Mapping CCUS technological trajectories and business models: The case of CO_2-DISSOLVED

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Abstract

According to the different climate change roadmaps (IEA, IPCC), Carbon Capture Storage (CCS) will play a key role in the climate change mitigation policy. Its development raises a trade-off between the deployment of large-scale projects (learning by replication), and the preservation of a large portfolio of competing technologies (learning by diversity), on each of its steps (capture, transport, storage). By now large-scale CCS projects are still few, most devoted to EOR (Enhanced Oil Recovery). Although EOR has provided a first feasible business model for CCS, CCS has still to prove its economic viability on a large variety of carbon emitters (power plant, industrial and bioenergy sources). A competing business model for CCS is to find other carbon uses and energy sources, better adapted to medium and small carbon sources. The paper presents such a technological solution, the CO_2 DISSOLVED project, which combines CCS in a dissolved state with geothermal energy.

Keywords Carbon Capture Storage, Geothermal Energy, Demonstration projects, Mitigation Policy, technological trajectories, CO_2-DISSOLVED.

1- Introduction

From a public policy point of view, demonstration projects should be used to assess CCUS (Carbon Capture Utilization and Storage) technologies and to promote their deployment (1) by proving their efficiency and enhancing learning effects. Building a comprehensive portfolio of large-scale demonstrations is then a way to increase overall knowledge on CCUS. But demonstration projects raise other issues for private actors (2), mainly linked to the level of investment costs, which are high in this capital-intensive technology. Moreover, this emerging technology exhibits a large technological diversity in each of its three steps (capture, transport, storage or utilization), making more difficult to find an appropriate technological articulation between them. Understanding the CCUS economic potential should then take into account (1) the diversity of technological trajectories for each step, (2) the combinatorial aspect of CCUS technologies between them, and (3) the radical uncertainty inherent in innovative activities. Testing all technological designs through demonstrators is then impossible, or at an exorbitant cost. Selection of demonstration projects appears as a key issue that is going to shape the future direction of CCUS. One strategy could be to select few projects with close designs and to scale them up, in order to benefit from learning effects between projects. For instance, public subsidies could focus only on demonstrators for coal electric plant applications, with post-combustion, MEA solvent, transport by pipelines and storage in a saline aquifer. On the opposite, another (extreme) strategy could be to choose the most different projects, with no duplication of technologies or technological combination.

The first purpose of this paper is then to address the problem of the trade-off between the preservation of technological diversity and the necessity of replication. This trade-off could look like an exploration-exploitation dilemma (3) for the CCUS community. Exploitation of the current knowledge on the dominant design of CCUS can result in quick improvements, in efficiency or costs. Exploration of others technologies, some of them less mature, seems more uncertain and involves longer time horizons. Reconciling these approaches is complex because financial resources are limited. An exploitation approach should be preferred if the business model of the (relatively) dominant design has proved its viability. However, it is clearly not the case today. We explain that the reason is a legacy of some features coming from CCUS infancy, i.e. its implementation in the EOR (Enhanced Oil Recovery) sector. The current inability to promote demonstrators at commercial scale is partly linked to the difficulty of defining and implementing a simple business model beyond EOR, for processing a service (capturing and storing an asset which could be released in the atmosphere at a nil, or low price) with no direct economic value.

The second purpose of this paper is to assess that CCUS development should not neglect the implementation of alternative technologies, more appropriate to small and medium sources of CO_2, and better adapted to the design of new energy networks. Enlarging the portfolio of technologies can also enable to create new business models, with other income sources coming from different carbon uses, and/or other energy sources. It will point out one of these alternative technologies, the CO_2-DISSOLVED technology, which combines geothermal energy and CCS, and have the ability to reduce its energy penalty and its environmental footprint.

