CARBON CAPTURE AND STORAGE: A CASE STUDY OF EMERGING RISK ISSUES IN THE iNTeg-RISK PROJECT†

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This paper describes the iNTeg-Risk Carbon Capture and Storage (CCS) case study including: identification of example hazards in the CCS process including capture, transport, injection and storage; analysis using bow-tie techniques; modification of risk matrix approaches to include potential releases in the very long term from storage sites; use of life cycle analysis approaches; possible key performance indicators (KPIs); and knowledge gaps in terms of addressing emerging risk issues. One of the key features of the CCS case study is the need to include the time dimension in the risk assessment. The assessment needs to include both short-term potential accidents (from capture, transport or injection) as well as very long term risks from storage.

KEYWORDS: emerging risk, CCS, bow-tie, time dimension, KPI, life-cycle analysis

INTRODUCTION

The European iNTeg-Risk (Early Recognition, Monitoring, and Integrated Management of Emerging, New Technology related Risks) project (EU-VRi, 2009) is aimed at improving the management of emerging risks, related to new technologies in European industry. iNTeg-Risk is an FP7 (Seventh Framework Programme for Research and Technological Development) project in the area of "Nano-sciences, Nano-technologies, Materials and new Production Technologies." It is a large-scale integrating project with 88 European and international partners. The project aims to build a new management paradigm for emerging risks, as a set of principles supported by a common language, agreed tools and methods, and key performance indicators (KPIs), all integrated into a single framework.

iNTeg-Risk is using a number of ERRAs (Emerging Risk Representative Applications), which are case studies of emerging risks to inform the development of the framework. The subject of this paper is one of these ERRAs, which concerns the emerging technology of carbon capture and storage (CCS). Each of the ERRAs explores emerging risk issues in specific areas and reports results in terms, which can then be used and generalised by subsequent parts of the iNTeg-Risk project. These subsequent parts include:

- Creating an integrated scientific and technology framework. This is the iNTeg-Risk Emerging Risk Management Framework (ERMF).
- Application, verification and validation of the tools and methods in the framework.
- A One-Stop-Shop for dissemination of the outputs and tools of the project.

This paper presents results from the CCS ERRA. The main focus of these results is on issues and solutions that can be generalised to other emerging risks and which can therefore contribute to the subsequent stages of the iNTeg-Risk project. Within the CCS ERRA, HSL led the work package and was responsible for considering safety issues from above ground installations (capture, transport, injection); INERIS considered environmental aspects and below ground (storage) installations; and 2B considered life cycle analysis approaches with inputs from HSL and INERIS.

In order for the results of different ERRAs to be comparable, the ERMF provides a common understanding of the dimensions of emerging risks (see Figure 1). These dimensions are:

- [T] Technical, Technological: Technical knowledge and technologies supporting the knowledge.
- [H] Human, Management: Skills of personnel and organization of the human resources.
- [C] Communication, Governance: A process with clear definition of the role and responsibilities of the management of a decision-making process involving several stakeholders, and the associated communication organization.
- [R] Regulation, Policies, Standardization: Clear and complete regulatory framework, standards and norms.

THE NEED FOR CCS AND THE RISK OF GLOBAL WARMING

The development of advanced clean energy technologies must be accelerated to address the global challenges of energy security, climate change and sustainable development. This pressing need was acknowledged by the Ministers from G8 countries (Canada, France, Germany, Italy,

Figure 1. The iNTeg-risk emerging risk management framework (EMRF)

Japan, Russia, the United Kingdom and the United States) at their meeting in June 2008 in Aomori, Japan. There is now a general consensus of scientific opinion that unless greenhouse gases in the atmosphere are controlled, the result will be global warming, with associated climate change, gradual melting of polar ice, and a rise in sea levels. The analysis by the International Energy Agency (IEA) (2008) projects that energy sector CO_2 emissions will increase by 130% above 2005 levels by 2050, in the absence of new policies or from supply constraints resulting from increased fossil fuel usage.

