Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 37 (2013) 2811 – 2818

Energy Procedia

GHGT-11

Identification of hazards and environmental impact assessment for an integrated approach to emerging risks of CO_2 capture installations

Nicola Paltrinieri[a,b,]*, Leo Breedveld[c], Jill Wilday[d], Valerio Cozzani[b]

[a]SINTEF Technology and Society, Safety Research, S. P. Andersens veg 5, 7031 Trondheim, Norway
[b]Dipartimento di Ingegneria Chimica, Mineraria e delle Tecnologie Ambientali - DICMA, Alma Mater Studiorum Università di Bologna, via Terracini 28, 40131 Bologna, Italy
[c]2B Consulenza Ambientale, via della Chiesa Campocroce 4, 31021 Mogliano Veneto, Italy
[d]Health and Safety Laboratory – HSL, Major Hazards, Harpur Hill, Buxton, SK17 9JN, United Kingdom

Abstract

New and intensified technologies are being defined within the field of Carbon Capture and Sequestration (CCS) and the uptake is set to increase dramatically. This contribution focuses on three representative installations for CCS capture, whose safety and environmental issues might potentially be underestimated based on their presence in other industrial fields, but with different scales and uses. A simplified Life Cycle Assessment (LCA) and the new hazard identification technique denominated DyPASI (Dynamic Procedure for Atypical Scenarios Identification) were used to identify respectively environmental impact and atypical accident scenarios and add a useful dimension to risk information that can particularly help in determining the best technological options.

Selection and/or peer-review under responsibility of GHGT
Keywords: CCS; HAZID; LCA; DyPASI; atypical accident scenario.

1. Introduction

The emerging field of Carbon Capture and Sequestration (CCS) is set to progressively increase the scale and extent of CO_2 handling in the near future. However, there is a general lack of substantial operational experience in such processes, which leads to significant difficulties in adequately identifying and managing the associated risks, despite the fact that CO_2 is already handled in many industrial applications, such as brewing, gas reforming and gas processing [1,2].

In particular, this contribution focuses on installations for CCS capture, whose safety and environmental issues might potentially be underestimated in feasibility projects because of their current partial presence in other industrial fields, but with different scales and uses. In fact, capture technologies

* Corresponding author. *E-mail address:* nicola.paltrinieri@sintef.no.

Selection and/or peer-review under responsibility of GHGT
doi:10.1016/j.egypro.2013.06.166

involve not only CO_2, which is asphyxiant and toxic at high concentrations (as reported by DNV [2]) and a greenhouse gas, but also hazardous (and in some cases pollutant) substances, e.g. as amines, oxygen and hydrogen.

Identification and proper management of the emerging risks related to CCS is thus a great challenge, also considering the public concern and the controversy that this technology raises in several of the countries that are running CCS programs. For instance, this is witnessed by the recent parliamentary debates in the United Kingdom [4] and the doubts raised by the Norwegian Ministry of Petroleum and Energy about the Mongstad project [5].

For these reasons, the European project iNTeg-Risk (Early Recognition, Monitoring, and Integrated Management of Emerging, New Technology related Risks) of the Seventh Framework Programme for Research and Technological Development - FP7 - aims to build, by means of a set of principles, agreed methods and Key Performance Indicators, a new management paradigm for emerging risks related to new technologies in the European industry.

This contribution illustrates how CCS emerging risks were addressed within the framework of iNTeg-Risk by means of a novel assessment approach comprising a life cycle perspective. In particular, a simplified Life Cycle Assessment (LCA) and the new HAZard IDentification (HAZID) technique denominated DyPASI (Dynamic Procedure for Atypical Scenarios Identification) were applied in order to identify respectively the environmental impact and the "atypical events" (accident scenarios deviating from normal expectations of unwanted events or worst reference scenarios). The overall objective is to develop sensible and practical risk management tools that enable CCS and other emerging technologies to be safely deployed.

2. Analysis context

The iNTeg-Risk project aims at the adoption of a new safety paradigm that will improve industry competitiveness as well as transform Europe towards a more risk informed and innovation accepting society [6]. For this reason the project addresses the overall risk and detrimental impact to society, in order to define specific techniques aiming to reduce impact on human health and environment. Thus, the approach of Risk Analysis is not the only one adopted, but also the LCA technique is considered in an integrated approach to the problem.

