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Topic and concerns related to the potential impacts of CO_2 storage: results from a stakeholders questionnaire

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Abstract

This paper illustrates the results of a questionnaire designed to explore the full range of topics and concerns related to the potential impacts of CO_2 geological storage. The questionnaire was compiled online by 45 European and international stakeholders from 16 different countries, including researchers, operators and regulators. The results provide a comprehensive picture of the variety of aspects that the respondents consider important from the point of view of impacts and long term safety of storage sites. The themes span from impacts on the environment to socio-economic and operational such as for instance building and management of storage sites.

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Keywords: CO_2 storage impacts, CO_2 leakage, CCS regulation, CO_2 storage safety, CCS public perception, CCS stakeholder questionnaire, CO_2 storage implementation, trust, risk assessment, emission reduction.

1. Introduction

The scope of this paper is to illustrate the results of a questionnaire designed to explore the full range of topics and concerns related to the potential impacts of CO_2 storage. The questionnaire was developed in the context of the

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FP7 RISCS project – "Research into impacts and safety in CO_2 storage" (http://www.riscs-co2.eu), to gain greater insight on the variety of arguments, concerns, ideas and demands in relationship to what is relevant for the stakeholders about the possible impacts of CO_2 Geological Storage. The research performed in the project concerned impacts' scenarios through the study of potential impacts on living organisms, and both on groundwater and marine water chemistry such as for instance ph. The objective of the project being to provide tools for developing appropriate legislation and helping to ensure the safe management of CO_2 storage sites, dissemination of the research outcomes had a particular relevance. To support such a process a number of activities were carried on with the project partners and with external stakeholder, to promote research integration and to ensure that the presentation of the data and knowledge gained in the project addresses the information needs of the end users. Within this framework it was important to identify all the aspects that could be of interest and concern with regard to the area of scientific investigation, to ensure the best exploitation of research outcomes, maximising the use of data to answer stakeholders' questions.

An open, qualitative questionnaire was prepared to explore the range of impact's topics and issues that might be of interest when considering CO_2 storage implementation. The objective was to collect a complete set of information about what is relevant for stakeholders concerning impacts, information that can be used by researchers to improve their connection with society and with the wider context in which the research on impacts is being developed, with a growing understanding of the links between the different topics that relate to CO_2 storage impacts. The results of the questionnaire provide a detailed overview of stakeholder driven input on storage impacts which might be very useful to all those who work in the field and aim at better communicating their work or improving its focus. In particular they can help researchers, operators and regulators ensure that all the topics which might be relevant are properly addressed.

2. Method

A questionnaire was prepared to collect direct input from stakeholders on CO_2 geological storage impacts, which could help RISCS researchers better address the dissemination of the project outcomes to CCS stakeholders. With respect to previous research on this topic, see for instance Wilson et al. [1], our interest focused on identifying impact categories with a bottom up approach, starting from a "listening" exercise of stakeholders' more pressing interests and aiming to an inclusive repertoire, which would give voice to all points of view. The preparation of the questionnaire was preceded by workshops with RISCS consortium partners, stakeholder exchange activities and an internal start-up questionnaire to gradually identify the elements and coordinates for the development of the present stakeholder questionnaire. The collection of direct input from stakeholders was meant to address both thinking and feeling with regard to impact issues, as fear and other feelings play an important role in the discussion on impacts and safety.

The objectives of the present questionnaire and work were:

- To collect detailed information from CCS stakeholders on impact issues to be considered for the safe implementation of CO_2 storage sites, as a first step for a comprehensive mapping of the areas that need to be addressed, either with further research or with existing research dissemination.
- To attempt a first conceptual organisation and categorisation of the impact issues raised by the respondents which could facilitate and support:
  - the dissemination work in better addressing the needs stakeholders more strongly feel about,
  - the work of decision makers in identifying lines for development of CO2 storage research and implementation which take into account the full range of issues that are considered important by stakeholders.

While the exploratory and qualitative work necessary to achieve such objectives would have taken advantage of individual face to face interviews, within the limits of the budget the option of a questionnaire with open ended questions seemed the more appropriate choice. The target group of respondents was the informal CCS international community that could be reached via e-mail through our own personal contacts with two stakeholder networks. The invitation to fill the questionnaire was sent in the period of February and March 2012 to about 1500 stakeholders of the mailing lists of CO_2GeoNet – The European Network of Excellence on the Geological Storage of CO_2 and ZEP – European Technology Platform for Zero Emission Fossil Fuel Power Plants, two main European organisations working on CCS, the first one a network of research organisations and the second one a European stakeholder platform. Stakeholders were invited to contribute their input based on their experience and information needs, to help identify and clarify the important issues that must be addressed, to ensure the safety of a CO_2 geological storage site. The questionnaire was formed by open questions to allow full freedom of answers to the respondents. This was intended to encourage answers which would be at the same time more reflective and more spontaneously guided by personal feelings, to increase the likelihood of connection to what is deeply felt as being important. As one of the respondents commented at the end of the questionnaire:

"The open-ended questions are very helpful in encouraging responses, and should allow a wide range of stakeholders to give a response they feel is appropriate/useful, and get quite a variety in response"

The open questions, in this respect, were used as an associative exercise [2], where the choice of topics mentioned reflects what was for the respondents most relevant, what they, among many aspects, have decided to pick out and bring to attention. In the questionnaire there was no mention of pre-selected impact categories based on previous research. Context of the questionnaire administration as part of the RISCS project, and content and structure of the questions, were the only reference dimensions used.

The sequence of the questions follows a psychological criterion, linking them first of all with the research context, then asking the respondent to focus empathically with the perspective of other stakeholder categories and recognising the importance of the subjective perspective. The first three questions connect to the research context in which the questionnaire has been developed, the focus on impacts in the RISCS project and the goal of the project to provide useful information to stakeholders engaged for the implementation of CO_2 storage projects. The other questions give visibility to the perspectives of different societal sectors that have a stake in the development of CO_2 storage research. At the same time the questions follow a psychological order that is meant to help the respondent focus more and more on what is deeply felt as being important.

The first question directly asks about impacts (*"What kind of environmental impacts do you think need to be considered when planning and operating CO_2 storage sites?"*); it is useful to focus on the topic and take a global perspective on the issue; the second question (*"Are there any missing pieces of information with regard to the long-term safety of CO_2 storage sites? Is there something you would like to know more about?"*) more directly asks the respondent to connect to internal needs, what is missing, what one would like to know, moving from the pure impacts of question 1, to something as important as safety; of course it also links to the research context, the production and dissemination of useful information. The third question (*"What scientific information could help you or other stakeholders dealing with potential impacts of leakage from CO_2 storage sites?"*) goes a step further, to a more concrete and practical consideration of impacts, asking the respondent to imagine, if he/she was in the position to make decisions for a storage site, what kind of scientific information could be of help. The respondent is thus encouraged to get deeper and deeper in the topic, being then ready to answer the following questions, assuming different perspectives. Thus the fourth question (*"From an industrial perspective, what do you think could be the major leakage impact issues with regard to the geological storage of CO_2?"*) concentrates on the industrial point of view and the problems that may arise from leakage; the fifth (*"Concerning the regulatory framework, what do you think is most important, to limit the impacts of possible leakage from a CO_2 geological storage site?"*) brings in the legal side and what can be done to set rules that will limit the probability of impacts; the sixth (*"From a layman's perspective, what would make you feel safe with regard to the implementation of CO_2 geological storage?"*) finally gives the opportunity to say what might be important for any and each of us, as simple citizens, to feel safe with the implementation of storage. The seventh question only asked for any additional comments.

The whole sequence allows articulated and complex thinking to emerge through the elaboration of the contribution of the respondents as a group. The single answers are considered as being part and elements of the wider social representation of CO_2 storage that the participants, as members of the international CCS community, can be assumed to share [3, 4]. Therefore in the analysis and elaboration work all answers have been considered, with very few exceptions due to out of scope content, and maintaining the original wording. No selection has been made as the complete set of answers has a value in itself and in more than one case there are important topics which have been mentioned perhaps by one respondent only. By taking this approach we want to make sure that all kinds of impacts are considered and included, independently from the numbers of stakeholders that have mentioned them. We expect, given the size of the sample (45 respondents), to cover all the main categories of impacts. Some of them may be important but not so present to many stakeholders, while other impacts might be negligible but well known to everyone, therefore more frequently discussed.