The remainder of this article is organized as follows: Section 2 reminds the current situation of Carbon Capture and Storage (CCS) with a large discrepancy between roadmaps targets and projects achievements. Section 3 analyses the portfolio of CCS projects (completed, operational or scheduled) to assess the replication/diversity trade-off. It shows that storage issues are at the core of CCS development. Section 4 explains the desirable feature of business models regarding storage in comparison with the EOR. Section 5 presents another business model for storage based on geothermal energy. Section 6 concludes.

2 - CCS and roadmaps: from expectations to reality...

CCUS technologies could play an important role in the fight against climate change, especially for stringent carbon emission targets. In this respect, Paris Agreement goes further the previous target of 2°C and promotes a 1.5°C global temperature increase. For corresponding scenarios in the IPCC AR5 report (meaning below 430ppm CO_2eq in 2100), many models cannot find a technological solution for the global energy mix without CCS and/or BECCS (Bioenergy and CCS). The same concerns appear in the case of a mitigation delay after 2030, even for higher targets (i.e. 480 ppm), if CCUS is not available (IPCC, 2014), (4).

The International Energy Agency (IEA) provides also interesting insights regarding CCUS forecasts in its technological roadmap (IEA, 2013), (5). For a less stringent target of only 2°C, they estimate that CCUS can cut off around 12% of the emissions in 2050, compared to a scenario of 6°C of temperature increase. By comparison, renewable energies and end-use efficiency lead to reductions of 32% and 38% respectively. Regarding CCUS, it means a significant increase of installed capacities, with an annual rate of around 15% by year until 2025.

CCUS could have applications in a wide variety of sectors (here without the application of CO_2 as an input for industrial purposes, except EOR). The primary field of application would be power generation and in particular coal-fired plants. According to IEA (2016), CCS on power generation would represent 44% of the cumulative CO_2 captured in 2030, and 55% in 2050, with a large preponderance of coal in both cases (6). It means also that in 2050, around three-quarter of emissions coming from coal power would be captured, i.e. 8% of the global energy production. However, implementation on industrial emitters is significant with around 30% of the emissions captured through CCS in 2050. For iron and steel, it means almost one-fifth of the emissions captured, one-third for chemicals or petrochemical (e.g. ammonia, methanol, ethylene), and half of the emissions from the cement sector.

To avoid a delay in the mitigation policy, early large-scale projects are needed to prove technological efficiency and to gain experience. According to the IEA report (7), current operational projects could store $30MtCO_2$/yr, whereas $400MtCO_2$/yr is necessary to be on the track of the 2°C target, in 2050 (7). This is a major challenge of a tenfold magnitude, as already mention by Nykvist (8) who detailed four tenfold challenges : i) scaling-up pilot plants 10 times ; ii) constructing 10 times more demonstration plants in 2020 ; iii) enabling 10 times more finding ; iv) rising price of CO_2 emission 10 fold (8). As a reminder, the IEA CCS

Roadmap in 2009 (9) forecasts 100 large-scale projects - e.g. CCS on a coal-fired plant of 1000MW is regarded as a large commercial scale in this report – for 2020.

However, only 17 large-scale projects[1] are currently operational (7). Two of them are related to power generation (Boundary Dam in Canada and Petra Nova in the USA). Boundary Dam was the first project that has tested the whole CCS chain on a coal-fired plant, with EOR the primary kind of storage. Two others are planned until 2020[2]: Rotterdam Opslag en Afvang Demonstratieproject (ROAD) in the Netherlands, and Sinopec Shengli Power Plant CCS in China. ROAD project is the only one (on the four) without EOR.