Addressing this increase will require an energy technology revolution involving a portfolio of solutions: greater energy efficiency, increased renewable energies and nuclear power, and the near-decarbonisation of fossil fuel-based power generation. The IEA CCS Technology Roadmap (2009) states that carbon capture and storage (CCS) is the only technology available to mitigate greenhouse gas (GHG) emissions from large-scale fossil fuel usage in fuel transformation, industry and power generation. The Roadmap sets out an ambitious programme of development of CCS including investment of approximately US$3 $\times$ 10^{12} between 2010 and 2050 to achieve a 50% reduction in CO_2 emissions by 2050. It follows that the next 40 years will see a massive development and implementation of this new technology, which currently has only a small (but increasing) number of small-scale demonstration projects worldwide.

CCS is therefore an emerging risk because it is

- introducing new technologies;
- massively increasing the uptake of these technologies, so that the frequency of hazardous events will increase;
- the number of hazards is growing with the number of installations; and
- the exposure to the hazards is growing.

TECHNOLOGIES INVOLVED IN CCS

The CCS chain involves:

- Capture of CO_2 from a generator such as a power station, steelworks, cement works etc. Several capture technologies are possible including post-combustion capture; pre-combustion capture producing synthesis gas; and oxy-combustion capture.
- Transport to the injection site. This is likely to be by pipeline, could possibly involve ship transport and may involve intermediate storage.
- Injection of the CO_2 into the storage.
- Storage in an underground saline aquifer, depleted oil/gas reservoir or coal bed. Storage is said to start when injection is completed. The injection well would be decommissioned and capped. Monitoring of the storage site may be required indefinitely and this may require monitoring wells to be maintained.

Figures 2 and 3 illustrate all these stages. The technology is still in development, with demonstration projects being planned, and a few being commissioned worldwide.

EMERGING RISK ISSUES

In line with the Integ-Risk paradigm, some main aspects of CCS risks include:

- From the technical point of view, an event or characteristic of one element of the system may have an impact on other elements – e.g. quality of the capture stage will drive the levels of impurities, hence the possible consequences such as corrosion during transport and injection, and also the geochemistry within the storage itself in the longer term.
- From the social point of view, the whole chain (technology) is at stake. This emerging technology has to demonstrate its safety and its low impact on the environment. It will be necessary to ensure feedback to various

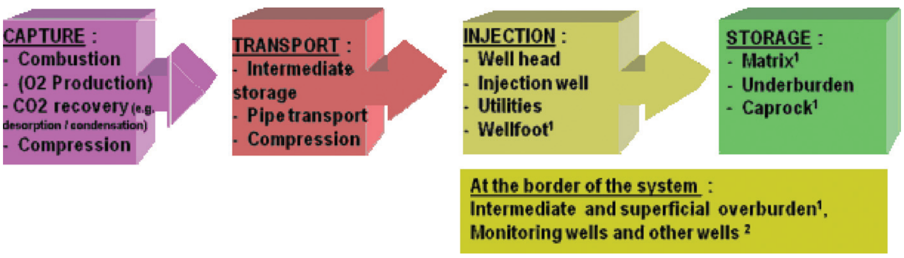

Figure 2. The CCS chain (Farret et al., 2010)

