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Carbon Capture and Storage: Risk and Public Perception

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Abstract

This paper assesses the financial impacts of the 2010 BP Oil Spill in the Gulf of Mexico and 2011 Fukushima Daiichi Nuclear Accident and develops a comparative risk relations matrix to estimate the potential damages of an accident of similar magnitude resulting from the risks (whether real or perceived) associated with Carbon Capture and Storage (CCS). Based on those results, this paper proposes further research to develop a novel international insurance scheme as a potential method for resolving long-term liability issues and making CCS more readily acceptable to the public.

Keywords: *CCS; Nuclear; Risk.*

1. Introduction

Scientists agree that anthropogenic CO_2 is the foremost cause of climate change. Carbon Capture and Storage (CCS) is a new energy technology that has been proposed as a leading solution for reducing global CO_2 emissions.[1]CCS involves the capture and separation of CO_2 from a large emitting source, like a (coal-fired) power plant, the compression of that CO_2 to a super-critical (liquid-like) state, the transportation of that CO_2 to an injection site and its injection into a geological formation.As with other energy technologies, CCS is associated with certain risks, both real and perceived, although largely considered negligible by experts. Real world events, however, have proven time and time again that what scientific experts often find to be statistically negligible, more often than their probabilities suggest, become a reality.[2] This paper assesses two recent catastrophic events from the energy industry as case studies to support this statement: the 2010 BP Oil Spill in the Gulf of Mexico and the 2011 Fukushima Daiichi Nuclear Accident. These incidents demonstrate that, in the development of new technologies, it is imperative such so-called 'negligible' risks are considered much more rigorously. Thus, this paper considers the financial impacts of both accidents and the risks (whether real or perceived) associated with CCS through a comparative risk relations matrix to estimate their relative potential damages for use as a CCS risk management tool, which could be used by proponents or policy makers in their assessment of large-scale CCS projects.

In many respects, the technical procedures involved in CCS are regarded as mature technologies. For decades, activities such as drilling wells, subsurface mapping, fluid injection, reservoir management, and many monitoring methods have been performed safely and successfully in the oil and gas (O&G) sector with a high degree of accuracy. However, site selection for storage has often been considered project limiting. That is, if a suitable storage site cannot be identified for a region within a reasonable time-frame, costs will be greatly increased coupled with extensive delays, resulting in the likely failure of a project. Therefore: (1)it is essential that storage site characterization begins as soon as possible in the consideration of any CCS project; (2) storage evaluations must consider potential impacts and interactions with other basin resources; (3) public concerns of risks associated with CCS generally concern aspects of storage. The perceived risks of leakage and induced seismicity are among the biggest challenges in CCS; and (4) most remaining issues regarding regulations for CCS involve the issue of long-term liability.[3]

An accident that results in the release of harmful materials will, in addition to any direct health and environmental consequences, produce direct and indirect effects on the economy of the surrounding area as represented in **Fig. 1**. In the event that an accident results in a major release of harmful materials to the environment, the economic consequences could be widespread and severe. To account fully for the impacts of an accident when considering the design or modification of an energy system, the economic consequences must be assessed and used to support the case for the inclusion of safety systems and design features intended to limit or mitigate the consequences. A significant environmental accident will produce dislocations in the local and, potentially, in the national and international economies as the lives of people and the functioning of local businesses are disrupted. It may also cause a real or perceived deterioration of the local environment and incur additional health costs.[4]As a response, this paper also suggests an international insurance scheme based on a percentage of carbon trading to resolve

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long-term liability issues, similar to other funding schemes targeted towards achieving a sustainable future.