The objectives of the application of such an approach to CCS technologies are three-fold:

- Identify any CCS-specific hazard phenomena that are not fully understood;
- Evaluate the impact on the environment of CCS technologies, which is assumed to be low, but this is an assumption that needs to be checked and validated;
- Demonstrate the need for an integrated risk perspective, comprising the life-cycle perspective and qualification of the risks of the CCS technologies along their entire life cycle.

2.1. Inclination to atypical accident scenarios

Emerging technologies such as Carbon Capture and Sequestration are characterized by relative lack of experience of their related risks. Existing statistics are insufficient to support risk management because the sample is too small and the system is changing. Accident scenarios that were not properly identified would represent a serious latent risk, because they may remain unidentified until they take place for the first time.

Two images, “black swans” and “perfect storms,” have struck the public’s imagination and are used to describe the unthinkable or the extremely unlikely [7]. Paltrinieri et al. [8] classifies these types of accident scenarios as “atypical”. They are accident scenarios that are not captured by standard risk analysis processes and common HAZard IDentification (HAZID) techniques because of deviations from normal expectations of unwanted events or worst case reference scenarios.

In order to deal with this challenging issue, Paltrinieri et al. [9] studied in detail a series of atypical accidents characterized by large magnitude and low probability (which facilitated their possible occurrence to be neglected) and showed that they arise from a combination of underlying and direct causes attributable to risk management and appraisal.

Thus, the phenomenon is complex and a holistic and careful analysis is needed in order to tackle the problem from several different points of view. A first response to this issue was the definition of the new HAZard IDentification (HAZID) technique denominated DyPASI (Dynamic Procedure for Atypical Scenarios Identification). It is a method aiming at the systematization of information from early signals of risk related to past accident events, near misses and risk studies. It supports the identification and the assessment of atypical potential accident scenarios as soon as these learning opportunities come to light. DyPASI is one of the results of the iNTeg-Risk project intending to obtain a more comprehensive risk analysis approach and was developed by observing its leading principles of continuous improvement and integration highlighted in its paradigm [9].

2.2. Need for a life cycle perspective

Power generation with Carbon Capture and Storage (CCS), which can substantially reduce CO_2 emissions from fossil electricity generation chains, represents an important option against the increase of atmospheric GHG concentrations and to mitigate climate change, while at the same time allowing the continued use of fossil fuels. In this context, CCS can be seen as a “bridge technology” for mitigation of climate change and towards a sustainable energy supply.

However, in line with the INTeg-Risk paradigm, several specific challenges are to be faced in the assessment of CCS technology environmental performance:

- While experience of CSS technology is lacking, significantly long timescales have to be taken into account because of the long-term nature of underground storage [10];
- CCS is a complex system composed of 4 main sub-systems: capture, transport, injection and storage. From the technical point of view, an event or characteristic in one given element of the system may have an impact on other elements;
- 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.

All these elements show the need for a novel risk assessment methodology comprising a life cycle perspective. The chain perspective is needed in order to deal with the social point of view, evaluating the environmental impact of CCS technologies over their entire supply chain. The uncertainty in data collection of future technologies, the various time-scales and the intrinsic systematic approach of Life Cycle Assessment (LCA) are issues that need to be addressed in this LCA case study.

2.3. CCS technologies considered

This analysis is meant to be a generic assessment for a non site-specific situation, and thus not a location and plant specific evaluation. In particular, the present study focuses on CO_2 capture plants. Three different case-studies were considered and represent the three main technology options for the capture of CO_2 from industrial sources such as power plants (see Table 1).

Table 1. CCS technology options considered

CO_2 source	CO_2 capture typology	Description
Pulverized Coal (PC) power plant	Post-combustion	Removal of CO_2 from flue gases produced by fuel combustion by scrubbing with an amine solution [11].
Integrated Gasification Combined Cycle power plant	Pre-combustion	The fossil fuel is used to produce syngas and the carbon, in the shape of CO_2, is removed by scrubbing with Selexol solvent before the combustion takes place [11].
Coal power plant	Oxy-fuel combustion	This technology involves a modification of the combustion process and can be defined as combustion in nearly pure oxygen, resulting in a flue gas that is mainly CO_2 and H_2O [11].