3 – CCS project portfolio: Between diversity and replication

3.1- Demonstration process: between diversity and replication

The technological diversity of CCS is present at each of its components: capture (i.e. post-, pre- and oxy-combustion), transport (e.g. shipping, pipeline), and storage (e.g. saline formations, depleted oil or coal reservoirs). But another major characteristic of CCS is its combinatory aspect: each component is relatively independent of the others, leading to multiple full chain possibilities. Moreover, CCS projects are highly site-specific since they have to match an emitter and an available storage site, making comparisons between projects more tricky. As a consequence, there are different investment levels for CCS projects, and therefore for CO_2 avoidance costs. This variety is even more important for industrial sources. Capture rate is another key point, since the price generally rises with capture rate, from 45% to 90% for a power plant, and 60% to 99% for industrial sources (5; 10). Thus, avoided carbon costs differences are large, ranking from €30/tCO_2 to €250/tCO_2.

Nevertheless, the development of demonstration platforms raises the question of the development of a coherent mix of technologies for each component, and for the full CCS chain. As it is impossible to test all the technology combinations, a consistent portfolio of demonstrators is needed, that has to be chosen according to technical and economic criteria. De Coninck et al. (2009) advocates for an international cooperation, with three additional principles for CCS projects development, i.e. transparency, cost-sharing, and communication (11). Even if projects are not scheduled at a global level, knowledge is – partially- currently shared in the CCS community (12).

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[1] Large-scale projects are defined here following the Global Carbon Capture and Storage (GCCS), i.e. projects involving at least 800 000 tCO_2 for a coal-based power plant, or at least 400 000 tCO_2 for other emissions-intensive industrial facilities (including natural gas-based power generation).

[2] Data are coming from the GCCS website : http://www.globalccsinstitute.com/

From a more general point of view, the implementation of CCS projects at a commercial scale aims at reducing the cost of CCS development in the long run. But this development is constrained by two opposite strengths: replication and diversity (2). On one hand, CCS technologies are extremely costly, so there is a crucial need to demonstrate the technology and to prove the potential of later cost reduction, through learning-by-doing. In agreeing on this strategy, several close projects have to be implemented about the same – or close – full CCS chain. Reiner (2) coined this effect as "*learning by replication*", which requires the choice of a prominent technology and its deployment on a large scale. On the other hand, choosing a cost minimizing technology needs also to assess a large portfolio of competing technologies, in order to benefit from "*a learning from diversity*" process.

A focus on a replication strategy should lead to the development of "mainstream" CCS projects, with two main options: pick up full chains which are relatively cheap compared to others today; prefer costlier full chain with a higher mitigation potential. The first option fosters projects such as natural gas processing with EOR application for instance, whereas the second fosters could encourage coal-fired power plants with post-combustion and storage in a saline aquifer. The first option seems – to a certain extent - less risky than the second, corresponding to a low-hanging fruits opportunity. On the contrary, bet on coal-fired applications is more a "picking the winners" logic.

A focus on a diversity strategy means that investors (whatever public or private) cannot assume today the best technologies, all technology combinations, or even the adequate application sectors, for the CCS long-run development. Projects have then to be very different, so there is a need for a diversified technology portfolio, to avoid redundancy and to allow comparability of outcomes. The diversity strategy could concern the sector, the components of the CCS chain, the whole chain value, or even the CCS site location, e.g. in OECD or non-OECD countries.

As previously mentioned by March (3), exploration and exploitation strategies are both necessary learning processes for organizations, but they are competing in their use of financial and human resources. The challenge of replication versus diversity has to be faced by the worldwide CCS community. Then both learning processes appear, either as complementary, or substitute and competitive: there is clearly a trade-off between them, especially when these technologies are highly capital-intensive, which is the case for CCS large-scale projects: most projects need a lump investment of around one Billion Dollars. Learning-by-doing effects push clearly projects developing mainstream CCS project, with post combustion on power plants, using amine as capture process, while other technologies are spreading mostly in other fields than power generation: industry, and bioenergy, in grafting CCS on process which were using previously CO_2 (which explains adding the U to CCS), or on contrary by completing other energy process that could reduce their Carbon emission by adding a CCS process (process combining Geothermal energy and CCS, algae and Bioenergy with CCS).