With this work we would like to provide the opportunity to the reader to gain an overview of the whole range of potential impacts and on this basis make an evaluation of the sectors that need improvement/work. This evaluation is not part of the objectives of the present article, which limits its aim to providing hopefully useful material for risk assessment professionals. Just as well, on many topics, there might already be scientific evidence which is unknown to the stakeholders who have responded, thus their input through the questionnaire allows identification of areas which need more dissemination.

Each answer provided has been first analysed with respect to the presence in it of one or more areas of content. When more topics were covered, the answer has been split in different items, one for each sub-answer that was given. Therefore the total number of items for each question does not correspond to the total number of respondents, but is usually higher. Frequencies have been counted, for additional information, but we would like to stress that they are not per se indicative of the absolute or relative importance of each category. This could form the interest of a new questionnaire for testing the categories that have emerged from this work. At this stage frequencies are only useful to help us better understand and empathise, in psychological terms, with the respondents. This is what it's in their mind, what they would more care about for the prevention of CO_2 storage environmental impacts.

Working on this inclusive corpus of data, the specific input of the researchers in the elaboration process has been in developing a categorisation of the answers and their conceptual organisation [5, 6]. An informal method was used to develop the impact categories, based on the researchers experience and in-depth knowledge of the topic. The categories and their organisation in concept maps is proposed as a tool for common work, which can undergo further modifications through exchange in the expert community, as such it has no ambition of demonstrated validity but rather aims at stimulating discussion and exchange.

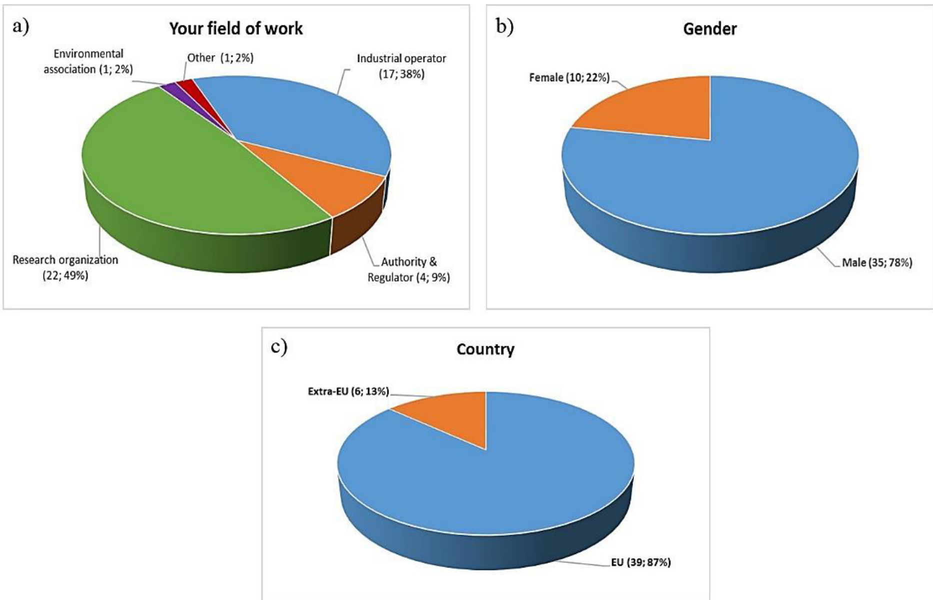

Fig. 1 Pie charts of the main characteristics of the sample of respondents.

3. Results: Open questions on CO_2 storage impacts

3.1. Foreword

The questionnaire was compiled online by 45 European and international stakeholders from 16 different countries, including researchers, operators and regulators (Fig. 1). Due to a high rate of undelivered it is difficult to know exactly how many stakeholders actually received the questionnaire. However, considering the initial list of

about 1500 addresses, ca. 6% entered the questionnaire system and ca. 3% completed the questionnaire. This contribution reports on the answers to the questionnaire on six key areas: 1) the environmental impacts that the respondents think need to be considered when planning and operating CO_2 storage sites; 2) missing pieces of information with regard to the long-term safety of CO_2 storage sites; 3) scientific information deemed relevant for dealing with potential impacts of leakage from CO_2 storage sites; 4) major leakage impact issues from an industrial perspective; 5) relevant regulatory framework's characteristics and issues for limiting possible leakage impacts; 6) factors that build trust in the safety of storage operations.
Before going to illustrate the answers on each topic, we would like to introduce some general considerations taking inspiration from the additional comments proposed by some stakeholders at the end of the questionnaire.

Although the aim of this work is to provide stakeholders with information on any potential CO_2 storage impact, it will be important to keep in mind that CCS has been evaluated by the IPCC as having the same level of risk of other common oil and gas sector activities [7]. The effort required, at this stage of development of the technology, to set the conditions for its safe implementation, should not make us lose sight of the real proportion of the risks:

"*A comparison of potential leaks from storage sites with massive leaks from natural sources (i.e. volcanoes or sudden emissions from underground natural CO_2 fields) would be useful to put CCS in perspective* (Research org)".

As another respondents puts it:

"*Don't forget risk is not a technical issue, risk is a social issue. Risk is the perceived danger, not the computed or logical danger*.(Authority).

From this point of view:

"*Consideration of the 'impacts' of CO_2 leakage perhaps thus also needs to reflect briefly on the less tangible impacts of a CO_2 release on an area, e.g. loss of trust in industry/government, loss of 'brand reputation' for tourism/produce, stigmatization of area (and, indeed, stigmatization of CCS)*" (research org.).

Comes to mind the contribution of Bradbury et al. [8] which points out the risk of focusing on risks and perhaps missing other aspects that people have at heart and that, once given due consideration, help reducing real risks. Bradbury and colleagues have identified three important categories of questions that people ask:

- How can we have a say in what happens? Who is in charge? Will the process be fair and will anyone listen to us?
- What will happen if something goes wrong? Can we trust the project developers and the government to take care of any problems? What have our previous relationships with these entities shown us?
- What is the benefit to our community? How does the proposed project fit into or improve our way of life?

In the words of a respondent to the RISCS questionnaire people need:

"*Good regulation and good visible regulation as well - people need confidence in science based regulation and clear understanding of personal needs (i.e. the landowner/dweller) being recognised.* (Research org)".

The answers provided by the stakeholders in the questionnaire could help in the development of good regulation by contributing to fill the knowledge gap mentioned by another respondent:

"*To my experience there is a big gap of knowledge about the points mentioned above (impact issues). This gap is taken advantage of by politicians, environmentalists and other lobby groups against the CCS technology and for their interests* (industrial operator)".

Having started from the input provided by the respondents with their final comments at the end of the compilation of the questionnaire, we hope it will be easier to place the following results in the wider context of impact issues discussion.

3.2. Question 1. "What kind of environmental impacts do you think need to be considered when planning and operating CO_2 storage sites?"

The first question is directed to identify all the potential impacts that should be considered when planning and operating a CO_2 storage site. In the words of one of the respondents *"both local and global impacts"* should be considered, since at the level of global impact "*if the injection leaks, the purpose of CO_2 geological storage, i.e. GHG decrease, would be nil*" (research org.). The total items for this question is 106, distributed in 8 subcategories, which can be grouped in two main areas (Fig. 3): impacts that are linked to the possible effects of CO_2, and impacts that in different ways relate to storage implementation. From a global read of the answers, the potential impact on freshwater resources appears as the most important specific area of concern, while leakage is often mentioned in a generic way, without specifying what kind of impact it could have. But let's see the categories more in detail (Fig. 3).