3. Methodology

Fig. 1 illustrates a general scheme of the methodologies used in this contribution. A more detailed description of their phases is provided in the following sections.

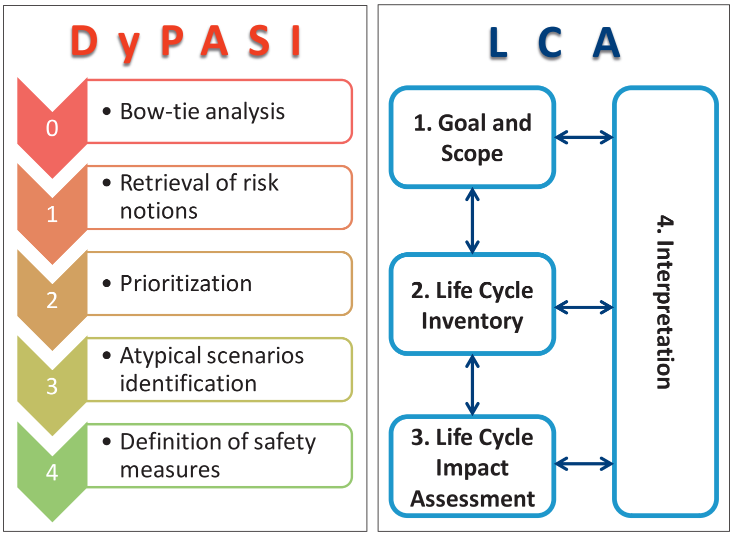

Fig. 1 General scheme of DyPASI and LCA

3.1. DyPASI

The application of DyPASI entails a systematic screening process that, based on early warnings and risk notions, should be able to identify possible Atypical Scenarios or Unknown Knowns. The well-established approach of the bow-tie analysis, which aims at the identification of all the potential major accident scenarios occurring in a process industry, was taken as a basis to develop the methodology. Its structure can be summarized in 5 main steps (Fig. 1):

0. As a preliminary activity DyPASI requires the application of the conventional bow-tie technique to identify the relevant critical events. This can be performed following conventional guidelines such as those outlined by the Centre for Chemical Process Safety [12].

1. In the first step of DyPASI application, a search for relevant information concerning undetected potential hazards and accident scenarios that may not have been considered in conventional bow-tie development is carried out. This uses some concepts from the IT area of study denominated Information Retrieval, in order to reduce potential information overload in the search activity.
2. Once the necessary information is gathered, a determination is made as to whether the data are significant enough to trigger further action and proceed with the process of risk assessment. As a support for this process of prioritization, a register collecting the risk notions obtained from the retrieval process and showing their relative relevance and impact can be obtained.
3. The potential scenarios are isolated from the early warnings gathered and a cause-consequence chain consistent with the bow-tie diagram is developed. This allows for the integration of the pattern of the atypical scenario into the bow-tie of hazards previously identified at step 0.
4. Finally, the definition of safety measures applied to the elements of bow-tie diagrams is the last step of the DyPASI procedure. The safety measures are described by safety barriers and related generic safety functions.

A more detailed description of the method can be found elsewhere [13].

For the sake of brevity, the most representative equipment handling hazardous substances were analyzed more in detail by DyPASI.

Equipment considered comprised:

- post and pre combustion capture CO_2 absorber;
- Air Separation Unit (ASU) (present in both pre combustion and oxyfuel combustion plants) considered as a unique distillation column; and
- oxyfuel combustion boiler/furnace and recycle pipe.

3.2. Life Cycle Assessment

On the basis of the available information on CCS technologies [14], the cases describing the coal power plants have been assessed in a simplified LCA. The simplified LCA follows the ISO standards on life cycle assessment (ISO 14040 [15], ISO 14044 [16]) and its structure can be summarized in four main phases (Fig. 1):

1. Goal and scope: preliminary phase with the definition of scope, functional unit, system boundaries, data quality requirements, assumptions and considerations on the critical review;
2. Life Cycle Inventory (LCI): The inventory is generally considered to be the most time-consuming among all LCA phases. The inventory covers the collection of all relevant environmental data;
3. Life Cycle Impact Assessment (LCIA): in LCIA the impact categories (e.g. acidification) are selected, the LCI results are assigned to the categories (classification), and category indicators are calculated (characterisation, normalisation, weighting, single score);
4. Interpretation: the final stage is the interpretation and evaluation of results. The results from the LCI and LCIA are analysed in order to identify environmental hotspots.