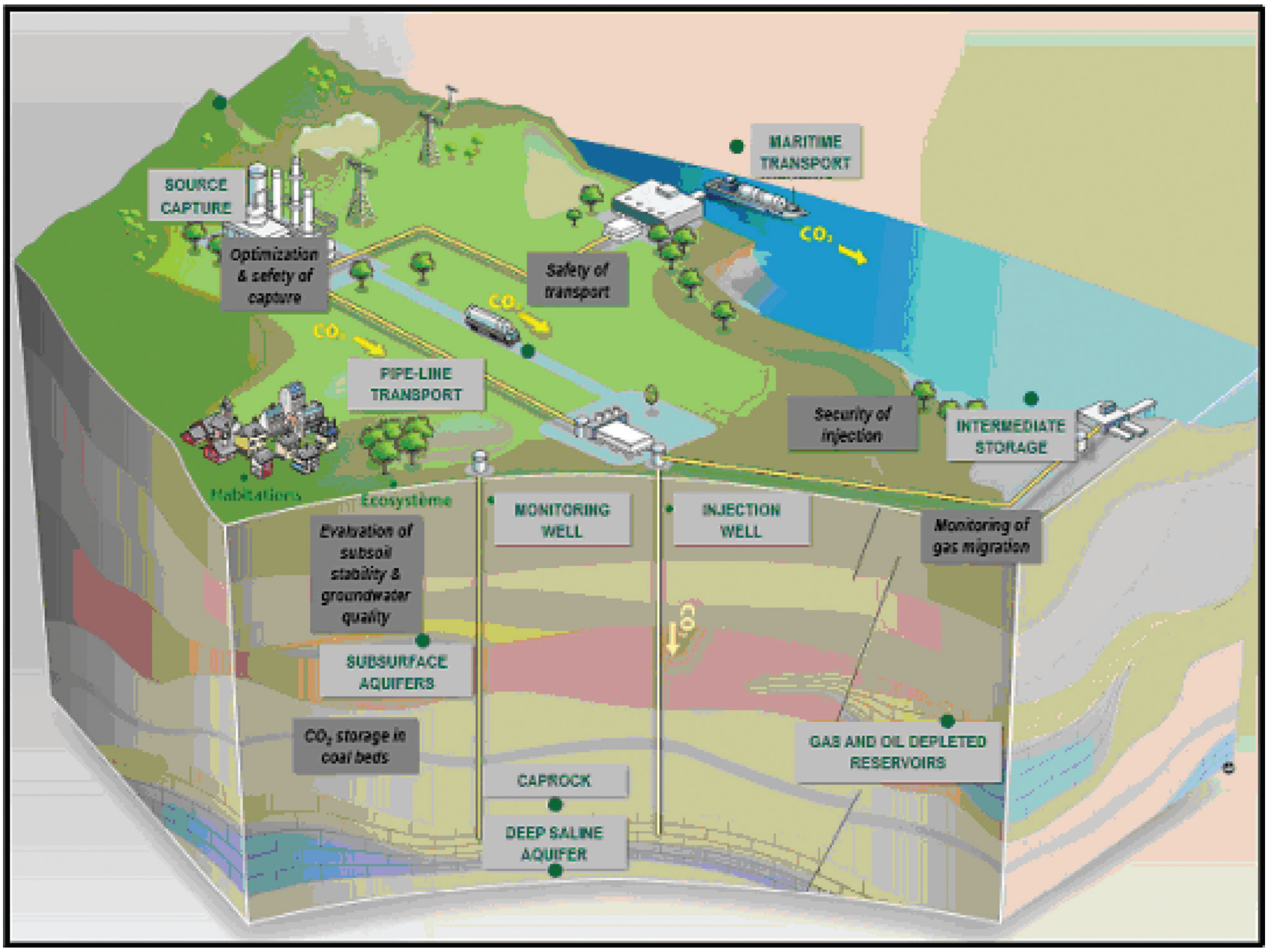

Figure 3. The CCS process chain (Farret et al., 2010)

stakeholders including: regulators, non-government organisations (NGOs), public/local associations etc. Inadequate risk communication could affect the uptake of CCS and hence impact on risks arising from global warming.

- Significantly long time-scales have to be taken into account in any risk assessment, particularly for CO_2 storage.
- There is a lack of experience – the oldest injection site was initiated in Sleipner in 1996. However, for surface systems, there is some formalised experience from industrial safety, and concerning long-term risks from underground storage, experience in nuclear waste disposal or in the underground storage of hydrocarbons may have some relevance.

All these elements highlight the need for a novel risk assessment methodology, and also provide a good basis on which to build the framework.

CARBON DIOXIDE RELEASE CONSEQUENCES

Hazards from CCS processes have been systematically identified in a number of studies. These include, for example, Connolly & Cusco (2007) and Wilday et al. (2009a). Although it is not classified as "toxic," CO_2 is more than just an asphyxiant and causes physiological effects including increased breathing rate and acidosis. Given the large quantities and flow rates which will be used for CCS, major releases could produce significant hazard ranges at concentrations high enough to have toxic effects. This has caused HSE to set both major hazards toxic dose criteria (HSE, 2009) and offshore impairment criteria (HSE, 2008) for CO_2. The Netherlands have also set major hazards criteria in terms of concentration (RIVM, 2009).