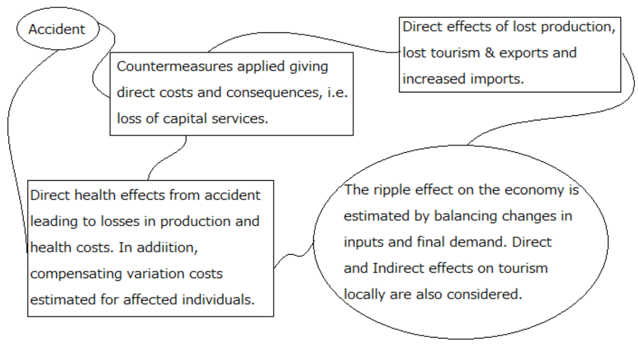

Figure 1 Schematic representation of how the direct effects of an accident give rise to a range of economic effects. Adapted from Higgins.[4]

While there have not yet been any accidents attributed to CCS, by assessing the resulting damages from other industrial accidents in the energy industry, like the BP Oil Spill and Fukushima Nuclear Accident, this paper aims totranslate the impacts of a catastrophic accident of similar magnitude resulting from the risks associated with CCS.

2. 2010 BP Oil Spill

The worst oil spill in the history of the O&G industry started on April 20, 2010 after an explosion at the BP-run Deepwater Horizon offshore drilling rig in the Gulf of Mexico released close to 5 million barrels of crude oil into the Gulf's waters until it was finally capped on July 15, 2010.In addition to the loss of life of eleven rig workers, the BP Oil Spill's effects have been significant ecologically, socially, and economically. Furthermore, some effects may continue or worsen and others may not have yet been realized or become apparent.[5] There is no doubt that the spill has damaged the coastal environment as well as the fishing and tourism industries of Florida, Alabama, Mississippi, Louisiana and Texas, with 5000 businesses and close to one million employees have been affected. Experts predict significant costs accruing from this offshore disaster and the corporate responsibility of oil well owners have become a heavily debated topic. In addition to nearly $12 billion in direct costs of plugging the well and another $17 billion in penalties as per the Clean Water Act and Oil Pollution Act (OPA), BP is also expected to be held liable for lost economic activity, lost federal, state, and local taxes and damages to the environment. The annual revenue of the tourist and fishing industries in the worst affected states is between $15 billion and $30 billion. Loss from tourism alone is estimated to be around $22.7 billion over the last three years.[6]Another huge economical area that has, and will be affected more, is the real estate market. Many people purchase vacation homes in Florida, especially along the coastal areas, but due to the oil spill, many economists are expecting this market to plummet, as has already begun. These estimates do not include the long-term damages inflicted by the contaminated oil on animal life and ecosystems. Local restaurants have also been affected, despite the FDA reporting seafood from the area to be safe for consumption. Chemicals in crude oil dispersants have also been known to cause a wide range of health effects in people and wildlife. As a result, the possible health care costs are unpredictable and could be immense. After a six month ban on all drilling in the area, restricted policy on offshore drilling could also harm new offshore production, the main economic driver for the region. Overall costs are estimated to top $90 billion and continue to grow.[7]

Many of the local effects on the economy also extend worldwide. Because BP is a world leader in energy and oil, the entire globe has been affected. As in America, people have been laid off in other parts of the world, especially in United Kingdom where its headquarters are located. The rising price of oil places an additional strain on the worldwide economy, further deteriorating personal budgets of individuals, their country, and continent.

3. Fukushima Daiichi Nuclear Accident

The cost of the March 11, 2011 Fukushima Daiichi Nuclear Accident has been estimated as high as $250 billion and will likely continue to increase. This disaster has had serious financial consequences for electric power companies operating nuclear plants (not limited to Japan). Goldman Sachs Japan estimates that the Tokyo Electric Power Company (TEPCO), which wasessentially bankrupted instantaneously by the accident, faces an extraordinary loss of $8.75 billion to decommission the damaged reactors and a $6.25 billion increase in fuel costs for 2011. The Japanese government estimates a staggering $72.5 billion in third party damage liabilities and,in October 2011, estimated that remediation for contaminated areas would cost $13 billion.[8]In addition to the physical destruction, the loss of electrical power limited Japan's capacity to recover. The shutdown of Fukushima was a huge blow to the recovery effort because it provided a significant portion of the area's power. Further complicating recovery was the Japanese government shutdown 43 of Japan's 54 nuclear reactors, which accounted for more than one quarter of the nation's electricity. In response to a complexity of problems, the Japanese government imposed mandatory cuts of 15% on major electricity users.[9]

