAR/A3. Ao?t 29. http://ec.europa.eu/environment/seveso/review.htm

(b) Michel, Laurent. 2010.Inventaire 2009 des accidents technologiques. Bureau d'Analyse des Risques et Pollutions Industriels (BARPI), Minist?re de l'Ecologie, de l'Energie, du D?veloppement Durable et de l'Am?nagement du Territoire. http://www.aria.developpement-durable.gouv.fr/barpi_2963.jsp

(c) Haastrup, P, et H Romer. 1995. An analysis of the database coverage of industrial accidents involving hazardous materials in Europe. Journal of Loss Prevention in the Process Industries 8, no. 2: 79-86. http://dx.doi.org/10.1016/0950-4230(95)00008-O

Remark on reliability testing and CO2 storage demonstration projects

If a fatality occurs too soon, it will be hard to justify that the risk per site is as low as 0.001 fatality per year.

According to the NIST/SEMATECH e-handbook of statistical methods (http://www.itl.nist.gov/div898/handbook/apr/section3/apr311.htm), to test statistically an MTBF of 1000 years with a 95% confidence level, one has to see the system working without failure for 3000 years. So when do we get 3000 years of storage experience in our scenario ?

Year	Storage sites	Cumulative experience	New sites opened per year
2007	3	3	1,5
2008	4,5	7,5	1,5
2014	13,5	66	1,5
2015	15	81	3,5
2016	18,5	99,5	3,5
2024	46,5	373,5	3,5
2025	50	423,5	18
2026	68	491,5	18
2038	284	2711,5	18
2039	**302**	**3013,5**	**18**
2040	320	3333,5	18
2041	338	3671,5	18
2042	356	4027,5	18
2043	374	4401,5	18
2044	392	4793,5	18
2045	410	5203,5	18
2046	428	5631,5	18
2047	446	6077,5	18
2048	464	6541,5	18
2049	482	7023,5	18
2050	500	7523,5	18

Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »
Summary of results (Table 4)

				Minimum	Maximum
Summary results table : expected fatalities from coal mining					
Coal mined	Fatality rate	Expected fatalities			
Gt (scenario)	per Mt mined	In 2050			
2,1	**0,0383**	**81**	Convergence to USA 1990-2007		
2,1	**0,0935**	**196**	Safety progress follows the USA curve	80,6	196,5
Summary table : expected fatalities for shipping coal					
Activity level	**Fatality rate**	**Fatalities**			
Tt Nm in 2050					
1,42	2,9	4,2	Extrapolated from tanking		
1,42	10,9	15,5	Extrapolated from all goods trade	4,2	15,5
Summary table : expected fatalities from coal on railroads					
Mkm	Fatality rate	Fatalities			
89,3	0,63	56	2009 ECS target are realised		
89,3	0,91	81	The 2001 USA risk rate applies	56,2	80,9
Summary table : expected fatalities in 2050 to capture the CO2					
Qty captured	Risk rate	Expected			
Gt CO2	Gt-1 a-1	Fatalities			
4,5	1,4	6,3	Accident record, low case		
4,5	1,7	7,5	Accident record, high case		
Workers	Fatality rate	Fatalities			
7500	3	0,23	Worker's safety, low case		
15000	14	2,1	Worker's safety, high case	0,2	7,5
Summary table : expected 2050 fatalities from pipelines					
Mkm	Fatality rate	Fatalities			
0,15	5	0,75	Lower expectation		
0,15	50	7,5	Upper expectation	0,8	7,5

Summary table : expected fatalities for shipping CO2

Shipping CO2 Tt Nm	Fatality rate Fat/Tt Nm	Fatalities 2050 expected			
2,25	2,9	7	Tanking, extrapolated		
2,25	11	25	All goods, extrapolated	6,6	24,6

Summary table : expected fatalities from injection

Workers	Fatality rate	Fatalities			
5000	20	1	Lower expectation		
15000	30	4,5	Upper expectation	1,0	4,5

Summary table : expected fatalities in 2050 from storage, method 1

Exposed population	Risk level	Expected fatalities in 2050			
225000	1E-06	0,23	MEM, small footprint		
900000	1E-06	0,90	MEM, large footprint		
Onshore sites	**Risk per site**	**Expected fatalities**			
450	0,001	0,45			
450	0,003	1,35		0,2	1,4

Total	**149,7**	**338,2**