There are knowledge gaps in modelling the consequences of CO_2 releases. For example, pipeline transport is likely to be dense phase (liquid above the thermodynamic critical pressure but below the critical temperature). A release is likely to produce some solid CO_2 (see Figure 4); there are thus uncertainties in CO_2 source term modelling (e.g. correct modelling of CO_2 to include solid formation, choice of source term scenario including conditions under which running failures of CO_2 pipelines would occur, effects of impurities, possible formation of hydrates and

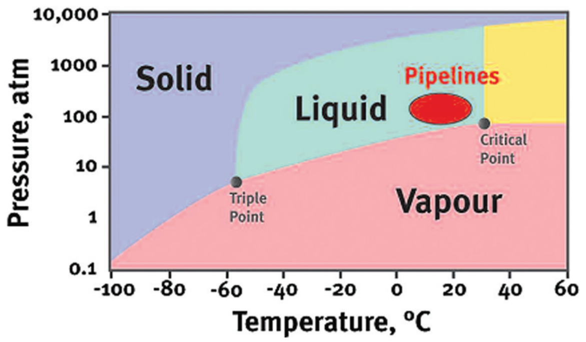

Figure 4. Phase diagram for carbon dioxide

clathrates etc.). Some of these uncertainties have been addressed by modifications to the DNV PHAST consequence modelling code (Witlox et al., 2009). This was used to model CO_2 releases from pipelines (Wilday et al., 2009b) and refrigerated storage (Harper, 2010) which show that technical evidence suggests that CO_2, when captured, transported and injected in the quantities required for CCS, has major accident potential. There are further knowledge gaps and uncertainties in modelling potential releases from underground storage.

HAZARD IDENTIFICATION AND BOW-TIE ANALYSIS

From more detailed hazard identification exercises such as Wilday et al. (2009a), a number of top events were chosen for further analysis within the iNTeg-Risk CCS ERRA (Farret et al., 2010). The three main targets considered were:

- Humans i.e. safety (acute effects) & health
- Ecosystems i.e. flora, fauna and microfauna.
- Human activities including exploitation of resources (mining, underground water etc.) or land use

Bow tie analysis (see Figure 5) was used to further understand the risks. This links the causes with impacting phenomena (IP). The following were identified as the main IP:

(1) **E – Explosions** (*effect : overpressure & thermal*)
(2) **F – Fires** (*thermal effects*)
(3) **SE – Sudden Emission/Emanation of gas** e.g. CO_2 mixture (*toxic effect*)
(4) **DE – Diffuse Emission/Emanation of gas** e.g. CO_2 mixture (*toxic effect*)
(5) **P – Pollution by CO_2 mixture** (*toxic effect or effect on resource*)
(6) **Po – other pollution** e.g. by brine at a long distance
(7) **M – Mechanics and ground movement** (*mechanical effect:deformation/acceleration)*
(8) **H – Hydraulics**: perturbation of the hydraulic regime, flow, overpressure etc. in the reservoir

The impacting phenomena are the result of undesired events. They are modified by safety measures (M) which can be categorised as:

- Safety barriers: prevention/mitigation – (hardware/organisational)
- Conception/ inherent safety
- Monitoring
- Protection the targets (land use, choice of the location of the injection well etc.)

DyPASI METHODOLOGY FOR IDENTIFICATION OF ATYPICAL EVENTS

For surface installations (capture, transport, injection) a bow-tie analysis was carried out in detail for a small number of top events using the MIMAH bow-tie methodology (Delvosalle et al., 2004) developed by the EC ARAMIS project. This provides a formal process for the development of bow-tie diagrams for specific types of process equipment. Equipment, which was considered in detail, included:

- Post combustion capture: CO_2 absorber
- Pre-combustion capture: CO_2 absorber and air separation unit (ASU), considered as a unique distillation column
- Oxyfuel combustion: Boiler/furnace, recycle pipe, ASU (same analysis as performed for pre combustion capture)
- Transport: compressor and pipeline

In addition, DyPASI (Dynamic Procedure for Atypical Scenarios Identification) (Paltrinieri et al., 2010a,b,c) was applied. DyPASI was developed in another workpackage of the iNTeg-Risk project and is concerned with the identification of "atypical events", i.e. those events which can be missed by other hazard identification techniques. The development of DyPASI focussed on the Buncefield incident, which had not been identified as a credible scenario despite events with many similarities having occurred previously worldwide. DyPASI was designed to form a complementary part of MIMAH and includes a review of relevant historical incidents, research and modelling.