The earthquake and tsunami disrupted many sectors of Japanese manufacturing. Compounding these challenges, the government's evacuation order after the accident at

Fukushima caused other businesses to close. With production halted, wholesalers and manufacturers turned to suppliers in different regions of Japan and in other countries. Furthermore, some countries placed restrictions on Japanese imports due to fears of radiation contamination. Tourism both locally and for the whole country was also severely affected by the perceived health risks of radiation, as exemplified by the coinage "fly-jins," foreigners who fled the country or cancelled their trips during the crisis in fear of the effects of radiation. Japanese Universities also observed a significant decrease of current and incoming International students in comparison with the previous years.

After Fukushima, there has been much discussion in Japan about whether to continue producing nuclear power. Before the disaster, 54 nuclear reactors provided 30%of Japan's electricity. The Japanese government had planned to increase that portion to 50% by 2030 with two new reactors under construction and 12 more planned. Only two reactors have been restarted since Japan began shutting down nuclear plants for regular maintenance and post-Fukushima inspections. Since reactors are generally not restarted after they are shut down, Japan risks losing most or all of its nuclear power. Recovering from the earthquake and tsunami will be challenging enough on its own, but adding more barriers to recovery by shutting down a major source of affordable energy makes little sense. According to the Japan Center for Economic Research, shutting down all of Japan's nuclear plants will cause a 1.2% annual loss in GDP, which equates $94 billion in annual losses. The Japanese government estimates that shutting down all nuclear power plants would result in a 10% power shortage and a 20% increase in electricity costs. Given Japanese industry accounts for 40% of the country's electricity use, such a shortage and price increase would prove extraordinarily harmful not only to industry, but also to consumers who will see the costs passed down to them.[9]

4. CCS Risks

4.1. Leakage

CCS will result in CO_2 being handled in much greater quantities than it is today. For example, a 1 GW coal-fired power plant will produce up to 30,000 t of CO_2-e per day to be captured and transported to long-term storage facilities.[10] Whereas in existing CO_2 facilities, an inadvertent release of CO_2 may have created a small-scale hazard, potentially only affecting those in the local vicinity, a very large release of CO_2 from a commercial scale of operation has the potential to produce harmful effects over a significantly greater area and, as such, would likely affect a much more significant number of people. Combining the known impacts from receiving a harmful dose of CO_2 with what could be a very large hazard zone due to the release of large inventories of CO_2 (particularly in its supercritical phase), creates the potential to introduce a major hazard where one does not currently exist.

Depending on the concentration of CO2 inhaled and the duration of exposure, toxicological symptoms in humans range from headaches (in the order of 3% for 1 hour), to increased respiratory and heart rates, dizziness, muscle twitching, confusion, unconsciousness, coma and death (in the order of >15% for 1 minute).Table 1 illustrates a significant danger to humans if they inhale CO_2 at concentrations above 7% in air (i.e. > 70,000 ppmv). It also highlights the effect of that toxicity increases rapidly for only small changes in concentration above a certain level, i.e. there is not a large difference between the values for the specified level of toxicity (SLOT) and the significant likelihood of death (SLOD).[10]

Table 1 Concentration vs. time consequences for CO_2inhalation.Adapted from Harper.[10]

Inhalation exposure time	CO_2 Concentration in air			
	SLOT: 1-5% Fatalities		SLOD: 50% Fatalities	
	%	Ppm (volume)	%	Ppm (volume)
60 min	6.3	63,000 ppmv	8.4	84,000 ppmv
30 min	6.9	69,000 ppmv	9.2	92,000 ppmv
20 min	7.2	72,000 ppmv	9.6	96,000 ppmv
10 min	7.9	79,000 ppmv	10.5	105,000 ppmv
5 min	8.6	86,000 ppmv	11.5	115,000 ppmv
1 min	10.5	105,000 ppmv	14	140,000 ppmv

Differences in CO_2 concentrations between different lethality levels and exposure times are relatively small. Concentrations for lethality levels of 1-5% and 50% for a given exposure time differ by a mere 33%. Although CO_2 is considered only mildly toxic to humans compared with hydrogen sulphide, for example, when they reach above concentrations of about 7% in air, humans become particularly sensitive to further increases.