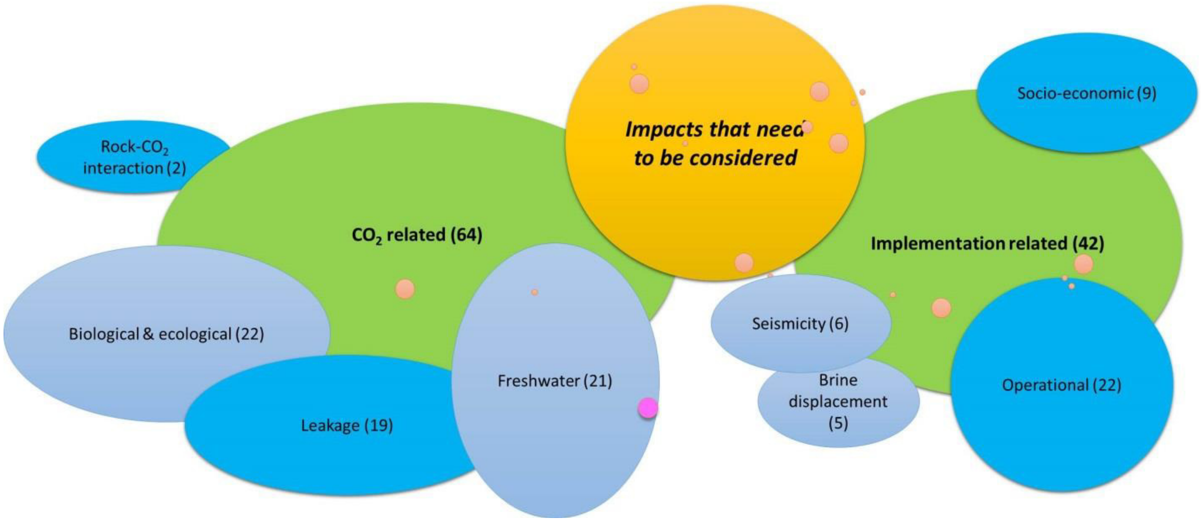

Fig. 2 Concept map of question 1.

3.2.1. *CO_2 related impacts*

The first macro-category for question one is born from concern about the possible effects of carbon dioxide either in case of some form of leakage or in the interaction with the subsurface structures. It includes potential impacts on freshwater (21), biological (humans, flora and fauna) and ecological systems (22), generic leakage risks (19), and rock – CO_2 interaction (2).

Impact on the ecosystem, the lifecycle of carbon balance and in particular on humans, animals and plants constitutes the broader category and touches on many different aspects: impact on population, human health, risk of suffocation, equipment hazards for the local community, surface and subsurface biosphere, biodiversity, impact at ecosystem level on keystone species, disturbance to marine wildlife near to sites for offshore storage (e.g. seismic surveys, increased marine traffic) during the exploration and installation phase, effects of carbonic acid in seawater, possible acidification, the atmosphere (air quality), impacts of CO_2 leakage on chemistry of surface sediments, pore water and overlying bottom water, and on benthic and pelagic marine organisms including responses on different levels of biological organisation i.e., genetics, eco physiology, behaviour, etc. going from organisms and species to communities.

Impact on freshwater is instead the most frequent answer that refers to a specific risk. A number of concerns are mentioned, starting from leakage of CO_2 into potable ground water, contamination or other influence on groundwater quality, changes in local hydrogeology or impacts on the hydrosphere, risk of salinization at surface of water resources because of inadequate zone isolation, contamination of potable water in seismically active places.

Leakage without further specification of its effects is mentioned by many respondents; it includes onshore, offshore, installation, reservoir, compressor and pipeline leakage; different forms and quantitative aspects of it: seepage, slow and diffuse or vice versa massive leakage, sudden releases due to breaks in the pipelines transporting CO_2, small slow or large uncontrolled leaks of CO_2 from pipelines.

Finally there is a category which refers to possible effects of CO_2 which not necessarily depend from leakage, like interaction between rock and CO_2 and mobilisation of heavy metals.

3.2.2. *Implementation related impacts*

In this macro-category are present impacts that could arise in relation to, or during, the implementation of CO_2 storage. The most numerous subcategory refers to storage operations through the life of the project (construction, operation and decommissioning) similar to other large industrial plants. It considers the operation infrastructure footprint, routine operational impacts, local disturbance of constructing/operation and pipeline construction, during construction traffic, noise, heavy trucks and rigs, impact of the monitoring systems, surface installations failure (leakage from pipes, pump, compressors, etc.), overpressure from the injection process, potential for fracture of geological formations. There are also two particular areas of technical interest in relation to implementation operations. One refers to the displacement of brine in the subsurface, which may enter areas of economic interest or lead to local emission of pore waters (e.g. reduced, methane containing, sulphide containing). The second one refers to fault stability and issues of induced seismicity and micro-earthquakes. The last group in this macro-category includes social and economic aspects: consideration of the social context, i.e. proximity of population or other industry, how people in the neighbourhood view these impacts; interaction with other socio-economic factors like shipping, fishing, marine nature conservation areas etc; energy use; environmental values conflicts with human stakeholders (e.g. negative perceptions of use of the area, human concerns over effects on biodiversity); conflict of interest with oil industry and geothermal; land use conflicts with human stakeholders, both for onshore and offshore storage (e.g. fishing, agriculture, tourism); risks to hydrocarbons.

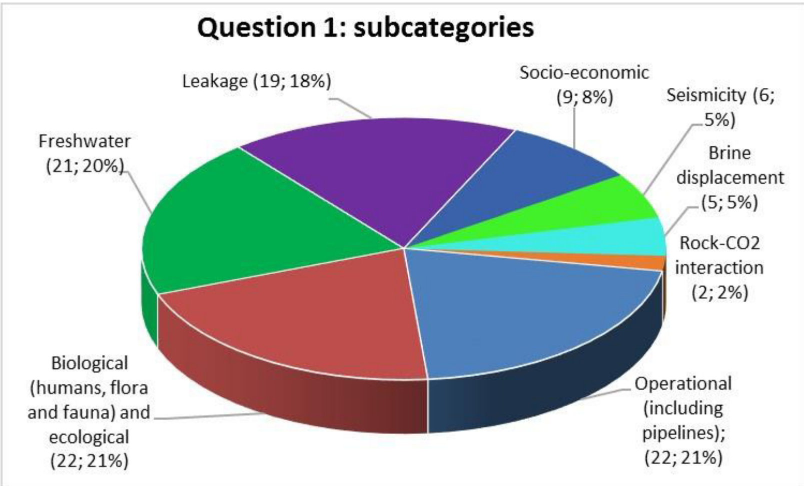

Fig. 3 Pie chart showing the frequencies/percentages for each subcategory of question 1.

3.3. Question 2 – "Are there any missing pieces of information with regard to the long-term safety of CO_2 storage sites? Is there something you would like to know more about?"

Regarding the missing pieces of information on long-term safety, one of the respondents observes that the question itself could be questioned, because the real issue is short term safety; once this is achieved there is confidence for the long term: *"The safety issue with CO_2 storage is most important during the operational phase. Later, reservoir pressure will slowly decrease. Mineralisation and segregation in the reservoir will also help. Storage mechanisms in e.g. gas reservoirs are known for periods as long as millions of years. Hence, there is no true long term safety risk"* (industrial operator). But let's now look into the macro categories identified for question 2 (Fig. 4), which provide interesting indications on the areas that require work to improve the long-term safety of CO_2 storage sites, either in itself or in the perception of the stakeholders (when the information requested is already available). First of all there is a strong need to better understand what happens in the reservoir and around it, the mechanisms of CO_2 behaviour in the underground and its interaction with the host environment. Another big block of answers relates to different aspects that are relevant for CO_2 storage implementation such as managing the storage site (something which is new for the length of time implied), monitoring and its costs (including those for the next generation), well design and reliability in time and finally legal rules and standards. Another important category which indirectly links to implementation is access to information. With regard to this, it is interesting to note that at least some of the information which is asked for is already available in the scientific domain, although clearly not sufficiently accessible; this can have important consequences, including the psychological feeling of lacking a satisfactory knowledge base as to how long term safety is ensured. Some of the respondents seem to be aware of this situation and point out the need of proper dissemination. Also noteworthy, in the leakage category, the request of information about a sudden release of CO_2 *"regardless of whether or not this is actually geologically possible!"*. As explained by the same stakeholder in answering question 5:

"*Following the nuclear accident at Fukushima, contingency planning should not be based on the assumption that a catastrophic event will never happen. That is, rather than saying 'there will not be a catastrophic release of CO_2 because we understand the technology and the geology', contingency planning should be based on the premise that 'although we are pretty certain there will not be a catastrophic event, if for some reason there was a large release, this is what would happen and this is what we would do'; at the early demonstration and roll-out stages, it will be especially important to take seriously any seemingly anecdotal or 'irrational' concerns stakeholders and publics may have (e.g. the dead animals at Weyburn) and to investigate these fully/offer alternative explanations for the phenomena people are experiencing*" (Research organisation)

Once again the relevance of risk perception with respect to real risk comes to the fore, here with a double sided implication:

- people's concerns, however absurd they may seem, may have some *raison d'être.* Taking them seriously into account can be essential
- if people's concern have no ground, it is equally important to take them seriously, to be able to address them and help people and decision makers make the right choices.

