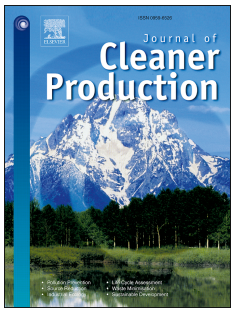
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# Opportunities and obstacles for $CO_2$ mineralization: $CO_2$ mineralization specific frames in the interviews of Finnish CCS experts

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## Abstract

Carbon capture and storage (CCS) is expected to significantly reduce carbon dioxide ($CO_2$) emissions for climate change mitigation purposes. Currently, the EU CCS Directive contains only geological storage as the storage option for $CO_2$ – excluding $CO_2$ mineralization as a storage option. Since all CCS technologies are currently in a relatively early stage of development, this exclusion seems unreasonable. Opportunities for the use of $CO_2$ mineralization and the main uncertainties that can potentially prevent the use of these opportunities are investigated in this paper. The analysis is done by means of framing methodology that enables the extraction of CCS experts' mental models concerning $CO_2$ mineralization from the interview data.

Four of the six frames found hold a quite pessimistic future for $CO_2$ mineralization. In addition, these frames were clearly strengthened when viewed within the global context. The way experts discuss CCS largely frames it in terms of carbon capture and geological storage (CCGS) and pushes $CO_2$ mineralization to the margins. Thus $CO_2$ mineralization is becoming even less likely to be included in policy making. At the same time, the slow progress of CCGS together with low public trust for the safety and sustainability of geological storage could strengthen the optimism found in two expert frames. Eventually this could weaken the pessimistic views and thus lead towards a more optimistic future for $CO_2$ mineralization. However, this would require significant progress in $CO_2$ mineralization technologies and especially increased publicity for such progress.

Keywords: $CO_2$ mineralization, opportunities, framing, mental models, Finnish CCS experts, interviews

## Introduction

A significant share of the total carbon dioxide ($CO_2$) emission reductions for climate change mitigation (~25% in IEA and IPCC scenarios [Metz et al., 2005; IEA, 2013]) are expected to result from carbon capture and storage (CCS). CCS consists of the capture of $CO_2$ from its source, its transportation to a storage site, and then its permanent storage. Each of these can involve a variety of technologies. Potential storage methods are geological storage (storage in oil and gas fields, deep saline formations, or in unminable coal beds), ocean storage, and $CO_2$ mineralization (i.e., mineral carbonation) (Metz et al., 2005). $CO_2$ mineralization can be divided into below ground (*in-situ*) mineralization and above ground (*ex-situ*) mineralization. The former involves the injection of $CO_2$ into the geological formation where it forms carbonates with alkaline-minerals, while the latter term is used for describing above-ground processes that require processing of the suitable mineral prior their conversion into carbonates. (Sanna et al., 2014) The in-situ mineralization is one form of geological storage and therefore the term "$CO_2$ mineralization" is henceforward used for describing the ex-situ mineralization.

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The disadvantages of geological storage include storage safety issues and risk perceptions. Storage safety is crucial, both for avoiding harmful effects to people and the environment, and in terms of unsuccessful long-term mitigation. Safety is also one of the most crucial factors affecting the public acceptance of CCS (Anderson et al., 2009; Eurostat, 2006; Johnsson et al., 2010; Shackley et al., 2005; van Alphen et al., 2007). There is evidence of project cancellations due to a lack of acceptance (Brunsting et al., 2011). Chaudry et al. (2013) find that CCS risks are prevalent also in expert discussions.

In $CO_2$ mineralization, $CO_2$ is fixed with calcium or magnesium oxide in a silicate mineral to form stable carbonate as the end product. $CO_2$ mineralization does not have storage safety issues, such as possible leakages, and thus monitoring is not necessary. (Eloneva, 2010) The $CO_2$ storage capacity of mineralization has been estimated to exceed the amount of $CO_2$ that would be emitted from burning all known reserves of fossil fuels (Metz et al., 2005). Compared to geological storage, $CO_2$ mineralization technologies have been criticized for a lack of technically attractive concepts and the negative environmental impacts of mineral handling operations (IEAGHG, 2013). However, an enormous amount of suitable raw materials already exist in the hoisted rocks of mines that produce industrial minerals and metals (Teir, 2008). In addition, mining operations would hardly differ from that of coal mining (Metz et al., 2005). Various different technological routes for mineral carbonation have been proposed and studied, but none of them has yet been commercialized.