Fig. 2 shows that, in all cases of a release of CO_2, the hazardous distances are significant and could therefore impact a significantly higher number of people in the vicinity of the incident. The total mass of CO_2 released has a significant influence on hazardous distances. The temperature of the CO_2 also has an influence with colder releases creating greater distances. In general, the hazard range for an instantaneous release of 1000 t of CO_2-e from storage may be in the range of 50 m to 400 m with large, cold, liquid phase storage producing the larger distances.[10]

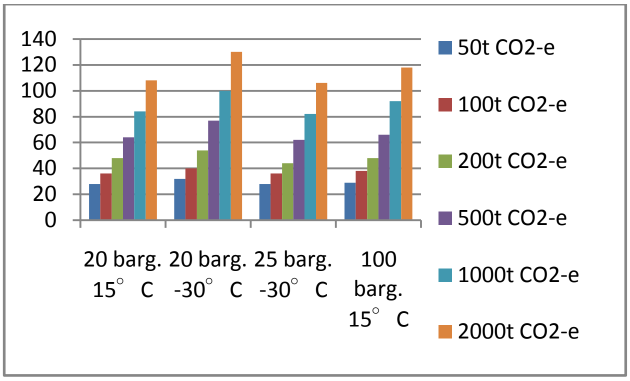

Figure 2 Hazardous distances vs. release scenarios (5 m/s wind). Adapted from Harper.[10]

4.2. Induced Seismicity

Recently, several induced seismic events related to O&G projects have drawn and heightened public attention. Although none of these events has resulted in a loss of life or significant structural damage, the effects have been felt by local residents, some of whom also experienced minor property damage. Induced seismicity associated with fluid injection and withdrawal is caused in most cases by a change in pore fluid pressure and/or changes in stress in the subsurface.[11]The factor that appears to have the most direct affect in regard to induced seismicity is the net fluid balance, although additional factors may influence the way fluids affect the subsurface.

O&G projects that maintain a balance between the amount of fluid being injected and withdrawn seem to produce very few seismic events. However, projects that inject or extract large volumes of fluids over long periods of time, such as CCS, may have the potential for larger induced seismic events. The risk of induced seismicity from CCS is currently difficult to assess because no large-scale CCS projects are currently in operation. As of yet, there have been no harmful induced seismic events associated with any CCS storage demonstration project.[11] However, the volumes of CO_2 injected at demonstration sites are small in comparison to the volumes being considered for the proposed commercial scale CCS projects. Unlike most water disposal wells, CCS involves continuous CO_2 injection at high rates under high pressures for very long periods of time. The potential therefore exists to increase pore pressures at a volume that is much larger than those affected by other O&G projects. Given that the potential magnitude of an induced seismic event correlates strongly with the magnitude of pore pressure increases and the volume in which it exists, it would appear that CCS may have the potential for significant seismic risk.

The *risk of induced seismicity* is defined as "the description and possible quantification of how induced seismic events might cause losses including damage to structures and effects on humans including injuries and death."[10] Therefore, if seismic events occur in an area where no structures or humans are present, simply put, there is no risk. However, the concept of risk can also be extended to include frequent occurrences of ground shaking that is a nuisance to humans.

Two spatial aspects of risk analysis are important to consider in the context of induced seismicity:

1. **Multiple structures that can be damaged:** a single well that induces earthquakes large enough to cause damage at the surface may damage multiple structures. If seismicity migrates during well operations, which is common for disposal wells, earthquakes have multiple opportunities to impact many structures. For example, even a small community located near a single well will have multiple structures with a range of vulnerabilities to ground shaking.