From this point of view, "leakage" can be considered a category which owes its importance not to the objective scale of potential risks related to it, but to the fact that it is a fear generating factor.

The fourth macro category regards a better understanding of leakage mechanisms and experimentation to understand long term impacts. Let's take a look at question 2 macro categories more in detail.

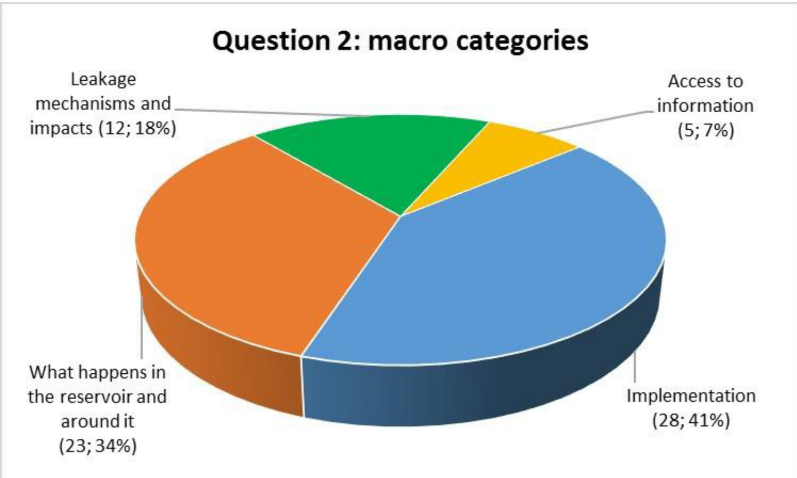

Fig. 4 Pie chart showing the frequencies/percentages for the categories of question 2; the numbers in parentheses refer to the item frequency.

3.3.1 What happens in the reservoir and around it (23)

The first and more numerous category regards the different reactions within and around the reservoir, the behaviour of CO_2 underground and long term chemical and mechanical development of storage reservoirs: pressure build up, reaction with minerals and velocity of mineralisation of CO_2, CO_2 solution into water and precipitation of carbonates, stability of residual trapping and dissolution in saline aquifers, flow of CO_2 in the reservoir, effect of deep groundwater flow on migration of sequestered CO_2, where CO_2 may migrate over long time scales (i.e.

thousands of years), impact of CO_2 injection on rock structure, under which conditions the buoyancy effect for injected CO_2 may be reversed due to an increment in water formation density, effect on aquifer water, role of impurities of CO_2 stream on storage complex, how to better predict the long-term time scale, stored CO_2 and earthquakes, lack of in-situ experiments at CO_2 storage sites under natural environmental conditions to verify hypotheses of laboratory experiments.

3.3.2 Implementation (28)

Includes 4 subcategories:

- Storage site management (7): an important area of interest is the challenge to manage and scale up storage sites. A variety of points are raised: behaviour of industrial-sized CO_2 storage sites, technology and understanding of pressure control/brine production in storage formations, how can humans manage a site for periods of the order of centuries, standards for remediation actions in case of leakage, maximum acceptable pressure over area with respect to geo-mechanics, especially with regard to pre-existing fractures under regionally perturbed geo-mechanical conditions.
- Monitoring and its cost (7): monitoring is another category that relates to implementation; aspects that from the point of view of respondents need to be addressed span from improvement of monitoring equipment both in technical and economic terms (and for onshore and offshore), proper understanding of background levels of CO_2, spatial resolution and precision of monitoring, cost estimation of the monitoring requirements for the next generations.
- Issues related to wells (6): wells are a specific point of attention, with regard to design, materials, stability and lifetime of cement.
- Legal issues (6): for the legal part the missing points concern how to ensure the storage will be secured and observed in the long term, ownership and accountability for the entire storage site life cycle (or at least the first 100 years), standards for remediation, how to define the boundaries of the area to be kept under control.

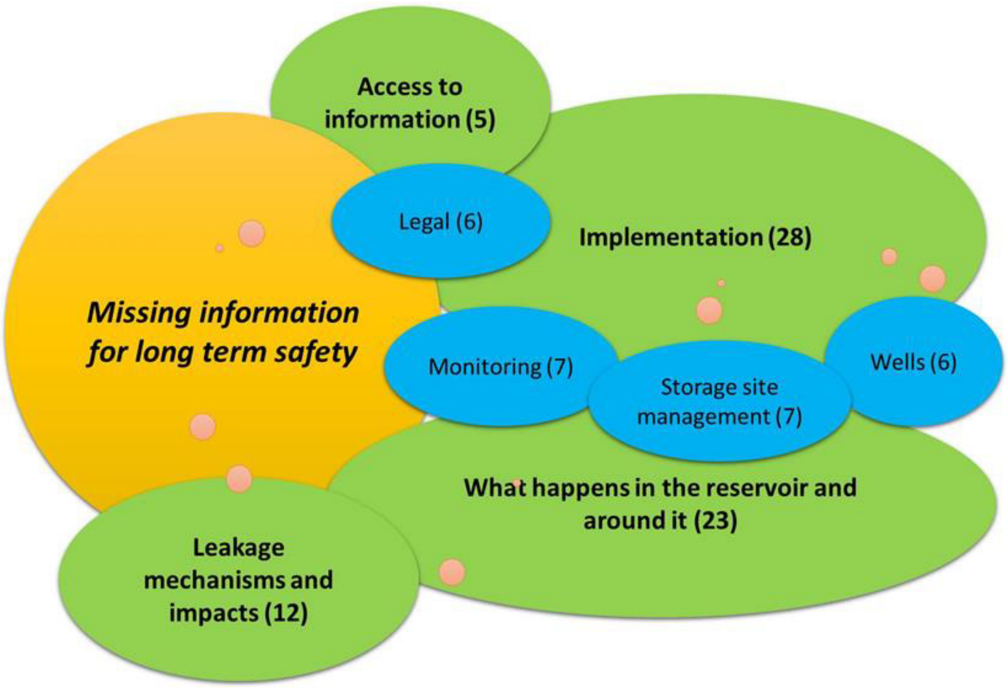

Fig. 5 Concept map of question 2.

3.3.3. *Leakage mechanisms and impact (12)*

Leakage mechanisms form another category on which the respondents would like more information in particular with regard to security of storage and potential for leaks (including scale and time), accuracy of leakage measurements, maximum rates at which CO_2 could escape through an old drill hole or well head and what would actually happen if a very large volume of CO_2 was suddenly released, fault seal mechanisms. The impact of leakage on biodiversity, the impact of impurities, long term information for the marine environment, long term experiments taking into account local adaptation, carry-over effects, acclimation, etc.

3.3.4. *Access to information (5)*

Respondents ask for easier access to information and professional literature, which is not usually or easily available in the public domain, including more user-friendly information..

3.4. Question 3: "What scientific information could help you or other stakeholders dealing with potential impacts of leakage from CO_2 storage sites?"

The request of scientific information to deal with impacts encompasses a wide range of topics which can be grouped in three main categories (Fig. 6a) that answer to different needs. Based on the respondents' answers, to be prepared to deal with potential impacts, stakeholders need first of all to be informed on key topics (Fig. 6b); secondly they need to have access to comprehensive databases and models. Finally they should be supported with the development of scientific tools and materials that make scientific outcomes more user-friendly, more understandable (**Errore. L'origine riferimento non è stata trovata.**).