The EU CCS Directive only includes geological storage as a storage option for $CO_2$ – excluding $CO_2$ mineralization (Zevenhoven and Fagerlund 2010) – and hence $CO_2$ mineralization is excluded from the EU Emission Trading System (EU ETS) as well. Since both geological storage and $CO_2$ mineralization technologies aim at reducing the volume of $CO_2$ emissions released into the atmosphere, it seems unreasonable that this policy already prefers one technology over the other. Further, as all the CCS technologies are currently in a relatively early stage of development, their profitability in the future, as well as other factors affecting their adoption, cannot yet be anticipated.

Institutions are social rules, which determine CCS development. Institutions can be formally defined, such as laws and regulations, or informally accepted, such as norms, practices, and strategies (e.g., Scott, 2013). The implications of different institutions on the development of $CO_2$ mineralization technologies were previously investigated by Kainiemi et al. (2014). It was found that since the CCS technological innovation system has been developed within the existing fossil fuel regime, the formal and informal institutions are based on this regime. To the fossil fuel regime, geological storage represents storage with which they are already familiar – for example from oil and gas drilling – while $CO_2$ mineralization is something totally new and outside the regime. Therefore, it would require a large shift in this regime and the institutions surrounding it to provide better conditions for the development of $CO_2$ mineralization. In addition to formal institutions (the EU ETS and the CCS Directive), the use of the term *$CO_2$ utilization* instead of storage to describe $CO_2$ mineralization (informal institution) were seen as possible paths towards the marginalization of $CO_2$ mineralization from CCS discussion and research.

Mental models affect how actors in technological innovation systems define and explain complex systems and subsystems to themselves. Therefore mental models also affect the formulation of the institutions that guide technological development. The aim of this paper is to use framing methodology (Goffman, 1974) to explore the mental models of CCS experts, who are actors in the CCS system, concerning $CO_2$ mineralization. This analysis is performed by analyzing how Finnish CCS experts frame $CO_2$ mineralization in in-depth interviews in order to determine the potential of $CO_2$ mineralization in particular, but also to

determine opportunities for the use of $CO_2$ mineralization as well as the main uncertainties that can potentially prevent the use of these opportunities. In Finland, multiple research groups are active in the field and thus the ways in which Finnish experts frame the technology are informative to CCS communities elsewhere. It is important to understand different ways of framing the $CO_2$ mineralization as a phenomenon because the frames used in communication significantly affect public opinion and powerful players have more power and opportunities to communicate their frames (Zaller, 1992). The following Methodology section introduces the use of the framing approach for analyzing the mental models of the experts, and presents the methods used for the interviews and their analysis. This is followed by a presentation of the found frames of the Finnish CCS experts in the Results and Discussion section. The effect of these frames on each other and how they fit into a global context are discussed as well. The paper concludes by presenting the main findings and their implications for the future development of $CO_2$ mineralization technologies.

# Methodology

## Mental models and framing

Framing is the selection and emphasis of certain aspects of the perceived reality, where the emphasized elements define a problem and its causation, evaluation, as well as its solution. Conscious and unconscious decisions are made when choosing what to include in communication, based on the beliefs of the communicator. Frames can be found in communicated texts or narratives, or through the use or absence of key words, phrases, stereotyped images, and expressions forming clusters of facts or judgments. (Goffman, 1974.) These frames can be shared by a number of people in the same social group, leading to a consensus regarding future actions (Entman, 1993). Frames reveal the values and assumptions behind actions; what is considered important and what is not (Hajer and Laws, 2006). These valuations can be shared among different groups of people and can be institutionalized into policy frames with the related organizational, procedural, and normative structures (Lenschow and Zito, 1998).

While frames highlight certain aspects of reality they can also direct attention away from the other aspects. The omission of alternative definitions and explanations of the issue, and recommendations regarding it, can affect the receiver of the communication as much as what is included (Kahneman and Tversky, 1984) and change a message radically (Edelman, 1993). If the receivers of the message do not have much previous information regarding the situation, they can be greatly affected through receiving information based on a single frame or interpretation (Entman, 1993).