This trade-off between replication and diversity, prevailing in the power generation industries, is even more pregnant for other carbon emitters, e.g. industrial sources and bioenergy. Indeed, each different sector faces its own technical issues (e.g. the amounts of CO_2, the composition of gas stream, the proportion of CO_2 in the flue), and has a different design (e.g. oxy-, pre- or post-combustion). As a consequence, capture technologies have to be adapted, with possible impacts on transport (corrosion effects on pipelines) or on storage (interaction of impurities with the reservoir). There is clearly a need for new technologies, better adapted to the characteristics of these carbon sources.

3.2 - Diversity of the current project portfolio

Obviously, with only 17 large-scale projects, all the combination of CCS cannot be tested. Table 1 shows however that Natural Gas Processing is the most investigating sector (8/17 projects), industrial separation for capture (15/17 projects), pipelines for transport (15/17 projects), and EOR for storage (13/17 projects). This whole chain - i.e. Natural Gas Processing (NGP), industrial separation, pipelines, and EOR – is replicated in 5 operating projects, from the first operation date in 1972 (Terrel project) until 2015 for the latest (Uthmaniyah project). The diversity of operating projects seems then relatively limited (even if each of them was innovative). Moreover, it does not reflect well the potential of each sector as evoked in the IEA roadmap or in IPCC modeling. Power generation is marginal (2 projects and only coal firing), as well as iron & steel (1 project, very recent: 2016), ethanol (1 project), and cement is absent. Even if storage in a saline aquifer is assumed to store most of the emissions in the long run, it is used in 4 projects on the 17 operating. It seems that the global portfolio of large-scale projects corresponds largely to a replication strategy, with a focus on the first option of low-hanging fruits, here NGP + EOR. The second replication option, i.e. CCS on coal-fired plant has only recently emerged.

Projects in construction or at an advanced stage can give insights about the CCS development in the short run, even if they can be canceled. Following the database, only one more scheduled project is using natural gas processing, other projects aiming at a better knowledge of the power sector (2 new projects). Chemical production projects (e.g. ammonia, urea, methanol) are leading this category (4 new projects), which was not at all the case before. Regarding capture, the efforts are still in diverse industrial separation technique and additional results are expected with post-combustion. Proportionally, more dedicated storage are planned too (4/11 projects). In terms of strategy, we note then an increase in sectoral diversification, no progress for oxy or pre-combustion, and a dominant role of EOR for next projects. The replication strategy then dominates for capture and storage.

Table 1: Number of large-scale CCS projects by lifecycle stage, industry and technology used, data from Global CCS Institute database (13), own calculations.

Steps in CCS chain		**Operating projects**	**In construction or advanced projects**
Industry	Power Generation	2	2
	Natural Gas Processing	8	1
	Synthetic Natural Gas	1	0
	Coal-to-Liquid	0	0
	Fertilizer Production	2	1
	Chemical Production	0	4
	Hydrogen Production	2	0
	Oil Refining	0	1
	Iron and Steel Production	1	0
	Ethanol Production	1	0
Capture	Pre-combustion	0	0
	Post-combustion	2	2
	Oxy-fuel combustion	0	0
	Industrial Separation	15	7
Transport	Pipeline	15	9
	Shipping	0	0
	Combination	0	2
	No transport required, direct injection	2	2
Storage	Dedicated geological storage	4	4
	Enhanced Oil Recovery	13	7

Because of the limited number of large-scale projects, pilots and demonstrators are today the most used tools to test CCS technologies, with a research focus. The same dataset enumerates 36 completed small-scale projects, 29 operational, 6 under construction, and 7 in advanced development. This gives another picture of the situation, (Table 2). These small-scale projects are assumed to prove technological availability, and then to contribute to a diversity strategy. It is indeed largely the case here. The sector diversity has clearly increased between completed and operational projects. Hydrogen, cement, iron & steel, methanol industries are all new sectors for small projects, even if hydrogen and iron sectors are also investigated in large-scale projects. Some planned projects are likely to test new sectors (e.g. refining).