2. **Multiple well locations:** if a small number of wells, for example, 10, are put into operation, the damage associated with earthquakes induced by those 10 wells can be summarized in **Table 2**. If we define PM as the probability of moderate+ damage given surface ground motion from one well, then the probability of at least one observation of moderate+ damage given that *N wells are in operation* can be calculated as:

$[P_M]_{Nwells}$ = probability of 1 or more moderate+ damaging motions for N wells = $1 - (1 - P_M)^N$ (1)
This probability increases with the number of Wells *N (for P_M=1%).*

Table 2 Probability of Damage Increases with Number of Wells. Adapted from NRC.[11]

Total number of wells (N)	$[P_M]_{N\ wells}$	Expected number of wells causing moderate+ damage
1	1%	0
5	5%	0
10	10%	0
100	63%	1
1000	99.9%	10

The important conclusion here is that, while the risk of minor, moderate, or heavy damage from induced ground shaking may be small for each individual well, a large, spatially distributed operation leads to a higher probability of such damage. This example illustrates that as an industry begins operation with a few wells, there may be no apparent problem with induced seismicity. However, as the industry expands to 100, 1000, or more wells, there is a significant likelihood that induced seismicity will cause damage to structures somewhere, as a result of the larger number of earthquakes and ground motions that are induced, eventhough the probability of any one well producing such ground motions may be small.

5. Risk Relations Matrix

Through assessing the impacts of other major accidents in the energy industry, like the 2010 BP Oil Spill and Fukushima Daiichi Nuclear Accident, and understanding the main risks and factors associated with CCS, it is possible to identify the likely sources and types of losses and estimate the damages they might incur.

The major risks and factors associated with CCS, dealing separately with capture, transport and storage in land-based geological formations and deep ocean ecosystems can be summarized as follows:

A. Global:
- Release of CO2 to the atmosphere

B. Local:
1) CO2 in atmosphere or shallow subsurface:
   a. Suffocation of humans or animals above ground
   b. Effects on plants above ground
   c. Biological impacts below grounds (roots, etc.)
2) CO2 dissolved in subsurface fluids:
   a. Mobilization of metals or other contaminants
   b. Contamination of potable water
   c. Interference with deep-subsurface ecosystems
3) Displacement:
   a. Ground heave;
   b. Induced seismicity;
   c. Contamination of drinking water by displaced brines;
   d. Damage to hydrocarbon or mineral resources[11]

Table 3 shows the types of losses than can occur in the case of an earthquake.

Table 3 Types of losses accounted for in economic analysis of natural disasters. Adapted from NRC.[11]

Loss Type	Descriptor
Direct Losses	Property (Private with residential and non-residential, Public infrastructure
Indirect Losses	Business disruption, Indirect loss from inter-industry effects, Loss of public services Household alternative accommodation Agriculture Transport networks Relief and Response costs Residential and Non-Residential cleanup wages and materials Postpone impacts – cuts in household spending
Intangible Costs	Fatalities, injuries, homelessness, health effects (debilitation) Lost tourism – Environmental, cultural and historic assets.
Net Regional Losses	Rebuilding assistance, survivor benefits, unemployment compensation, aid repayments, node and network disruptions, bottleneck losses outside earthquake affected area, systematic financial and institutional disruption losses.

Since no two CCS sites are the same, in order to quantify the risks associated with any CCS project, risk assessments must be conducted on a site per site basis. Three CCS demonstration projects had recently been announced in Japan at Iwaki, Tomakomai and Kitakyushu, however, following the Great East Japan Earthquake, investigation for CO_2 injection in the Iwaki area was suspended indefinitely. The focus has thus shifted towards the large-scale CCS demonstration project at the Tomakomai Area in Hokkaido for the period of 2012 -2020. This study therefore examines that location.100,000t of CO_2-e or more per year is to be stored in two separate reservoirs under the seabed off the shore of Tomakomai Port at approximately 1100 m and 2400 m, respectively. Two injection wells are to be drilled beside the injection facility.[11]It is imperative to have a clear understanding of the characteristics for the surrounding area to anticipate who could be affected by and what socio-economic, health and environmental impacts any accident could imply. **Table 4** describes the socio-economic status of the Tomakomai area.