The main simplification concerns the use of LCA data sources, in order to compensate the partial lack of data on upstream and downstream processes and power plant construction and dismantling. The LCA data sources used are:

- Ecoinvent version 2.2, containing 4224 processes [17];
- ELCD version 2.0, recently developed by the Joint Research Centre (Ispra – Italy) of the European Commission, containing 317 processes [18].

Furthermore, apart from the coal power plants and transport infrastructure, other capital goods have not been considered, because it was assumed that they do not have an important impact on the life cycle assessment.

The information found [15] allowed consideration of cases of coal-based power generation with pre-combustion or post-combustion CO_2 capture. Unfortunately, for reasons of data availability and data consistency, the scenario of oxy-fuel combustion was left out of the simplified LCA. This omission was assumed to be covered by the LCA results of Bauer [19] on oxy-fuel combustion.

4. Results and discussion

Sets of detailed bow-tie diagrams referring to different types of equipment and Loss of Containment (LOC) scenarios were obtained for each case-study by means of DyPASI and bow-tie analysis, giving a comprehensive overview of related potential accident scenarios.

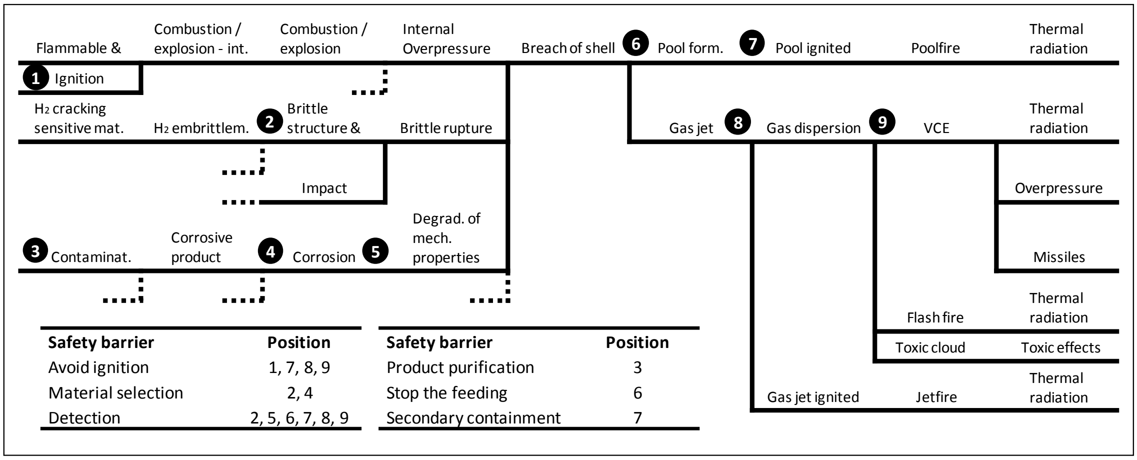

Fig. 2 Bow-tie diagram referring to a breach of the pre combustion absorber shell in a IGCC power plant.

As a representative example, Fig. 2 shows the bow-tie diagram referring to a breach of the pre combustion absorber shell in a IGCC power plant. Noteworthy elements of this diagram are the possible brittle rupture due to hydrogen embrittlement and the elements related to the presence of flammable substances. In fact, this equipment, in addition to CO_2 and the solvent, handles hydrogen and traces of H_2S [15].

Mechanical stress due to external causes, insufficient material properties or degradation of mechanical properties due, for instance, to corrosion, are common causes of a breach of an absorber shell. In particular, it is well known that CO_2 forms an acid solution in the aqueous phase, which can give corrosion issues. Also impurities, such as mercury, are corrosive. Nevertheless, the corrosion rate depends on the temperature, so a relatively low corrosion will take part in the colder parts of the plant. For instance, a higher corrosion rate is expected at the inlet and outlet of the stripper where higher temperatures occur [20].