Whatever the advance of projects, the power generation is the most represented sector. It corresponds to half of completed project, a quarter of operational projects and less than two-thirds of planned projects. Totally, 25 pilots and demonstrators have been tested, with a strong focus on capture (18 projects). Further analysis would be required to assess the degree of diversity of power projects, but it results in a global strategy of replication to improve knowledge in this area. This is consistent with the idea that most of the CCS potential is linked to power generation.

Table 2: Number of small-scale projects (pilot and demonstrators) by sector, at different stage of development. F means Full chain ; C, project focus on capture ; S: project focus on storage. Data from Global CCS Institute database (13), own calculations.

Sector	**Completed (36)**	**Operational (29)**	**In Construction or Advanced Development (13)**
Power Generation	18 (3 F)	7 (4 F ; 3C)	8 (3F ; 5C)
Natural Gas Processing	2 (S)	4 (2F ; 2S)	1 (F)
Coal to Liquid	1 (F)	0	0
Fertilizer	1 (S)	1 (C)	0
Chemical	1 (C)	1 (F)	0
Hydrogen	0	1 (F)	0
Iron and Steel	0	1 (C)	1 (C)
Ethanol	0	4 (3F ; 1C)	0
Methanol	0	1 (F)	0
Lime and Cement	0	0	1 (C)
Industrial Production	1 (S)	1 (F)	0
Ethanol and Fertilizer	0	1 (S)	0
Power and refining	0	0	1 (C)
Industrial and Power	0	1 (S)	0
Various and Not applicable	11 (2C ; 9 S)	0	1 (S)

BECCS (Bioenergy and CCS) is represented with 5 operational small projects (towards one large project operational today), and all about ethanol production except one for co-firing with coal to produce power (a project in an advanced stage). Two projects are about iron & steel, and cement is represented with four projects. In both sectors, the full chain is not tested, but only the capture process. In the various and not applicable classes, there is a significant part of projects about methane recuperation and storage in lignite seams. The storage diversity is then higher than before, and often linked to the hope of new revenues (methane recuperation).

Globally, there are a lot of projects specialized in one step of the CCS chain. Most projects regarding the capture steps only are implemented for sectors whose CO_2 exhaust streams are complex to purify or at a low degree of concentration. On the contrary, a lot projects with a full chain are linked to sectors where the CO_2 recovery is easier.

Pilots and demonstrators allow exploring new technologies and applications for CCS technologies. They should prefigure the development of next projects at commercial scale. As as consequence, if these small scale projects are not built quickly, there is a risk of delay with respect to the roadmaps. Some sectors may be more affected, e.g. cement industry, or BECCS application (no for ethanol production, but for cofiring with coal, second generation of biofuels, pulp factories).

This analysis highlights that there is currently a dominant replication strategy, notably with the use of EOR for storage and the research of CO_2 sources with limited separation costs with other gases. This strategy of low-handed fruits is not the only one. There is also a will to develop CCS in the power sector (mostly coal-fired plant) that results in a lot of small projects. Eventually, there is a progressive tendency to enlarge the scope of investigated sectors towards complex industrial applications such as cement, iron, and steel, but this trend is too slow.

4 – Going beyond EOR: Other business models for storage?