Table 4 Socio-Economic Status of Tomakomai Area. Adapted from Abe.[12]

Tomakomai City has two ports and one airport. It is also home to Japan's largest paper industry and a large industrial complex including oil refineries, coal-fired power plants and auto-assembly plants.			
Location:	South-Western Hokkaido (ca. 800km North of Tokyo)		
Area::	561 Km^2		
Population:	174,069		(2010)
Economy:	Manufacturing	1.169 billion yen (US$14M)	(2008)
	Agriculture	1.6 billion yen (US$19M)	(2008)
	Fishery	2.7 billion yen (US$32M)	(2008)
CO_2 Emissions	2.8 million t/y		(2007)

Based on the criteria presented in this paper, six risk scenarios have been proposed for the risk relations matrix: Instantaneous release of ≤ 1000 t CO_2-e; Catastrophic release of≤ 100,000 t CO_2-e; Induced Seismic Activity ≤ 5.5 (richter scale) (no release); Induced Seismic Activity ≤ 5.5

combined with catastrophic release; Catastrophic Earthquake resulting from Induced Seismic Activity ≥ 5.5 (no release); and Catastrophic Earthquake resulting from Induced Seismic Activity ≥ 5.5 combined with catastrophic release. **Fig. 3** is a sample of the risk relations matrix.

The average coal-fired power plant per megawatt of peak capacity employs 0.18 people in operations and maintenance on a permanent basis.[13] Thus, the average 300 MW coal-fired power plant would employ 54 people in operation & maintenance on an ongoing basis. If there was an instantaneous release of ≤1000 t of CO_2-e, the only likely receptors would be workers within closest proximity of the CO_2 plant and injection site. If we assume the previously ascertained SLOT and SLOD toxic loads, dependent on its rate of leakage and dissipation, we can assume a fatality rate of 1% - 5% and 50%, respectively. This assumes claimants would be able to seek maximum damages in line with occupational wrongful death claims. Also, it does not consider long-term or permanent/generational damages to the agriculture and fishery sectors; rather those values are simply based on annual revenues. Nor does it quantify indirect losses or consider penalties for CO_2 emissions returning to the atmosphere and other trans-boundary issues. Therefore, the lower and upper boundaries of damages from the accident would be $170,000 and $376 million, respectively. If, however, we had a catastrophic release of ≤ 100,000 t CO_2-e, assuming the whole population (174,069) of the surrounding area would be at risk and dependent on its rate of leakage and dissipation, along with the weather and wind conditions, the impacts would be much further reaching. The lower and upper boundaries from such an accident would be $547 million and $121 billion.

Induced seismic activity can have a range of effects. If the seismic activity falls within a range ≤ 2, it is unlikely to have any noticeable impacts. If however, it falls in the range of ≥5.5, noticeable ground shaking is likely to be felt in the local vicinity and can cause structural damage to infrastructure in the nearby area. In the worst case scenario of a catastrophic earthquake resulting from induced seismic activity≥ 5.5 combined with catastrophic release, we could see insurmountable economic impacts. The Japanese cabinet office reported that the overall infrastructure damages from the Great East Japan Earthquake on March 11, 2011, one of the worst earthquakes in the world, totalled $44 billion, including damage to railways, roadways, and other transportation hubs, which could not be operated safely or were closed for repairs.[8]This puts potential damages of a major CCS accident in the range of $165 billion. Coincidentally, from Tomakomai, the nearest nuclear power plant is located a mere 120km away in the city of Tomari