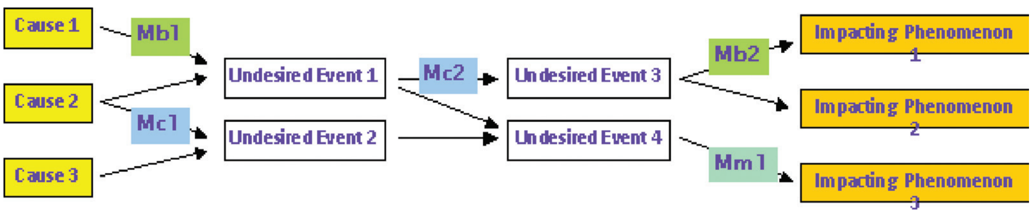

Figure 5. Generic bow-tie diagram (Farret et al., 2010)

Even though CO_2 is not classified as toxic, using DyPASI for the CCS analysis ensured that the MIMAH methodology considered events due to the toxic effects of CO_2. The condition of "high concentration of CO_2" was introduced by DyPASI as a prerequisite for the MIMAH dangerous phenomenon of "toxic cloud" within the bow-tie diagrams.

UNDERGROUND STORAGE

A number of factors affect possible releases from underground storage and introduce considerable uncertainty. Firstly, in depleted oil fields, many ancient wells are unknown, and many are poorly plugged (completed). Secondly, within or along a well many different pathways are possible (through the cement, after its lixiviation, along the interface casing/cement or cement/rock, within the excavation damaged zone of the rock (EDZ)) and it is difficult to know, in the longer term, if a well will be safe even if it was well-understood/characterised and well-completed (plugged). There is also a lack of knowledge of the impurities (nature, rate), which will be injected into the sink along with the CO_2. Impurities can have important effects on the hazards. The behavior of key systems in the longer term is also difficult to quantify, such as the well and its plugs, the caprock and its interface with the reservoir. Taking into account the heterogeneity of the local geology is also a challenge (e.g. existence and location of faults, or local changes of key parameters).

INCLUDING THE TIME DIMENSION IN RISK ASSESSMENT

When considering risks from CCS, significantly long time-scales have to be taken into account because of the long-term nature of underground storage and this has been considered by Farret et al. (2010). The total time to be considered needs to be at least 1000 years, the duration of an efficient storage. All emerging risks exhibit a time dimension to some extent because of time taken for any new technology to be developed and implemented; and for any new risk to emerge, be recognised and be controlled. For CCS the time dimension is even more important because of the need to prevent reintroduction of stored CO_2 into the atmosphere well into the future, when it is possible that the location of injection wells and storage sites could have been forgotten.

For CCS, some risks concern only the exploitation phase (e.g. explosion in the surface equipment). However some events may concern all time periods (e.g. a seismic event), and some specific causes that occur in the exploitation period (e.g. amount of impurities, location and other concept design aspects of injection wells) may also have consequences in the longer term. It is necessary to assess and manage all these risks within a single framework. The solution to this has been to develop a three-dimensional risk matrix as shown in Figure 6, which combines: probability P, severity S and time period T. For illustration purposes, this considers three life periods for the CCS system:

- exploitation (30 to 50 years),
- monitoring (to a maximum of 150 to 200 years – this includes the period where there is no longer active monitoring but where the memory of the site remains),
- longer term (up to 1000 years, which means that the site and its risks may be forgotten by the society).