4.1- The EOR legacy

Building up a business model of a new technology such as CCS needs to prove, not only its economic viability at a reasonable carbon avoided cost, but also its ability to be implemented on a large scale. It is important to point out that CO_2 industrial capture and utilization are not a recent concern. CO_2 separation from natural gas appeared in the 1950-60’s (8), while its utilization has been experienced for a long time by chemical industries, in the production of chemicals, plastics, fertilizers, food and beverage, and other materials and fuel (14). More recently, Oil and Gas Industries has deployed CO_2 utilization at scale in using Enhanced Oil Recovery (EOR) technologies that are currently on the basis of CCS technologies. The EOR concept comes from motivation far from the energy transition: it has been the combination of the existence of a *source* of carbon, linked to its separation with gas, which gives it an easy capture method, to its *use* as a convenient mean to EOR. Transport problems, when they occurred, have been easily solved by the deployment of carbon pipelines. This combination of different factors, by the same actors, namely, oil companies, their industrial suppliers and subcontractors, has enabled the successful deployment of EOR demonstrators which are massively dominating the portfolio of CCS projects, as stated in the previous section. But extending this first self-financed business model to become a large-scale mitigation technology is highly problematic, on each part of the process:

1) For EOR, the capture process appears to be easy to implement, as gas separation, the most used capture process, is clearly necessary for the gas production. So, it seemed a good deal to use it as a recovery device, rather than releasing it in the atmosphere: it changed a costly trash into a useful input.
2) Moreover, the use of carbon to enhance the recovery of oil pits gives a useful storing device, as depleted oil fields give a convenient, sure and socially acceptable device for storing carbon. So, in this case, it is possible to isolate business models of the first projects, in the USA, Canada, or Norway. The question still remains of its ability to be implemented on a far broader scale if it could be thought as a credible mitigation technology.
3) Lastly, the transport of carbon through pipelines on long distances allowed to test the technology on a wide range and proved to be easily accepted by the neighbourhood.

Then, EOR allowed the development of now mature technologies, and with which main proponents of CCS are first firms who develop this technology for EOR and then thought about extending it to other sources of CO_2.

4.2- From EOR to a CCS wide scale deployment

As CCS technologies are dominated by the design of EOR technologies, a kind of *path dependency* has been created: technologies of first movers are adopted at a first step, and once adopted, they will be chosen by new users, in a self-enforcing process. According to (13), EOR should dominate the CCS deployment, with a potential of 4 to 8% of the total effort required to mitigate climate change at a 2050 horizon. Then, EOR technologies influence the design of CCS technologies, but extending them to other carbon sources and sinks raises numerous drawbacks, mainly:

- There is a global mismatch between the highest EOR storage potential regions (namely, oil and gas producing regions), and the highest CO_2 emissions regions (13).
- Capture technologies are various, costly, and depend on carbon source
- Storage on a large scale should be done in saline aquifer, which integrity is not as good as that of depleted oil wells.
- Source and carbon sinks could be distant, then transport should be costly and rise some acceptability issues
- Operators are different for each carbon sources - such as power plants, industrial sites or bioenergy producers - and they are not vertically integrated with their storage facilities like Oil and Gas companies.

So the main challenge is by now to incent these stakeholders to work together, in sharing technologies, skills, and financial means. According to the Herzog survey (15), a sustainable business model should have to conciliate:

- A demand pull, i.e. the ability to give an *use* to carbon as an *input*
- A technological push, i.e. technologies able to capture carbon as an *output* at a reasonable cost

And a combination of:

- Public financial supports,
- Business drivers,
- Regulatory drivers able to impose “capture ready” plants.

In his survey of the different pilots and demonstrators CCS worldwide, Herzog (15) details more precisely how some projects have been successfully operated. The most interesting case is that of Boundary Dam, in Canada, in which the combination of EOR revenues and financial DOE subsidies offset CCS costs on a coal-fired retrofitted power plant, enabling the project to obtain a Levelized cost of electricity equal to that of a Natural Gas power plant, as stated in Figure 1, (16). Herzog points out that this combination leads to a kind of “best case” study, which conditions could be unlikely to happen again.