6. Liability and Insurance

The BP Oil Spill provided the first major test of the US oil spill containment and response apparatus put in place by the Oil Pollution Act (OPA). OPA holds each "responsible party" liable for the costs of containment, clean-up, and damages sustained as a result of a spill. In addition to protecting the environment, environmental laws serve a secondary purpose of reassuring the public that industrial activities can proceed in a safe and environmentally responsible manner. However, if major spills can persist for several months before being resolved, one may question whether or not OPA is adequate. Some environmentalists go so far as to argue that deepwater oil production is simply too risky to be allowed to continue because the BP Oil Spill ran unabated for 3 months even with OPA.[5]

Providing financial assistance and compensation for losses in a large-scale disaster is always a major post-recovery task. Decisions on assistance and compensation will affect not only the pace of recovery, but also economic growth and attitudes toward preparedness for future disasters. In Japan, the earthquake and tsunami caused catastrophic damage to infrastructure, property and industry in affected areas. The damage was compounded by the subsequent nuclear accident, which caused the evacuation of all people within 20 km of the reactor.[14]

Ever since the first nuclear reactors were built, there has been concern about the possible effects of a severe nuclear accident, coupled with the question of who would be liable for third-party consequences. This concern was based on the hypothesis that a cooling failure causing the core to melt down could result in major consequences akin to those of Chernobyl.[13] It was apparent that potential damages could be widespread, creating the need for compulsory third party insurance schemes for nuclear operators and international conventions to deal with trans boundary damage disputes. Conversely, nuclear power was also recognized as a valuable contribution to meeting the world's increasing energy demands and thus to continue doing so, individual operator liability had to be limited and risk had to be socialized.

Risk Scenario	Description	Factors	Direct Losses ($1000)																Indirect Losses
			Human				Infrastructure			Agriculture			Manufacturing			Fisheries			
			Description		low	up		low	up	Description	low	up	Description	low	up	Description	low	up	
Instantaneous release ≤1000t of CO_2-e	Leakage resulting from direct CO_2 capture; pipeline failure; failure at injection well	Source of release; Weather conditions; Wind speed and direction, etc.	Occupational risk (chronic, and acute cardiovascular and respiratory risk at concentrations exceeding 3%); Asphyxia at concentrations above 15%	Fatality	314	8,911	Associated plant damage, eg. pipelines	0	100	Negligible	0	100	Negligible	0	100	Negligible	0	100	Business disrupt-ion, Loss of public services; Relief and response cost
				Hospital	0	5,000													
				Non-hospital	0	100													

Figure 3 CCS Risk Relations Matrix. (*Based on 2011 Virginia (5.8) and Great East Japan Earthquake (9.0) Earthquakes.)[9, 15]

Risk Scenario	Description	Factors	Direct Losses ($1000)																Indirect Losses
			Human				Infrastructure			Agriculture			Manufacturing			Fisheries			
			Description		low	up		Low	up	Description	low	up	Description	low	up	Description	low	up	
Induced Seismic Activity ≥5.5 (no release)	Significant ground shaking	Magnitude; Local geology; Site-characteristics etc.	Loss of life and injuries resulting from ground shaking, infrastructural damage, barriers to emergency response.	Fatality	314	8,911	Damages to resdiences and other infrastructure, i.e. businesses; public buildings; roads and other transportation networks.	0	300,000*	Loss of livestock and harvestable land resulting from ground shaking, Loss of production	0	19,000	Loss of infrastructure resulting in loss of production	0	14,000	Negligible	0	100	Business disrupt-ion, Loss of public services, Relief and response costs
				Hospital	0	5,000													
				Non-hospital	0	100													