It is also possible to present this as one conventional probability/severity risk matrix for each time period, as

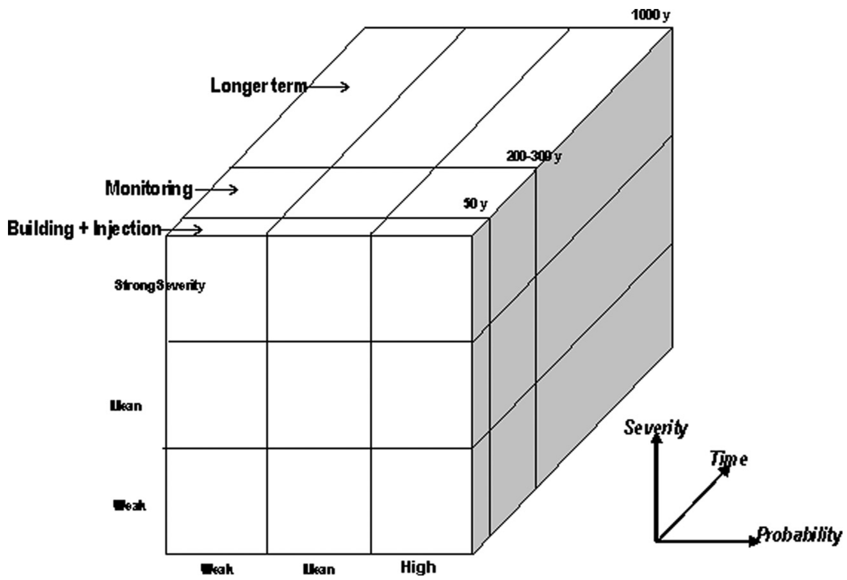

Figure 6. Three-dimensional risk matrix to introduce the time dimension into risk assessment (Farret et al., 2010)

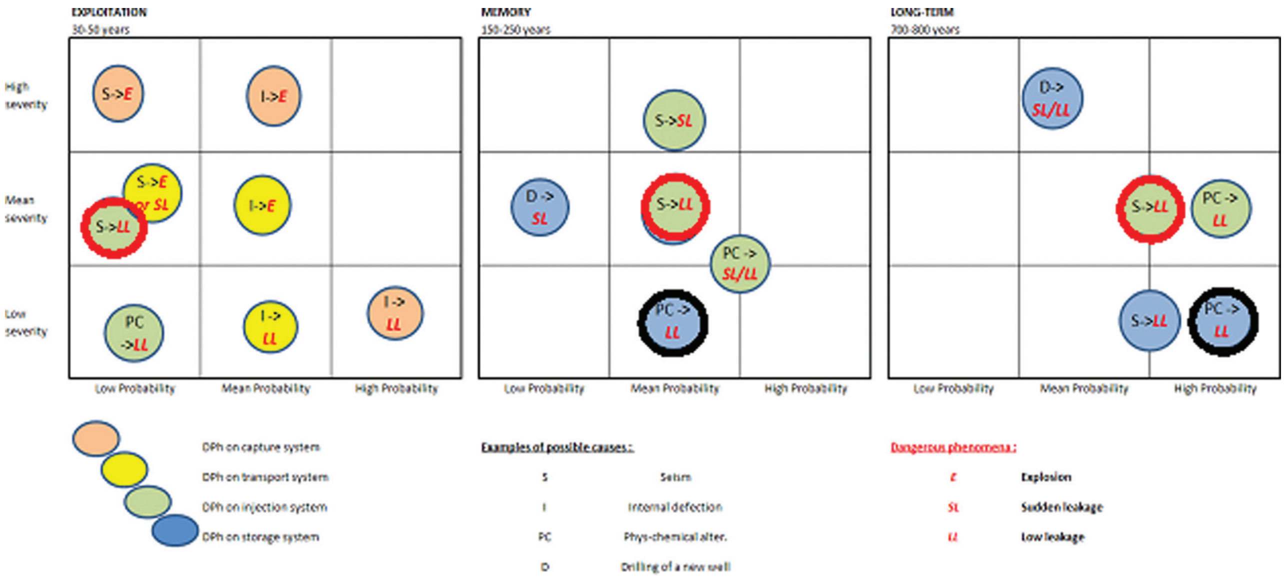

Figure 7. Alternative representation of three-dimensional risk matrix including the time dimension (Farret et al., 2010)

shown in Figure 7. As can be seen, events can be plotted on the matrix and their development can be seen over time. It would also be possible to take account of uncertainty be means of different sized envelopes to represent events.