Finally, it must be specified that the consequence of a toxic cloud in this first bow-tie diagram is not only due to the presence of hydrogen sulphide, but also to the high concentration of CO_2, whose toxicity has been indicated by other studies before [3].

LCA impact category results were expressed for the analysed case-studies and compared with analogous power plants without CCS.

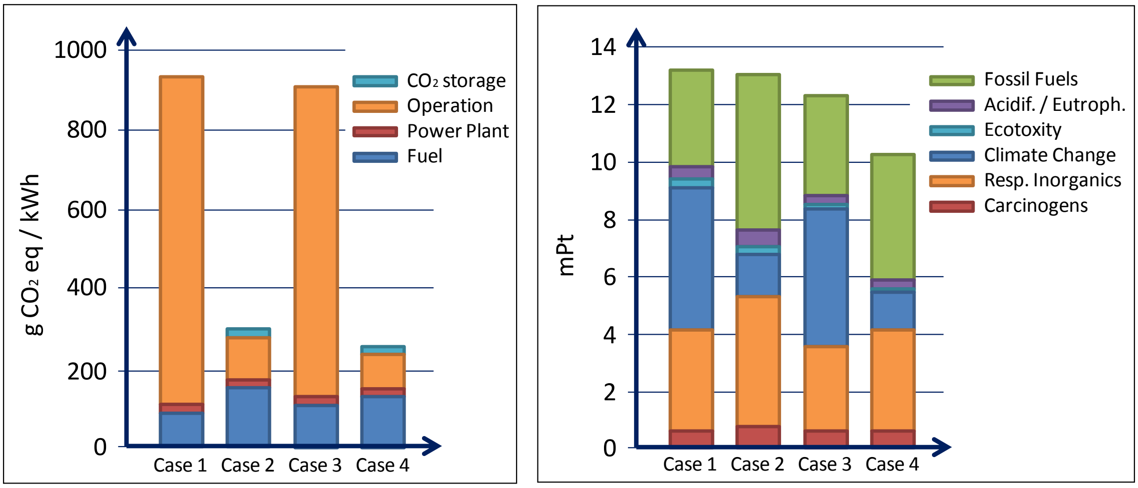

Fig. 3 Greenhouse gas (GHG) emissions (IPCC method) (a) and overall environmental impact (Ecoindicator 99 method) (b) for a PC power plant without (case 1) and with (case 2) post-combustion CO_2 capture and storage and a IGCC power plant without (case 3) and with (case 4) pre-combustion capture and storage.

As representative examples, Fig. 3a shows GHG emissions for a PC and IGCC power plant without and with CCS calculated for a time horizon of 100 years. In this case the reduction of emissions is about 70%. Fig. 3b shows the overall environmental impact for the same cases, but the calculated impact reduction due to CO_2 capture is only about a few percentage points.

This demonstrates that the overall assessment of the environmental performance of CCS technologies is highly dependent on the weighting of GHG emissions against other impacts and that further analysis is needed.

IGCC power plants with pre-combustion carbon capture and storage gives a relatively better environmental performance than PC power plants with post-combustion carbon capture and storage.

Due to practical reasons, oxy-fuel combustion was omitted. However, according to Bauer [19], PC power generation with oxy-fuel combustion carbon capture gives an environmental performance similar to the IGCC power generation with pre-combustion carbon capture and storage.

5. Conclusions

The hazards related to new technologies of CO_2 capture were investigated. A HAZID analysis was carried out on new substances, equipment and activities through a specific tool apposite to the identification of atypical accident scenarios. A number of potential hazards were identified which will require the adoption of safe design principles to eliminate, prevent, control or mitigate them. This is in the context of the overall objective to develop sensible and practical risk management tools that enable emerging technologies to be safely deployed.

Moreover, despite the fact that an issue for emerging risks is the availability of adequate data to allow LCA to be performed, LCA added a useful dimension to information about risks that can particularly help in determining the best technological options. The overall assessment of the environmental performance of CCS technologies was found to be highly dependent on the weighting of GHG emissions and further analysis is required. However, a preliminary result is that IGCC power plants with pre-combustion carbon capture and storage were found to be a better option in terms of environmental performance.