Widely accepted and adopted frames can be very powerful. Presenting an argument outside a widely accepted frame can lead to problems of credibility for the communicator or can prevent the message from being understood correctly. (Gamson, 1992) Therefore solutions outside the remedies of widely accepted frames exceed the boundaries of what is considered acceptable discourse and are unlikely to be considered in policy (Entman and Page, 1994). Policy can directly affect technology choices, either through direct recommendations or other supporting policy instruments, or through framing the context for the technologies or applications that are considered solutions to the problem at hand. (Jorgensen et al., 2009; Klein and Kleinman, 2002)

In the Finnish energy regime, influential stakeholders have been found to be highly homogenous and relatively stable (Ruostetsaari, 2010). The regime is oriented around the dominant industries with persistent dominant goals that are stable, with only some reframing through major exogenous pressures, including EU membership and climate pressures. These reframings mean that new energy policy goals do

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not always lead to the adoption of new technologies but change the meanings given to existing dominant strategies. (Kivimaa and Mickwitz, 2011) For example, in bioenergy, the intersection of forestry and energy and the traditional key actors of Finnish industry were the main sources of bioenergy framings (Huttunen, 2014).

Framing can be used to analyze stakeholder views because it reveals connections between the beliefs, assumptions, and goals of the stakeholders and the actions they promote. Different actors form different frames on the same policy issues and therefore the identification of different frames can be significant in solving policy problems. (Schön and Rein, 1994) Framing can also reveal the relations of the different actors to one another as, while formulating a frame, they also frame themselves and others in certain roles (Laws and Rein, 2003). In the system, the more powerful actors have more influence in framing the positions of others (Huttunen, 2014).

Expert frames for opportunities and uncertainties for CCS in general have been previously analyzed by Hansson and Bryngelsson (2009), who emphasized the role of expert opinions in influencing political decisions to promote new and previously unutilized technologies. They maintain that since there are no existing CCS systems, apart from those in the minds of experts, the opinions of these experts have a significant impact on policymaking. Chaudry et al. (2013) used content analysis to analyze interview data describing expert views in four US states. They found out that CCS is framed through the technical, political or regulatory and economic uncertainties, while health and safety risks and environmental benefits are not discussed much. Still, the bulk of the framing literature focuses on geological storage, such as the comparison between media frames and expert frames of the alleged leak at the Weyburn storage facility (Boyd et al., 2013). Even in this relatively simple case with a single technology and an actual project, expert framings varied significantly, even if there was little conflict over the physical facts of the case.

Therefore the framing methodology can reveal how actors within the CCS and mineralization innovation systems frame issues with CCS policy and CCS development in general. Their frames indicate what different actors consider important and unimportant, and what aspects of current policy they consider problematic and what actions should be taken to correct these problems. As frames are built by each actor through selecting and combining facts regarding the issue and according to their own values and assumptions, the frames reveal information on the mental models of these actors. Mental models are relatively enduring and easily accessed conceptual representations of complex realities (Doyle and Ford, 1998) – in essence, simplifications of complicated systems that are easier to understand than the system itself. Although mental models make the represented system easier to understand, they are also prone to the omission of feedback loops, time delays, and non-linear relationships. The use of framing allows specifying the reasoning used behind mental models and reveals the logic behind stakeholders' models as well as their connections to desirable actions.

The development of novel technologies, and particularly CCS, typically contain mental models with omissions, oversimplifications, and non-linear relations: for instance, risk timescales can extend thousands of years, scale-up (through piloting and demonstration) feeds into the technology's development, and the commercial breakthrough of one technology can establish a lock-in of that variant of the technology (Vergragt et al., 2011).

## Methods, interviews, and the data

This study analyzes how mineralization is framed in Finnish CCS expert discussion. In this article the term 'expert' is used to describe an actor with a professional interest in CCS and the analysis is based on in-depth

interviews. The study was conducted as a part of a project on the Risk Governance of Carbon Capture and Storage (RICCS, 2011–2014). The project aims to enhance the reliability, adaptiveness, and acceptability of CCS technologies by engaging the general public, CCS technology developers, and decision-makers into an early stage appraisal of the risks related to the further development of CCS. One of the empirical methods of the project was stakeholder interviews, which were conducted at the actual CCS development sites in Norway, Germany, and Finland. This study is based on the stakeholder interviews concerning Finland.

The interviewees were selected with an aim that the relevant companies, universities, research institutes, and the government would all be represented. An environmental non-governmental organization (ENGO) was selected to represent the public. Both management and R&D from the two companies that were seen as most involved with CCS in Finland were included. One researcher was interviewed from a university and one was from a research institute. University administration was also represented by one interviewee. The government was represented by one civil servant. In total, nine people were interviewed, each interview lasting between one to two hours.