LIFE CYCLE ANALYSIS

Life cycle analysis (LCA) is a formal technique that allows comparison of options on the basis of a number of factors which are predominantly environmental in nature. CCS was used as a case study for considering LCA approaches. The application of LCA to CCS by means of a simplified LCA study (Breedveld et al., 2010) has highlighted some interesting aspects:

- The overall assessment of the environmental performance of CCS technologies is highly dependent on the weighting of GHG emissions against other impacts. This is particularly illustrated by Table 1 which shows the life-cycle effect of CCS technologies in terms of the change in greenhouse gas emissions, as evaluated using different LCA methodologies;
- Integrated Gasification Combined Cycle (IGCC) with pre-combustion carbon capture and storage gives a better environmental performance than pulverised coal boiler, subcritical, with post-combustion carbon capture and storage;
- The significance of upstream and downstream processes and the trade-off between GHG emissions and other impacts, illustrate the need of a life cycle approach in order to evaluate CCS technologies.

Table 1. Estimated performance of CCS using different LCA methodologies (Breedveld et al., 2010)

LCIA-method	Best performance CCS	Worse performance CCS
IPCC 2007	Reduction of 73%	Reduction of 63%
Ecoindicator 99	Reduction of 17%	Increase of 2%
Recipe 2009	Reduction of 38%	Reduction of 23%
CML 2001	Reduction of 12%	Increase of 6%
EDIP 2003	Increase of 13%	Increase of 40%
EDIP 2003 without bulk waste	Reduction of 14%	Reduction of 1%

An issue for emerging risks is the availability of adequate data to allow LCA to be performed. This inevitably leads to uncertainty in the results. Nevertheless LCA adds a very useful dimension to information about risks that can particularly help in determining the best technological options. However the uncertainty highlights difficulties for risk communication and also the need for demonstration projects and further development of the technology.

KEY PERFORMANCE INDICATORS FOR EMERGING RISK

Key performance indicators (KPIs) are being developed by the iNTeg-Risk project so as to help measure and track emerging risk issues (ERIs). These are high level KPIs which are concerned with the control of an emerging risk on a global scale, rather than being specific to any particular installation. Indeed, the KPIs need to be capable of use even at the concept stages of any new technology, before any installations have been built.

Some ERIs that are relevant to CCS include:

1. the time factor and the need to consider both short term and very long term risks;

2. uncertainty: this will be in common with most emerging risks as it is in their nature that risk assessment is necessary before the technology or other risk drivers have been fully developed;
3. non-acceptability is itself an intrinsic risk, since CCS is itself a solution to the risk of global warming.

The following examples refer to the iNTeg-Risk EMRF which is shown in Figure 1 and which defines the dimensions of risk as T (Technical), R (Regulatory, Standards), H (Human) & C (Communication, Governance):

- T: Is there a consensus between experts (about what the additional risks are, how they can be measured or controlled)?
- C/T: Are we able to identify all major sources of uncertainty? Are we able to estimate this uncertainty, or at least to compare to the uncertainty of other risks?
- H/T/C: Have the risks of the interface with other plant installations been evaluated?
- R: Are all the risk issues covered by adequate regulation?

KNOWLEDGE GAPS

A number of gaps in knowledge specific to emerging risk from CCS were identified. However iNTeg-Risk is interested in knowledge gaps that can be generalised to emerging risks as a whole. Key knowledge gaps include:

- T/R: **Risk assessment.** There will be uncertainties and gaps in knowledge of how to model risk for many emerging technologies as many of the inputs are uncertain until the technology is further developed. This impacts both major hazards risk assessment and LCA. It is possible to be precautionary but this can be unhelpful in communicating risks. Experimental validation of models may be needed and may require consensus about the issues to facilitate joint funding.
- T/H/R: **Lack of expertise concerning the technology.** This includes lack of standardisation of design features that can reduce and control risk. It also includes the need to educate a new workforce in the hazards of a new technology.
- C: **Risk communication.** Risks need to be communicated to the public and politicians in such a way that rational decisions can be made about the uptake of a new technology and the controls needed. It is not clear what is the best way to achieve this communication.

CONCLUSIONS

The European iNTeg-Risk project is concerned with improving the management of emerging risks, related to new technologies in European industry. This paper describes a CCS case study from the standpoint of identifying issues which can be generalised and applied to other emerging risks.

Hazard identification needs to have a wide scope and not be limited by classification issues. For example CO_2, while not classified as toxic, can still give rise to major accident hazards when stored or transported in large enough amounts.