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Risk Scenario	Description	Factors	Direct Losses ($1000)																	Indirect Losses
			Human				Infrastructure			Agriculture			Manufacturing			Fisheries				
			Description		low	up		Low	up	Description	low	up	Description	low	up	Description	low	up		
Catastrophic Earthquake resulting from Induced Seismic Activity ≥5.5 combined with catastrophic release	Severe ground shaking (possible tsunami). Contamination of drinking water by displaced brines; Damage to hydrocarbon or mineral resources; Leakage by vertical transport into the atmosphere; leakage by vertical or lateral transport into aquatic ecosystems or underground drinking-water reservoirs	Magnituede; Epicenter; Local geology; Population resiliency; Source of release; Weather conditions; Wind speed and direction, etc.	Loss of life and injuries resulting from severe ground shaking , severe infrastructural damage; barriers to emergency response. Risk to general population (chronic, and acute cardiovascular and respiratory risk at concentrations exceeding 3%); Asphyxia at concentrations above 15%.	Fatality	314	8,911	Damages to residences and other infrastructure, ie. Businesses; public buildings; roads and other transportation networks	0	44,000,000*	Loss of livestock and harvestable land resulting from severe ground shaking , Loss of production. Suffocation of animals above ground; Effects on plants above ground; Biological impacts below grounds (roots, etc).	0	19,000	Loss of infrastructure resulting in loss of production	0	14,000	Disruption of aquatic ecosystems resulting in loss of production	0	32,000		Business disruption; Loss from inter-industry effects, Loss of public services; Household alternative accomodation; Transport networks; Relief and response cost; Residential and non-residential cleanup wages and materials; Postponed impacts-cuts in household spending, Lost tourism, environmental, cultural and historical assets.
				Hospital	0	5,000														
				Non-hospital	0	100														

Figure 3 CCS Risk Relations Matrix. (*Based on 2011 Virginia (5.8) and Great East Japan Earthquake (9.0) Earthquakes.)[9, 15]

That is, as with everything else in industrial societies, the state was required to accept responsibility as insurer of last resort, which means ultimately the burden of costs lies upon taxpayers. Considering the huge revenues generated by the nuclear industry, this should be considered unacceptable. The structure of insurance for nuclear power plants is different from ordinary industrial risks. Insurance is enlisted with either one of the many national insurance pools, which brings together insurance capacity for nuclear risks from the domestic insurers in the local country, or into one of the mutual insurance associations such as Nuclear Electric Insurance Limited (NEIL). These are set up by the nuclear industry itself. Third Party liability involves international conventions, national regulations channeling liability to the operators and pooling of insurance capacity in more than twentycountries.[14]

Currently, there is no available insurance for the long-term liability of CCS. The commercial uptake of CCS hinges on the emergence of a credible carbon price and incremental costs and risks that will not be so high as to dissuade investors. Clearly, a new insurance mechanism is required to deal with the catastrophic possibilities outlined in this paper. Therefore, this research recommends that CCS follows a similar path towards the development of an insurance scheme like those stipulated above for the nuclear industry. However, rather than taking the shape of national insurance pools, which Fukushima (for which there was no limit on liabilities) has proven to be inadequate in the case of a major accident, this paper proposes further research towards the development of an international insurance pool based on the carbon trading market. If a credible carbon price can be met, pooling a percentage of the money generated from the trading of each ton of CO_2 internationally over the duration of CCS activities, with the appropriate regulatory overview, could provide highly significant (if still not sufficient) financial assistance in case of a major accident.

7. Conclusion

This paper has shown that the current regulatory structures and insurance schemes available in the energy industry are inadequate to respond to the financial impacts of major accidents as demonstrated by the 2010 BP Oil Spill in the Gulf of Mexico and Fukushima Daiichi Nuclear Accident. A comparative risk relations matrix was developed to estimate the lower and upper boundaries of potential damages of a major accident resulting from the risks associated with CCS. Based on those results, this paper proposes further research on international insurance pools based on a proportion of the carbon trading market as a method for resolving long-term liability issues and making CCS more readily acceptable to the public. By capturing a small percentage of the money generated by the international carbon trading market, it would be reasonable to assume that a majority of accidents, which are at the lower end of the risk assessment matrix, can be covered internally. This research recognizes, however, that even such a scheme is unlikely to cover accidents of worst case scenarios at least in the short-term, whilst also recognizing that accidents of this scale are unlikely. This paper also recognizes CCS, as was the case with nuclear energy, as an attractive and necessary technology towards sustainable energy development and concludes that such an insurance scheme could aid its uptake by resolving long-term liability concerns.

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