All interviewees are experts in the field of CCS. Some are specifically involved in $CO_2$ mineralization but some stakeholders have little knowledge of it and therefore the number of $CO_2$ mineralization specific frames found from the interviews was low and some frames can be based on the comments of only one or two stakeholders. However, this allows us to analyze both the mental models of CCS experts with no $CO_2$ mineralization connections (who are the actors involved in the formation of institutions that may slow down $CO_2$ mineralization development) and the mental models of $CO_2$ mineralization experts. This gives us information on the opportunities presented by $CO_2$ mineralization, but also information of the changes that would be required in the institutions of the CCS technological innovation system and the mental models of its actors in order for these opportunities to become realizable.

Interviews were constructed to ensure that technical, economic, governance, as well as social issues were discussed with all interviewees. Some underlying issues that are widely discussed in the literature were selected to support the interviews, which otherwise were conducted in an organic manner, focusing on the interviewees personal narrative with as little interference from the interviewers as possible in order to reveal the mental models they held of the CCS system and to allow them to frame the issues freely.

The interviews were transcribed by an independent company. These transcriptions were then read by two of the project researchers, who coded those parts of the text that pointed to the role of CCS, now or in the future. The coding procedure was inductive, based on the data: individuals statements were classified on a typology on how they addressed the role of CCS, as understood by the coder. This raw coding was then discussed, their main points were written down with relevant citations attached and built into frames – or aggregated into clusters of expressions, phrases, key words, and definitions. In this study, the focus is on the interviewees' perceptions of $CO_2$ mineralization. Thus, the categories were built into frames, or organized by the cause that they were based on, including the future outlook for $CO_2$ mineralization in that frame.

## Results and discussion

### $CO_2$ mineralization frames formulated from the Finnish CCS expert interviews

At the end of the analysis, six frames were formulated (Table 1). One of the most pessimistic frames reflects a mental model according to which $CO_2$ mineralization is too slow, too energy-intensive, requires great amounts of minerals and therefore has high costs. One of the interviewees stated: *"those required*

*amounts of rocks and their handling they are so huge reaction speeds are so slow …"* and *"… how can you get the reaction speed increased to very different from what it is right now and that, without using unreasonable amount of energy for it, at least for me nobody has been able to tell that"*. The other interviewee stated that*: "Let's assume that the process would work so energy efficiently then that requires huge amounts of minerals. And plus it requires that mining, quite demanding kind of mining activity".* The future of $CO_2$ mineralization in this frame, named the ***high-cost*** frame, is skeptical and it holds the idea that $CO_2$ mineralization should only be used for specific applications. However, the ***high-cost*** frame received criticism from an interviewee working on $CO_2$ mineralization for omitting the fact that in $CO_2$ mineralization the capture step can often be left out.

$CO_2$ mineralization is also seen to be at very early stage of development, which was stated by interviewees, for example: *"if compared to this geological storage then carbonation […] It [mineralization] has 10 years of progress or even 20 years of progress needed"* and *"They seem to be at there at the quite early stage of the learning curve".* This frame, named the ***immature technology*** frame, assumes that it will take a long time until $CO_2$ mineralization technology is mature enough to be commercialized. The future of $CO_2$ mineralization in this frame is uncertain and it depends on technological development and cost effectiveness in relation to other CCS options. Universities are seen to be in a key position in the further development of the technologies, as companies can be hesitant to invest in new applications until they are shown to work in practice.

The definition of CCS as $CO_2$ capture, transport, and geological storage was also considered problematic by two of the interviewees. One stated, for example: *"there will be a law now coming, legislation as they call it, the European directive from April 2009 must be implemented in Finland, and that's about CCS. But that CCS, what they mean there is underground storage, so that's a bit different. So it doesn't really address mineralization."*, *"But again, $CO_2$ from natural gas, that has convinced the population that CCS means storing $CO_2$ underground, and the other options have been shadowed under. $CO_2$ mineralization is also CCS. But if you read the European directive on CCS from 2009, it says there that CCS means the capture of $CO_2$ and transporting it to an underground storage site and putting it underground. Well, that's not what CCS is. So that's something to bear with.", and " if people know about CCS, they think it's about storing $CO_2$ underground. Even in Finland where that cannot be done. So there's a big reprogramming to do of people."* Another stated that: *"Now I cannot recall whether it was in the new Emissions trading directive there was something that seemed problematic […] if carbon dioxide is transported from some plant then it cannot be reduced from the plant's emissions unless the transported carbon dioxide is stored in geological storage formations. And if it goes like that then it creates obstacles for mineral carbonation […] in that way, that of course the interest from the industry towards it would diminish …"* This frame, which is based on the mental model that CCS is falsely defined as the capture, transport, and geological storage of $CO_2$, was named as the ***false definition of CCS*** frame***.*** Just like the ***immature technology*** frame, it holds an uncertain future for $CO_2$ mineralization. Opportunities are seen, but they require that $CO_2$ mineralization is acknowledged as one option for storing $CO_2$.