3.4.1. *Specific information areas (36)*

The topics include knowledge of the storage system and the wider geological context, understanding of leakage mechanisms and related impacts, monitoring and mitigation measures. More in detail the respondents indicate the need of specific information on:

- Storage mechanisms (7): storage procedures and technologies, how CO_2 is trapped; how CO_2 flows and reacts in a CO_2 storage reservoir and its overburden; response of CO_2, caprock, etc. to seismic activity; long term geochemical fate of CO_2 in storage reservoirs; with data from real case studies and industrial scale storage sites.
- System assessment (4): detailed geological assessment of proposed site in view of its ability to contain CO_2; qualitative and quantitative risk assessment; knowledge of regional groundwater flow systems; old wells assessment.
- Local underground resources (1): groundwater aquifers, gas or other resources in the vicinity of storage site.
- Leakage mechanisms and impacts (18): the likely expression of the CO_2 at the surface (i.e. small point source, broad, but low, fluxes, etc.); probability of diffusive and concentrated leakage; expected leakage rate in case of leakage; speed/distance at which 'leaking' CO_2 spreads; risk of CO_2 eruption and impact zone definition (radius of impact); at what leakage rates/flux we will observe adverse impacts (thresholds); short and long term impacts on human and animal health, the biosphere and ecosystems of small and large scale CO_2 release in the atmosphere and the marine environment; influence of long term exposure to CO_2 for plants and animals; duration of any negative impact on local environment and the rate at which the area will recover.
- Monitoring (3): how CO_2 leakages can be detected; spatial resolution and precision of monitoring; improved monitoring equipment.
- Mitigation measures (3): knowledge of what might be done to stop potential leaks; methods of leakage mitigation; standards for remediation.

3.4.2. *Datasets and models (9)*

With regard to datasets and models (9), several aspects are covered, including both the collection of data from the actual storage site and the accessibility of models and datasets from scientific research (static and dynamic reservoir models; full set of monitoring data, including baseline, regular ecosystem assessments, MMV records within the subsurface, the soil surface and the atmosphere; datasets about the potential changes of growth and biological diversity within the ecosystem above a storage site; better models and data on long-term storage integrity;

atmospheric modeling near the surface to reliably predict CO_2 concentrations in the air; dispersion modeling of varying rates of CO2 leak into air and water column).

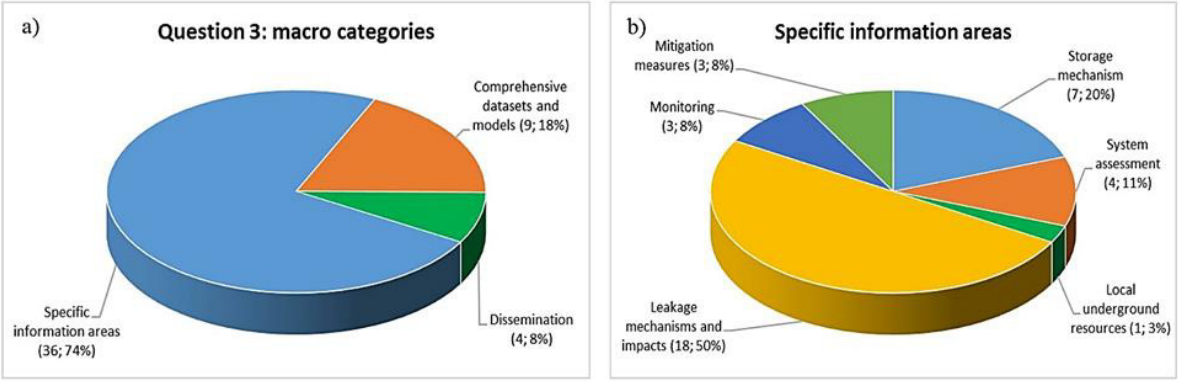

Fig. 6 Pie chart showing the frequencies/percentages for the categories of question 3.

3.4.3. *Dissemination*

The category of Dissemination (4) refers to the need of improving the usability of scientific information to support stakeholders in dealing with the potential impacts of CO_2 storage. It includes suggestions on research contents that need further dissemination and suggestions to improve understanding of modeling (a good overview of results from current storage sites and more test sites to build confidence in storage; show that CO_2 leakage is occurring naturally in many places in the world without dramatic consequence; user-friendly modeling tools that we could use to understand the science better; public model inter-comparison as is routine in IPCC climate model comparisons).

With question 3 once again emerges the relevance of disseminating already existing information.

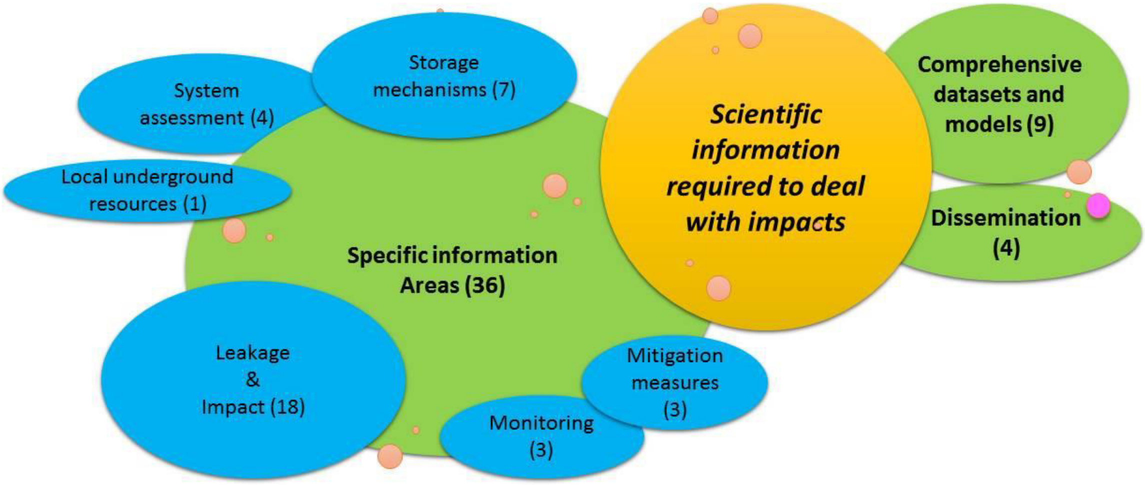

Fig. 7 Concept map of question 3

3.5. Question 4: "From an industrial perspective, what do you think could be the major leakage impact issues with regard to the geological storage of CO_2?"

From an industrial perspective the main concerns are: 1) public perception and related trust and reputation of operators and 2) financial issues. A second group of issues relates to leakage and its impacts on water, human health, flora and fauna. Finally issues of long term liability and conflict of interest with other operators (Fig. 8, 9).

3.5.1. *Prevention.*

Leakage prevention appears a fundamental dimension, not only to avoid impacts but also to enable storage in the first place: "*Leakage impacts will need to be negligible for CCS to be a credible technology that could be consented to be built and operated. Issue therefore is to prove that major leakage is not a credible scenario*"(industrial operator). In this respect one of the respondents identifies major risks that need to be considered: "*Important are the processes that could damage the integrity of a storage reservoir in 1 to 5 km depth. These are e.g. earthquakes or already existing and gas-permeable faults. But these factors have to be excluded before a decision pro a certain storage site is taken*"(industrial operator).

3.5.2. *Consequences for the operator.*

Nevertheless, should leakage ever occur, it would hit operators in two main domains:

- Financial implications (9)
- Reputation, public perception (12)

  Leakage could impact operators with a number of financial consequences: loss of EU ETC allowances, waste of money spent for doing the storage, cost of displacement of people, etc. But may be even worse could be the impact on public perception as it could bring a loss of trust and credibility, loss of reputation, loss of acceptance of CCS while *"having to continue to manage the site against potential public negativity"* (research org.). Another undesired consequence could be additional regulations and supervision. Assuming that leakage is very unlikely, an issue from an industrial point of view is: *"how to explain the risk of CO_2 leakage, as opposed to the hazard or probability".*(industrial operator)

  Other issues impacting the operator are related to the duration of the long term liability, which could be extended in case of leakage and the possible conflict with other operators, should the CO_2 migrate or pressure changes affect other underground activities.

- Long term liability (2)
- Conflict of interest (3) with other operators in oil industry or geothermal.

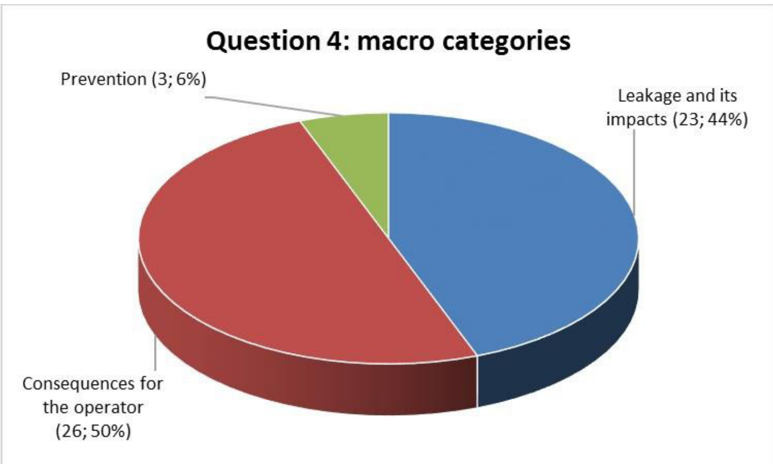

Fig. 8 Pie chart showing the frequencies/percentages for the macro categories of question 4.