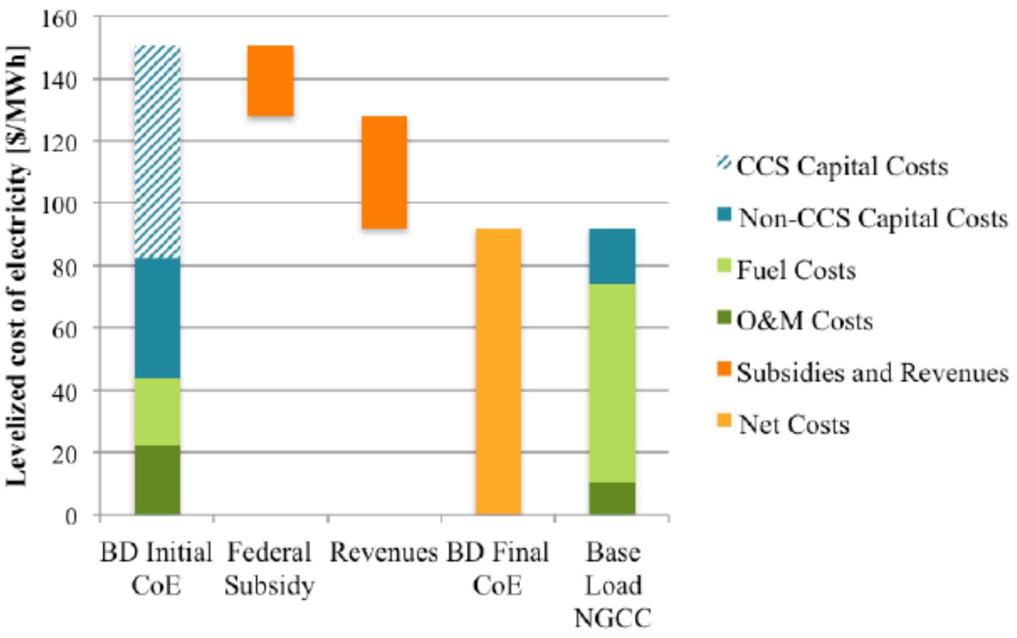

Figure 1: Levelized cost of electricity estimates of the Boundary Dam retrofit by cost category compared to a base load NGCC plant

Source: V. Clark, 2015 (16)

5 - Coupling CCS and Geothermal energy: Lessons from the CO_2 - DISSOLVED project study

5.1 - CO_2-DISSOLVED concept

CO_2-DISSOLVED is an innovative concept that aims to combine geothermal energy and carbon storage on the same geologic site. The CO_2 stored does not improve the energy performance of the whole system but benefits from the (re-)injection of brine in the saline aquifer to be stored too. If rewarded by a carbon market, the CO_2 stored becomes a additional revenue for geothermal energy production, or vice-versa (i.e. geothermal energy is an additional revenue for CO_2 storage), depending on the point of view of investors.

More precisely, the brine of a saline aquifer is pumped for heat recovery locally by a production well. After use, the cooled brine is enriched with the CO_2 coming from a factory (here a bioethanol plant). The CO_2 is then injected and stored at a dissolved state into the same saline aquifer, by an injection well. The whole system is depicted in Figure 2, and a comprehensive description is available in Kervévan et al. (2014), (17). The rate of CO_2 solubility in the brine is limited. This is a key feature of the system because it means that the volume of CO_2 stored is also limited, and lower than its storage capacity in a supercritical state. As a result, CO_2-DISSOLVED technology is specifically designed for small or medium emitters, a kind of emitters scarcely targeted by CCS technologies.