In addition to a CCS definition that excludes $CO_2$ mineralization, $CO_2$ mineralization was felt to be unsupported by the CCS related journals and conferences: *"I mean, there are magazines now, there is the International Journal of Greenhouse Gas Control, but they tend to not accept papers on mineralization. They do accept if you have paper on mineralization saying that it's taking ridiculous amounts of material, or ridiculous amounts of energy. Then they take your paper, but if you have a serious paper, it takes a long time to get it reviewed and you wait for two years to get it published."* and *" The IEA GHG organization, the*

*greenhouse gas, big conferences, the International Journal of Greenhouse Gas Control. They are not really supportive for $CO_2$ mineralization, and that is a bit of a, that's a problem for the technology deployment"*. Financial support was also considered to be mainly dedicated to other CCS technologies: *"I think about five percent of the budget goes to $CO_2$ mineralization and 95 percent goes to talking about CCS, writing about CCS, thinking about CCS"*. This frame, named the ***unsupported by the CCS community*** frame, also holds a challenging future, in which $CO_2$ mineralization is likely to stay in the margins compared to other CCS technologies.

Problems with carbon capture and geological storage (CCGS) – such as the risk of leakage, the lack of action, and gaining a bad reputation – were seen as an opportunity for $CO_2$ mineralization. One of the interviewees stated: "*that carbon dioxide has been transported to quite far for the permanent storage. That adds to its costs, risks. So I see clear advantages if it can be fixed with some solid substance on Finnish ground.*" Another stated that, for example: *"… people are getting worried, this underground storage, it isn't happening. Too much talking and there's only money moving around and there's only paper and then legislation and emission trading, and the $CO_2$ keeps coming and there's no reduction there, there's nothing happening. And so people are looking for alternatives."* and *"mineral, they are stable, the $CO_2$ is more stable in a mineral than in the air actually. So the fact that there is no leakage, that just might be something for the public acceptance […] But if you start to do a discussion and asking the public: this is CCS underground storage, this is CCS using mineralization, what do you think is best? Then I think I'm pretty sure that I know what the outcome is. Want the pile of white powder or a bubble under your house, pressurized bubble under your house."* The future of $CO_2$ mineralization in this frame, named the ***opportunities in the weaknesses of CCGS*** frame, is promising. New patents and pilots in the field of $CO_2$ mineralization are seen as positive progress. In this frame, it is thought that the focus should be shifted from CCGS to $CO_2$ mineralization, especially in Finland. While high public acceptance is not expected for $CO_2$ mineralization, it is thought to be higher than support for CCGS if these two choices are presented to the public.

The large $CO_2$ storage potential within the availability of the suitable raw materials for carbonation, as well as the lack of geological storage sites in Finland, are also seen as an opportunity for $CO_2$ mineralization. One of the interviewees stated: *"For example just like in Finland […] there is so called urge to increase mining activities for the sake of other minerals. When we look at that symbiosis, it feels that mineral carbonation might have that kind of quite a good potential, if it can be integrated into the mining industry"* Another stated that, for example: *"But again, too much time has been wasted, I think, in putting money on a dead horse, I mean, that how I call it. Why would you keep sitting on that horse, we know that you cannot store $CO_2$ in Finland."* and *"At some point you must conclude, this not a good idea, this we cannot do. We are not as fortunate as they are. We are not Norway with a lot of gas, but we are Finland with a lot of minerals. We don't have underground capacity, but we are smart people, we have a lot of geologists."* Within this frame, named the ***large $CO_2$ storage potential*** frame, the future for $CO_2$ mineralization is optimistic in Finland (although dependent on the mining industry). It is thought that the focus should be on $CO_2$ mineralization instead of on other CCS options.

### $CO_2$ mineralization frames in a global context

The majority of the interviewed Finnish CCS experts share a critical view of $CO_2$ mineralization. Our analysis sheds light on the experts' mental models behind their reasoning. In the following, we discuss the implications of our findings. At first, we explicate the role of different frames in the global context, focusing on the universality of the frames. After that, we explain how different ways of framing $CO_2$ mineralization function simultaneously and affect each other.