The DyPASI methodology for taking account of atypical events in hazard identification was helpful when applied to CCS.

It is important to include the time dimension in any risk assessment of emerging risks and even more so for CCS. A three-dimensional risk matrix has been proposed for this purpose.

Life cycle analysis can add value to risk decisions but the lack of input data for rapidly developing technologies leads to high levels of uncertainty in the results.

High level KPIs can be useful in measuring the progress of emerging risk issues.

For CCS (and probably other emerging risks) the possible unacceptability of the risk is also a risk e.g. CCS is a solution to the emerging risk of global warming.

Knowledge gaps for emerging risks, in general, include uncertainties in risk assessment; lack of experience, including lack of standards and the need to educate a new workforce; and the best way to achieve risk communication with politicians, the public and other stakeholders.

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REFERENCES

Breedveld L, Paltrinieri N, Wilday J, Farret R, (2010), Application of LCA to carbon capture and storage, 2B report, Version 1 – August 7th, 2010.

Connolly, S, Cusco, L, (2007), "Hazards From High Pressure Carbon Dioxide Releases During Carbon Dioxide Sequestration Processes," IChemE Symposium Series No 153.

Delvosalle C, Fiévez C, Pipart A, (2004), ARAMIS Deliverable D.1.C, WP 1, Faculté Polytechnique de Mons, Major Risk Research Centre.

EU-Vri, (2009), iNTeg-Risk Info Sheet (November 2009), ver. 15.0, http://www.integrisk.eu-vri.eu/home.aspx?lan=230&tab=51&pag=62

Farret R, Hebrard J, Gombert P, Lahaie F, (2010), Risk assessment of the entire CCS technology: a necessary adaptation of the systemic risk analysis methods for industrial safety, INERIS report INERIS-DRS-09-102637-10460A, v5.

Harper P, (2010), The Inclusion of CO_2 as a Hazardous Substance in the Seveso Directive, HSE paper to EC Review of the Seveso II Directive, http://www.hse.gov.uk/seveso/co2-hazardous-substance.pdf

HSE, (2008), Assessment of the Dangerous Toxic Load (DTL) for Specified Level of Toxicity (SLOT) and Significant Likelihood of Death (SLOD), http://www.hse.gov.uk/hid/haztox.htm, revised 21.10.08

HSE, (2009), Indicative human vulnerability to the hazardous agents present offshore for application in risk assessment of major accidents, SPC/Tech/OSD/30, http://www.hse.gov.uk/foi/internalops/hid/spc/spctosd30.htm

IEA, (2008), *Energy Technology Perspectives 2008*, http://www.iea.org/techno/etp/ETP_2008_Exec_Sum_English.pdf

IEA (2009) Technology Roadmap Carbon Capture and Storage, http://www.iea.org/papers/2009/CCS_Roadmap.pdf

Paltrinieri N, Wardman M, (2010a). Integ-Risk deliverable D1.4.4.3, Integ-Risk project, 2010.

Paltrinieri N, Wardman M, Dechy N, Salzano E, Cozzani V, (2010b), Towards a checklist for identification of atypical event scenarios, 2nd Integ-Risk Conference Proceedings. Stuttgart 14th–18th June 2010.

Paltrinieri N, Wardman M, Dechy N, Salzano E, Cozzani V, (2010c), Atypical major hazard scenarios and their inclusion in risk analysis and safety assessments, ESREL 2010. Rhodes 5th–9th September 2010.

RIVM, (2009), Evaluation of the acute toxicity of CO_2, http://www.rivm.nl/milieuportaal/images/20091002_Evaluation_toxicity_CO2.pdf

Wilday AJ, Moonis M, Wardman MW, Johnson M (2009a), Safety in Carbon Dioxide Capture, Transport and Storage, International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) Technical Report No 2009/6.

Wilday AJ, McGillivray A, Harper P, Wardman M, (2009), A comparison of hazard and risks for carbon dioxide and natural gas pipelines, IChemE Symposium Series No 155, 392–398.

Witlox HWM, Harper M, Oke A, (2009), "Modelling of discharge and atmospheric dispersion for carbon dioxide releases", J. Loss Prev. Process Ind. 22 pp 795–802.

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