Acknowledgements

The authors gratefully acknowledge financial support for the European Commission under the iNTeg-Risk VII framework project (CP-IP 213345-2).

References

[1] Cordella M, Tugnoli A, Spadoni G, Santarelli F, Zangrando T. LCA of an Italian Lager beer. Int J Life Cycle Ass 2008, 13 (2), 133-139.

[2] Tugnoli A, Landucci G, Cozzani V. Sustainability Assessment of Schemes for Hydrogen Production by Steam Reforming. Int J Hydrogen Energ 2008, 33(16), 4345-4357.

[3] Det Norske Veritas – DNV. Mapping of potential HSE issues related to large-scale capture, transport and storage of CO_2, Report No: 2009-1993. Høvik, Norway: DNV; 2009.

[4] UK Parliament. Parliamentary debate on Carbon Capture and Storage, Scotland. http://www.theyworkforyou.com/whall/?id=2012-01-17a.217.0 (20 January 2012).

[5] Carbon Capture Jorunal. Statoil advice to ministry on Mongstad, Carbon Capture and Storage Journal, March 4, 2011.

[6] EC project iNTeg-Risk. Definition of the new iNTeg-Risk paradigm: description of the different risks, emerging risks and the way of dealing with emerging risks including the interaction with relevant stakeholders (T-H-C-R). Deliverable D.2.1.1.1 of EC project iNTeg-Risk 2010, 7th FP, Grant: CP-IP 213345-2.

[7] Paté-Cornell E. On "Black Swans" and "Perfect Storms": Risk Analysis and Management When Statistics Are Not Enough. Risk Analysis 2012. In Press.

[8] Paltrinieri N, Dechy N, Salzano E, Wardman M, Cozzani V. Lessons learned from Toulouse and Buncefield disasters: from risk analysis failures to the identification of atypical scenarios through a better knowledge management. Risk Analysis 2012, 32(8), 1404-1419. DOI: 10.1111/j.1539-6924.2011.01749.x.

[9] Paltrinieri N, Dechy N, Salzano E, Wardman M, Cozzani V. Towards a new approach for the identification of atypical accident scenarios. Journal of Risk Research 2012. In Press. DOI: 10.1080/13669877.2012.729518.

[10] Wilday J, Paltrinieri N, Farret R, Hebrard J, Breedveld L. Addressing emerging risks using carbon capture and storage as an example. Process Safety and Environmental Protection 2011, 38, 482-491. DOI: 10.1016/j.psep.2011.06.021.

[11] Intergovernmental Panel on Climate Change - IPCC. Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press, 2005, New York.

[12] CCPS - Center for Chemical Process Safety. Guidelines for Hazard Evaluation Procedures. America Institute of Chemical Engineers (AIChE), 2008. New York, USA.

[13] Paltrinieri N. Development of advanced tools and methods for the assessment and management of risk due to atypical major accident scenarios. PhD thesis. Alma Mater Studiorum – University of Bologna, 2012, Bologna.

[14] US Department Of Energy - DOE. Cost and performance baseline for fossil energy plants DOE/NETL-2007/1281. Volume 1: Bituminous coal and natural gas to electricity, final report (original issue date, May 2007). Revision 1, August 2007.

[15] ISO 14040, 2006: Environmental management – Life cycle assessment – Principles and framework. CEN, EN ISO 14040:2006 (www.iso.org).

[16] ISO 14044, 2006: Environmental management – Life cycle assessment – Requirements and guidelines. CEN, EN ISO 14044:2006 (www.iso.org).

[17] Ecoinvent. Version 2.2 of the ecoinvent database. Swiss Centre for Life Cycle Assessment, supplier of the ecoinvent database 2010 (www.ecoinvent.ch).

[18] European Life Cycle Database - ELCD v2.0. Europ. Comm. 2010, JRC-Ispra. (http://lct.jrc.ec.europa.eu/assessment/data).

[19] Bauer C, Heck T. Carbon capture and storage, lifecycle assessment and external costs of future fossil power generation. EC NEEDS project 2009 (www.needs-project.org).

[20] Shao R, Stangeland A. Amine used in CO2 capture, health and environmental impacts. The Bellona Foundation 2009.