3.5.3. *Leakage and its impacts.*

- Leakage (8). Concern from an industrial point of view is the possibility of leakage in itself. A large release would imply major liability and financial problems and "*Catastrophic leaks on shore could stop the deployment of CCS. Most likely this would occur during transport to the storage site. A slow leak could also slow down technology deployment*". When looking at things from the industrial perspective, it appears the respondents bring more focus on sudden and large release, for instance: *"I feel more concerned about a sudden leakage (from a rupture/cracks) with an associated CO_2 released further producing a local high CO_2 concentration atmosphere and associated hazards, than by a small continuous leakage (providing that it is small enough of course! a criterion on the pressure decrease evolution could be set!?)"*(research org.). Leakage here also brings technical questions on how to stop it.
  - Water contamination (6).
  - Impact on human health (4), related to it the issue of the specific safety measures required, different from those to protect against a hydrocarbon release. The personnel working around injection wells could be affected and more generally leakage could impact humans with suffocation.
  - Impact on micro-ecosystem, biosphere, flora/fauna (5).

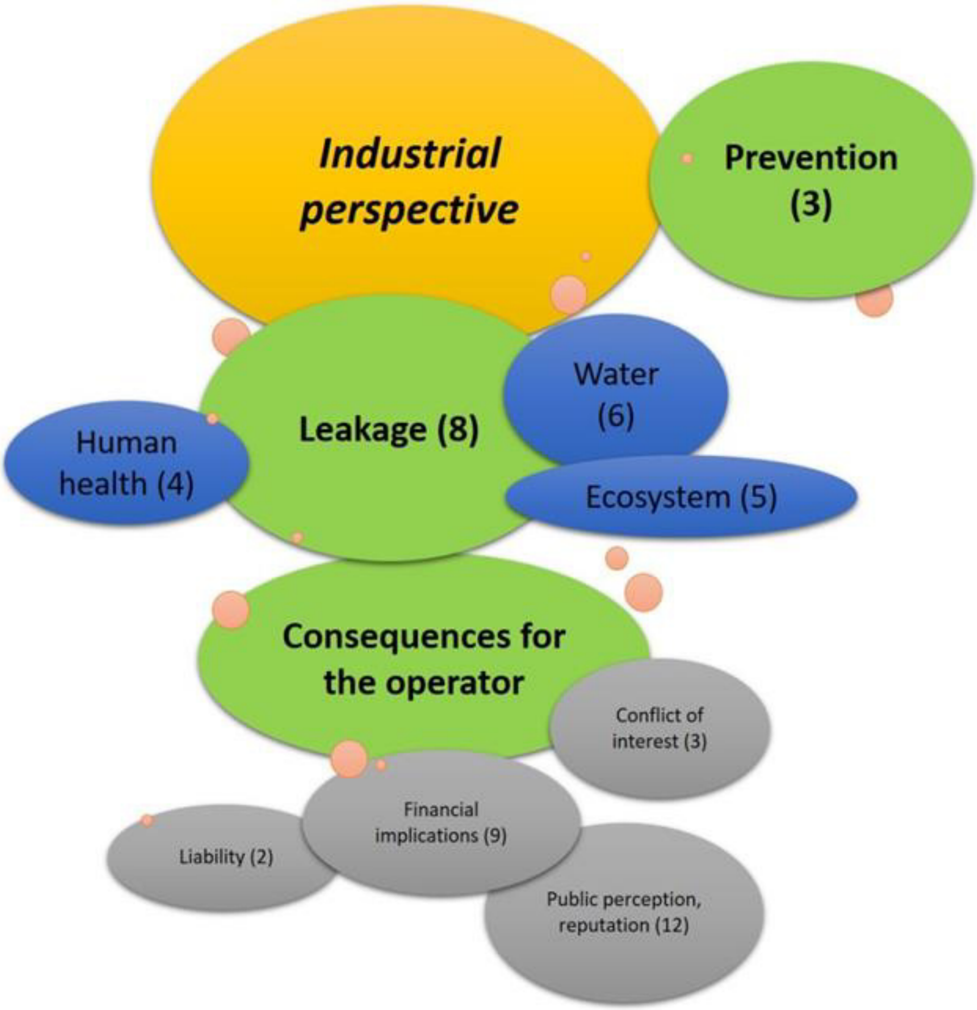

Fig. 9 Concept map of question 4.

3.6. Question 5: "Concerning the regulatory framework, what do you think is most important, to limit the impacts of possible leakage from a CO_2 geological storage site?"

With question 5 the respondents are asked to focus on the issues that concern CO_2 storage regulation, in particular those aspects of the regulatory framework that are directed to reduce, as much as possible, the impacts from any leakage occurrence. The answers can be categorised in 3 macro-areas (**Errore. L'origine riferimento non è stata trovata.**).

3.6.1. *Regulatory philosophy*

The first macro-category relates to the approach taken in developing regulation and to the philosophy underlying regulation choices. The respondents provide input on the principles that should guide decision makers. The framework should be *balanced and flexible* and avoid excess regulation to allow for proper management without inhibiting development:

"*Regulation is always a balance of responsible but not over onerous regulations. It is understanding risk and ensuring that high risk areas are properly monitored. Regulators will need to be moderately flexible to allow this to occur effectively*." (research org.)

"*Existing EU/UK storage regulation is stringent enough. Anymore regulation before a single project exists, to demonstrate that the regulations are appropriate, would stop CCS in its tracks*." (industrial operator)

Requirements should be based on scientific evidence and field tests and a guiding criteria could be to refer to "*how the safety of the storage site is going to be preserved in the long-term*" (industrial operator). Other respondents suggest the relevance, within a regulatory approach, of specific competence on certain technical areas, for instance:

"*understanding of the technologies that prevents leaks and how reliable they are and therefore what is the credible scale of the issue*." (industrial operator)

"*knowledge about discharge mechanisms and removal of CO_2 by geochemical reactions at greater depth and near the discharge into major rivers and lakes*" (research org.).

On a different level, taking into consideration the impact of legislation itself, it is suggested that regulations could indirectly and strategically contribute to limit leakage impacts through specific requirements for the operators. From this point of view it is considered important to:

"*make the environmental assessment part of the costs of the installation, industry needs to fund the monitoring safety and potential impacts*"(research org.);

"*make the liability for the industrial operator high enough to avoid excessive risks taken by them*" (industrial operator).

Of course this links to the point above on balance and flexibility, helping us better understand the issues involved. This is also true for two specific indications which appear to stem from a similar concern. One states that to take fears seriously into account no site should be allowed in inhabited areas; the second one that contingency plans should be put in place also for risks that are not considered as such by the experts but are feared by the people. We have already seen in question 2 the request of information even if the event considered is not possible, here once again clearly emerges the importance of perceived risk with respect to real risk. These are points that have first of all an emotional relevance, therefore it is very important to work on them to find solutions that can make people feel at ease with the technology. The risk of overregulating or even spending money for measures that are recognised by the experts as being unnecessary is concrete.

Another point that the respondents consider important from a regulatory perspective is giving due consideration to public participation, which also implies that "*the data should be made publicly available to the science community and public*"(research org.).

Last but not least there should be "*instruments for the competent authority to act in case the operator fails to stop the leakage*" (industrial operator).