Even though some $CO_2$ mineralization methods have been claimed to have economic potential (e.g., Verduyn et al., 2011), the experts' widely accepted view is that $CO_2$ mineralization is a very expensive method (e.g., our interviews; Sanna et al., 2014). The ***high-cost*** frame is very effective in blocking out any further discussion of $CO_2$ mineralization since it poses the question: 'What is the point of considering the potential of a technology and developing it when it is too expensive?' As noted by one of the interviewees, studies comparing the costs of different CCS methods often add capture costs to $CO_2$ mineralization, only comparing the storage costs of the two options (e.g., Olajire, 2013). This leads to the dominance of a misleading mental model regarding the costs of $CO_2$ mineralization. Yet resistance to the ***high-cost*** frame is likely to arise among those CCS experts who work with $CO_2$ mineralization, as they can be assumed to be more optimistic about the costs or even contest the truthfulness of the frame.

The ***immature technology*** frame is also quite widely adopted among CCS experts everywhere (e.g. IEAGHG, 2013; Sanna et al., 2014), although some piloting and demonstrations of the technology have been presented (Sanna et al., 2014). Nonetheless, both the immaturity and expensiveness of $CO_2$ mineralization are situations that have the potential to change if further technological development occurs. In addition, while CCGS technologies are certainly currently more advanced than $CO_2$ mineralization ones, for serious climate change mitigation purposes that rely on geological storage, a significant development in the $CO_2$ capture step and more experience in $CO_2$ storage in deep saline formations are needed as well (GCCSI, 2013).

CCS is consistently defined as capturing of $CO_2$ emission and transporting it to geological storage site for permanent storage in journal articles that analyze stakeholder perceptions of CCS (for example,Evar, 2011; Lock et al., 2014; Oltra et al., 2010 [although the latter also mentions ocean storage as an option]; Shackley et al., 2009;). In other studies on similar topics, CCS has not even been clearly defined and the only recognized method for storing $CO_2$ is the geological one (e.g., Ashworth et al., 2012; Hansson and Bryngelsson, 2009). These misconceptions, together with the absence of $CO_2$ mineralization in the EU ETS and the EU's CCS Directive, certainly strengthen the ***false definition*** frame. In a key position for weakening this frame are: legislators, companies, and CCS experts working with CCGS. The common definition of CCS will not change until $CO_2$ mineralization is included in legislation, the EU ETS, and in CCS research in general. Based on current developments in the field, however, it seems that the opposite is happening and $CO_2$ mineralization is becoming more strongly considered to be separate from CCS (Kainiemi et al., 2014).

Last year, in the International Conference on Greenhouse Gas Technologies (GHGT-11, 2013) only one session was dedicated to $CO_2$ mineralization while 11 sessions were dedicated to geological storage. Additionally, a journal that traditionally publishes a wide range of research results on different CCS applications has started to encourage authors to submit their papers on $CO_2$ mineralization to the Journal of $CO_2$ Utilization and even considers $CO_2$ mineralization as one $CO_2$ utilization option (Gale, 2013). The ***unsupported by the CCS community*** frame is evidently present in these examples. One of the reasons for the strength of this frame might be that CCS began to develop from within the fossil fuel regime; meaning that $CO_2$ mineralization is foreign to the relevant stakeholders and thus outside their areas of expertise and interest (Kainiemi et al., 2014). This was also noted by one of the interviewees: *"But on the other hand I can also understand the energy people. The power plant people. They are not interested in chemical engineering. They understand electricity, they understand hot water, they understand steam, they understand steam turbines. And then building a chemical plant next door is not what they are interested in [...] And that's a trend that you have in general – that many companies go back to their core business."*

Experts who operate in the existing fossil fuel regime and are involved in CCGS often highlight the negative prospects of $CO_2$ mineralization that are illustrated in the ***high-cost, immature technology, false definition*** *and* ***unsupported by the CCS community*** frames. Because, at the same time, the existing regime is strongly institutionalized, these actors are in a powerful position to communicate their frames to other stakeholders and the public. The good visibility of critical frames underlines the role of $CO_2$ mineralization as a marginal CCS method. It is important to note that all four frames that share a pessimistic view of $CO_2$ mineralization are tightly interlinked. For example, a strong ***unsupported by the CCS community*** frame is very likely to strengthen the ***false definition*** frame. While $CO_2$ mineralization only has a marginal role, or its role is unclear or even missing, in the conferences and journals dedicated to CCS, stakeholders are apt to think that geological storage is the only relevant storage option available. On the other hand, a strong ***false definition*** frame serves as a signal to the CCS community that it is acceptable to exclude $CO_2$ mineralization from the discussion of CCS. Similarly, strong ***high-cost*** and ***immature technology*** frames may strengthen the ***unsupported by the CCS community*** frame by providing seemingly acceptable justifications for the marginalization of $CO_2$ mineralization.

While the pessimistic frames of $CO_2$ mineralization are mutually interlinked and may strengthen each other, it is worth remembering that those are not unchangeable. More optimistic frames operate in the same institutional reality that constantly defines the global future of CCS. For example, the number of large-scale CCGS projects is currently declining as projects have been cancelled or put on hold (GCCSI, 2013). This kind of development could reinforce the ***opportunities in the weaknesses of CCGS*** frame – although it is likely to require simultaneous progress of $CO_2$ mineralization as well. Public trust in the safety and sustainability of geological storage (Brunsting et al., 2011; Johnsson et al., 2010), and sometimes even the skepticism of experts about it (Hansson and Bryngelsson, 2009), could certainly strengthen the frame as well, but it requires that the public is made aware of $CO_2$ mineralization and its permanent $CO_2$ storage capacity. In addition, while ENGOs and the public could be more positive in terms of the lack of risks, the acceptability of $CO_2$ mineralization could suffer if large-scale mining operations would be established for the purposes of $CO_2$ mineralization. In Finland, for instance, other recent experiences and media coverage of the problems related to mining operations – particularly in regard to the Talvivaara mine (e.g., Peurakoski T., 2014; Saavalainen H., 2014) – could, in turn, lower the acceptability of the technology as well.

## Discussion

The mental model behind the ***high-cost*** frame is that $CO_2$ mineralization is too slow, too energy-intensive, and that it requires great amounts of minerals (and therefore has too high costs). The ***immature technology*** frame is based on the mental model that $CO_2$ mineralization is currently at a very early stage of development. The mental model behind the ***false definition*** frame is that CCS is falsely defined as the capture, transport, and geological storage of $CO_2$. The idea that $CO_2$ mineralization is unsupported by the CCS related journals and conferences and lacks significant financial support is the mental model behind the ***unsupported by the CCS community*** frame. The ***high-cost*** frame seems to be strongly supported by most of the CCS experts in Finland and elsewhere, and the ***false definition*** frame is certainly strengthened by the absence of $CO_2$ mineralization in the EU ETS and in the EU's CCS Directive, as well as by the definition of CCS in CCS relevant journal articles as the capture, transport, and geological storage of $CO_2$. The ***unsupported by the CCS community*** frame is strengthened by the marginalization of $CO_2$ mineralization in relevant CCS conferences and journals. Strong ***high-cost*** and ***immature technology*** frames give reason for this marginalization, while a strong ***false definition*** frame gives the CCS community the message that this marginalization is acceptable. In addition, the ***false definition*** frame is strengthened by the strong

***unsupported by the CCS community*** frame as, due to marginalization, stakeholders are led to think that geological storage is the only relevant storage option there is.

The mental model behind the ***opportunities in the weaknesses of CCGS*** frame is that $CO_2$ mineralization can benefit from the problems with CCGS (such as the risk of leakage, the lack of action, and gaining a bad reputation). The ***large $CO_2$ storage potential*** frame is based on the mental model in which there is an abundance of the raw material for $CO_2$ mineralization, while Finland lacks geological storage sites. The slow progress of CCGS, as well as low public trust for the safety and sustainability of geological storage, could strengthen the ***opportunities in the weaknesses of CCGS*** frame and eventually (together with the reinforced ***large $CO_2$ storage potential*** frame) weaken the strengths of the ***false definition*** and ***unsupported by the CCS community*** frames, leading to a more optimistic future for $CO_2$ mineralization. However, this would require the significant progress of $CO_2$ mineralization technologies and, especially, increased publicity for that progress (leading to weaker ***high-cost*** and ***immature technology*** frames).