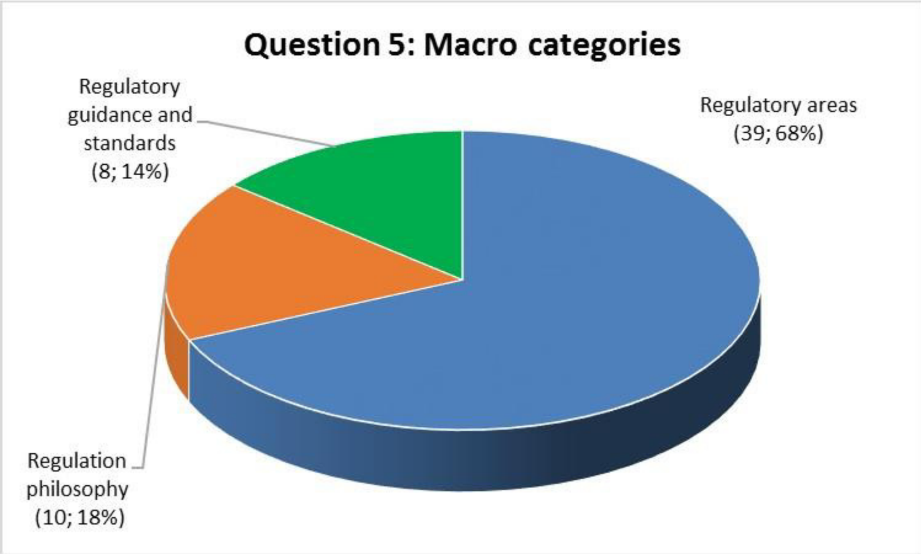

Fig. 9 Pie chart showing the frequencies/percentages for the macro categories of question 5.

3.6.2. *Regulatory guidance and standards.*

The active role of the authority is further stressed in relation to the definition of standards that should provide guidance for the implementation of CO_2 storage. A number of areas are mentioned for which the authorities should develop and establish appropriate standards:

- Reference baseline values
- Monitoring requirements
- Site selection criteria
- Industrial standards for wells
- CO_2 measurement in the ground and the atmosphere
- Limits for CO_2 content in ground water
- Definition of CO_2 as a material to be stored (as for example for radioactive waste)
- Limits for CO_2 impact: limits for suffocation are usually defined on occupational level - is it enough?
- Limits for CO_2 influence on e.g. trace metals concentration is not defined: main and minor components and trace metals in potable water are usually defined in hygienic Decrees and mostly not well arranged
- Limits of storage of CO_2 per volume of ground.

3.6.3. *Regulation areas.*

The third macro category relates to the areas that should be covered by regulation. Not dissimilar from those identified in the existing regulation the respondents indicate the importance of the following:

1) site selection and characterisation (including engineered features, wells)
2) baseline
3) monitoring plans
4) regular review of storage and monitoring data
5) demonstration of conformance by the operator
6) remediation plan and toolbox
7) ownership and liability

Concerning the last point, the respondents stress the importance of defining liabilities for the entire storage life cycle (long term or at least the first 100 years) and of providing financial security.

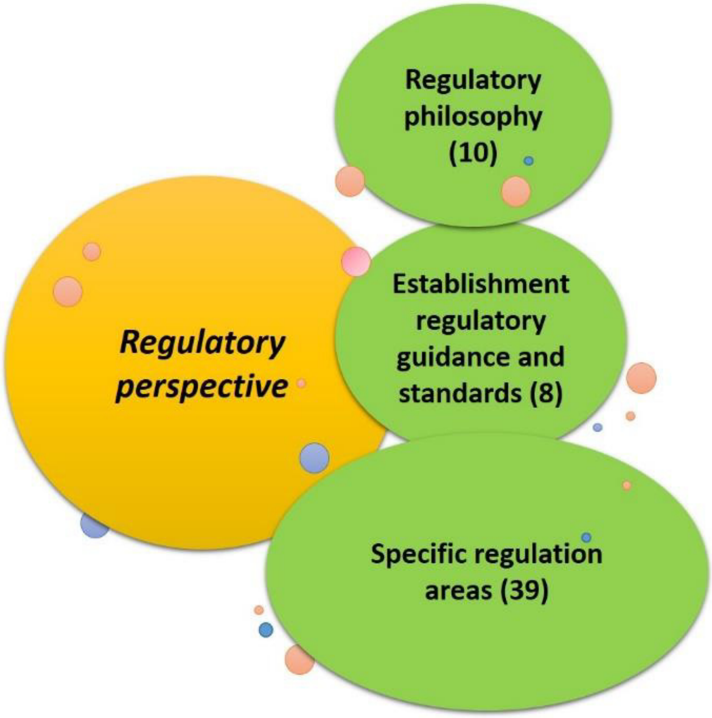

Fig. 10 Concept map of question 5.

3.7. Question 6: "From a layman's perspective, what would make you feel safe with regard to the implementation of CO_2 geological storage?"

When assuming the perspective of the layman the respondents point out first of all the importance of implementation procedures and of good information and communication. Demonstration of storage safety together with Trust and Nimby issues form another block of categories, which bring to the surface the uneasy situation for the citizen, which finds him/herself between the need and the lack of trust.

For question 6 we can identify 5 macro-categories (**Errore. L'origine riferimento non è stata trovata.**):

- Procedures (22)
- Information and communication (14)
- Demonstration (9)
- Trust (8)
- Nimby (5).

3.7.1. *Procedures (22)*

A first group of answers indicates the quality of the procedures as a main factor that can make people feel safe. Several aspects are covered, from project's start to end: a tightly regulated industry, detailed high quality EIA; proven/validated methods and technology; clear owner/responsible entity of the site; industrial approach with clear roles for operator and regulator; constant and appropriate monitoring (with biological alert) and publication of the monitoring data; the fact that the company that stores CO_2 is responsible for measurements/monitoring with comparisons of data with previsions, shown to the public; sufficient funds in place to assure that measures can be taken in case of leakage; sufficient instruments for the supervisor to act in case of leakage and if the operator has not taken sufficient measures. A particular sub-category can be identified with regard to this area, concerning control procedures. Several answers (7) stress the need of procedures of independent or State supervision: exploration activity controlled by a fact-centred authority, like the mines bureau, before storage is started; strict governmental supervisory and direct monitoring of safety; review of the plans by independent experts (and assurance of comprehensive nature of these plans); third party review of the storage behaviour.

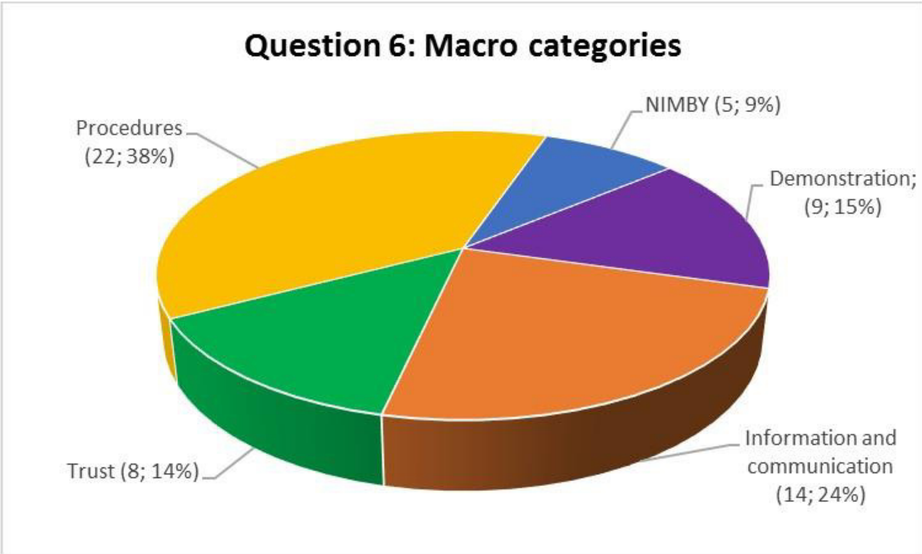

Fig. 11 Pie chart showing the frequencies/percentages for the macro categories of question 6.

3.7.2. *Quality information and communication (14)*

Quality information and communication that addresses local concerns throughout the storage lifecycle appears to play a key role as a factor that can make people feel safe (in line with Bradbury et al. research findings previously mentioned). Many aspects are mentioned: transparent and easily available information; sufficient and fact based knowledge about the technology; documentation of results from test and industrial sites in an understandable document; open public consultation; transparency of the project; visits to actual sites; awareness of the parameters under which it is guaranteed that CO_2 storage would work; information on the effects of CO_2 leakage on people (and non-humans/ecosystems) living nearby, and also detailed information on measures that would be taken in the event of a 'worst-case scenario' leakage (e.g. evacuation plans, time it would take for CO_2 to reach my house from the leakage point, longer-term health effects); answers to local concerns about the storage, not the general climate issues; enable people to check that monitoring is going on (surface monitoring is important, null results are good); explanation of the results of studies and simulations in a way that everyone can understand the real "risk" in comparison to the climate change risks.