## Conclusions

Mental models and the terminology used to talk about technologies limits technological futures. We have shown that the way experts discuss CCS largely (but not totally) frames it in terms of CCGS and pushes $CO_2$ mineralization to the margin. A total of six $CO_2$ mineralization frames were formulated from the in-depth interviews of Finnish CCS experts. Four of these frames (***high-cost***, ***immature technology, false definition*** and ***unsupported by the CCS community****)* hold a quite pessimistic future for $CO_2$ mineralization, while two of them (***opportunities in the weaknesses of CCGS*** and ***large $CO_2$ storage potential***) were more optimistic.

In our case, there is strong evidence of the practical effects of the experts' framings: the fact that the EU's CCS Directive focuses exclusively on CCGS. These effects are often unintended consequences, but our analysis suggests that stakeholders dealing with public policy and funding should be highly aware of them. Examples and simplifications carry enormous power. As $CO_2$ mineralization is not widely framed as a suitable solution to reduce $CO_2$ emissions, it is pushed outside the discourse regarding these solutions and is becoming even less likely to be included in policy making. Decision-makers in legislation, research & development, and project management should be aware of their own framings. In this case, decisions made on the open-ended idea of CCS – any combination of capture, transport, and storage – were made by framing some part of these technologies through the lens of a particular technology, which can lead to inefficiencies. If the call to action for stakeholders in the CCS community is taken (Ashworth et al. 2010), a critical self-inspection of the framings within the community is crucial.

Unintended consequences of CCS framing can manifest themselves in the interactions with the general public. Too often, these interactions are interpreted as if a rational expert community was interacting with an uninformed public, when often understanding the different framing underlying opinions and conclusion would prevent conflict and build trust between actors. For example, Hall et al. (2015) find that demonstrations of safety do impact societal response, but public resistance on CCS emphasized the 'unproven' aspects of the operations. These unproven factors could easily be those that even expert stakeholders frame differently and an open acknowledgement of this would ease interactions with local publics.

This analysis was based on data concerning Finnish experts. In Finland, the research and the development of mineralization are active and therefore Finnish experts' opinions are interesting in the context of mineralization debate. While "$CO_2$ mineralization frames in a global context"-section shows that the found frames seem to be rather universal, further comparative research is also needed. In the future CCS will

involve different cultures located for example in emerging and developing economies. Under different cultural circumstances the framing might also be different. The frame comparison with Finnish experts could still serve the CCS community by supporting the discussion across cultural regimes.

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**Table 1 $CO_2$ mineralization frames formulated from the Finnish CCS expert interviews**

| Frame | Mental model behind the frame | The future for $CO_2$ mineralization in this frame | |
|---|---|---|---|
| **High-cost** | $CO_2$ mineralization is slow, energy-intensive, requires huge amounts of minerals, has high costs | Negative | This frame holds the idea that $CO_2$ mineralization should only be used for specific applications |
| **Immature technology** | $CO_2$ mineralization is at an early stage of development | Negative | Dependent on technological development and cost effectiveness |
| **False definition of CCS** | CCS is falsely defined as the capture, transport, and geological storage of $CO_2$ | Negative | Opportunities exist but require that people and legislation start to understand $CO_2$ mineralization as one option for storing $CO_2$ |
| **Unsupported by the CCS community** | $CO_2$ mineralization is unsupported by the CCS related journals and conferences. The absence of significant financial support for $CO_2$ mineralization. | Negative | $CO_2$ mineralization is likely to stay in the margins when compared to other CCS technologies |
| **Opportunities in the weaknesses of CCGS** | $CO_2$ mineralization benefits from the problems with CCGS: such as the risk of leakage, the lack of action, and its bad reputation | Positive | New patents and pilots are seen as progress of $CO_2$ mineralization. Public acceptance higher than for CCGS. |
| **Large $CO_2$ storage potential** | An abundance of the raw material for $CO_2$ mineralization. The lack of geological storage sites in Finland. | Positive | Dependent on the mining industry |

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Highlights

- We analyze how Finnish CCS experts frame $CO_2$ mineralization in in-depth interviews.
- The way experts discuss CCS largely frames it in terms of carbon capture and geological storage (CCGS) and pushes $CO_2$ mineralization to the margins.
- As $CO_2$ mineralization is not widely framed as a suitable solution to reduce $CO_2$ emissions, it is pushed outside the discourse regarding these solutions and is becoming even less likely to be included in policy making.
- The slow progress of CCGS, as well as low public trust for the safety and sustainability of geological storage, could strengthen the optimism found in two expert frames and eventually weaken the pessimistic views.
- A more optimistic future for $CO_2$ mineralization would also require significant progress in $CO_2$ mineralization technologies and especially increased publicity for such progress.

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