3.7.3. *Demonstration (9)*

For other stakeholders what is necessary for citizens to feel safe is concrete, either technical or operational, demonstration: proven analogues, results from field tests in comparable geological settings, large scale demo showing it works, research on regional-scale impact of industrial-scale CO_2 injection, scientific studies that confirm the efficacy and safety of operation, track record of verifiable performance that demonstrates it is safe.

3.7.4. *Trust (8)*

An interesting category revolves around trust, which is explicitly mentioned in some answers as a qualifying dimension for feeling safe. However, the conditions that might give place to trust rely on different kinds of assurances: that there are no risks; that CO_2 is guaranteed not to leak; that CO_2 concentrations in my area of operations would not, under any circumstances, reach hazardous levels for human or animal health; that technical principles common for natural gas storage would be applied to CO_2 storage; Government demonstrating its commitment to CCS and hence also its desire to ensure CO_2 storage is safe on behalf of the general public; serious companies undertaking the storage, with some contingencies included for if things go wrong. But also in negative form: "*a lot comes down to trust. Geologists seem to get things wrong quite often or else cannot really explain events, such as fracking/seismic case in NW England. They tend to be overly confident, as all experts are*" (research org.). This category, which has often fallen under the lens of scientific investigation, is probably the most elusive, as trust seems to be evoked precisely because of its absence. Trust could make people feel safe, the problem is…there is no trust, as also the following category comes to indicate.

3.7.5. *Nimby (5)*

Last but not least we find another very interesting category, that of those who would feel safe only if the storage site would be far away from where they live: being a long distance from the infrastructure and storage site; be it far away from populations (preferably off-shore); knowing that the depth and distance from shore of storage sites was such that a leak, should it reach the surface, would cause minimal impact to the local air quality; selection of sites offshore and distant from large urban developments; so long as the storage site is offshore and the geological formation doesn't outcrop onshore geological storage "feels" safe. In the case of these responses, the issue of trust is bypassed, removing the technology from the vicinity of human settlements. These answers seem to indicate that there is a certain number of people who cannot even imagine conditions that would make them feel safe near a storage site. This is something difficult to understand from an expert point of view: "*It's difficult for me to be a layman on this issue, but people will only feel safe if CO_2 is guaranteed not to leak. It's a crazy situation where we have millions of miles of potentially dangerous and explosive domestic and industrial gas pipelines around the world, yet CO_2 leakage, even if it is from a well, is perceived to be dangerous, notwithstanding it can be managed relatively easily and there are very low level risks to humans. We need to break the myth that a CO_2 storage site can end up with a Lake Nyos outcome*" (research org.).

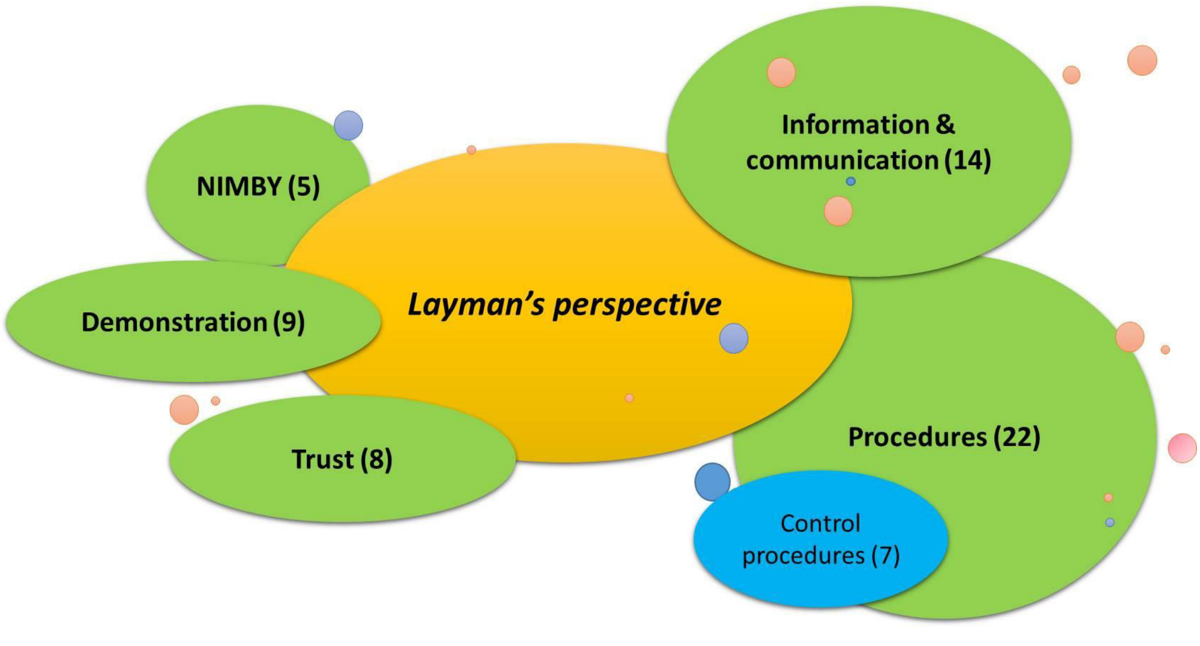

Fig. 12 Concept map of question 6.

4. Comments and conclusions

The RISCS questionnaire results provide a comprehensive picture of a variety of aspects which the respondents consider important from the point of view of impacts and long term safety of storage sites. With the contribution of all respondents a very complete perspective over CO_2 storage impacts and the ways to keep them very low emerges. The themes span from impacts on the environment to socio-economic and operational such as for instance building and management of storage sites. Concerning the areas studied in the RISCS project, namely leakage impacts, it is interesting to note that leakage often appears as a generic category which requires to be addressed, independently from the fact of causing impact or not. This relates to the importance of leakage as a fear generating factor which, as such, should always be seriously addressed. Among the more specific leakage impacts indicated, the most important one is the potential impact on groundwater resources.

With regard to the long term safety of storage sites, the two main areas on which the demand for scientific information focuses are implementation issues and understanding of what happens in the reservoir. The attention here shifts to what happens in the underground when CO_2 is injected and its long term fate and to storage site management challenges.

Concerning the scientific information that could help dealing with potential impacts of leakage, a broad range of topics is considered important for decision makers, but also the (public) availability of datasets and the quality of scientific information in terms of accessibility and user-friendliness.

When assuming the perspective of the operators, the impact reveals a prevailing socio-economic nature. Here respondents indicate leakage prevention as the key dimension: should leakage happen the consequences are expected to be serious not so much on the environment as for the industrial operator, both financially and in public perception and reputation terms. When considering the impact of leakage in itself, apart from the socioeconomic consequences, water contamination is the first cause of concern.

From a regulatory point of view, the importance of the regulatory “philosophy” stands out, as it will inform regulatory guidance and standards. An evidence based framework is advocated, avoiding excess regulation to allow for proper management without inhibiting development.

Finally, from a layman’s perspective, the quality of procedures emerges as the best guarantee for safety together with the quality of information and communication. However the difficulty in trusting the full safety of storage is strong and for some stakeholders it is possible to feel safe only with storage sites being far away.

The information collected with the RISCS Stakeholder questionnaire is very rich and probably fairly complete. It can provide a good basis for developing a map of CO_2 storage impacts that need to be addressed. The results highlight that there are at least two big areas that require substantial improvements: the definition of procedures and best practices for storage implementation and the dissemination of existing knowledge, both in terms of accessibility and user-friendliness. Detailed information is provided on the aspects that the stakeholders suggest should be covered, seen from different angles. A first conceptual organisation and categorisation of the impact issues raised by the respondents has been produced with a concept map approach. As a next step it will be interesting to explore this conceptualisation, as greater control of impact risk can probably grow also from greater awareness of how we conceptualise the issue.

The input received from the questionnaire has informed the communication activities in the RISCS project and the production of the RISCS Guide for impact appraisal [9]. Many of the requests of information made by the stakeholders can find and answer in the RISCS Guide or other research publications. However a lot still needs to be done to improve both the production and the dissemination of relevant information for managing impacts.

The outcomes of the RISCS questionnaire can be a tool for reflecting, sharing and developing a better understanding of impact issues in their general dynamics; additionally, we hope they can find application as a useful reference for performing the task of addressing, one by one, the potential impact issues related to the geological storage of CO_2.

Acknolwedgements

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