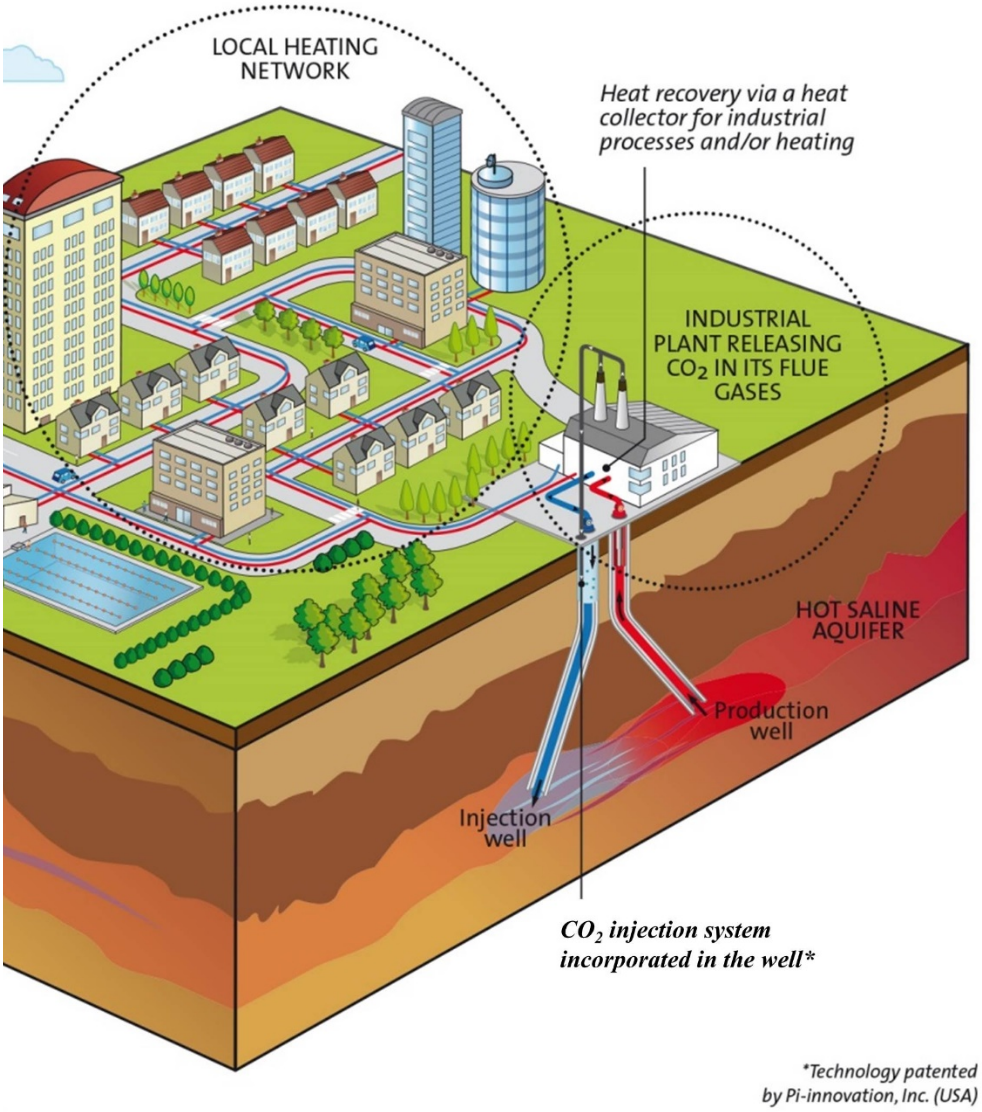

Figure 2: Schematic view of the CO_2-DISSOLVED concept (17)

Another novelty regards the capture step. If the exhaust stream from the factory contains only CO_2 or nearly, a direct injection can be considered, after a compression step. Conversely, CO_2 may have to be separated from other gases. In this case, the 'Pi-CO_2' technology has been investigated (Blount et al., 2014), (18). This capture system uses only water as a solvent. Basically, the concept is to inject the exhaust stream at the bottom of another well, at a hydrostatic pressure of around 60bars. As the flow is going up, other gases are progressively separated. At the surface, a simple degassing is sufficient for CO_2 recovery. This pure CO_2-stream is then ready for injection in the brine. 'Pi-CO_2' is assumed to be less costly than monoethanolamine (MEA) solvent for capture purpose, notably because it is less energy-intensive.

The technical potential of CO_2-DISSOLVED has been identified in France and Germany by Castillo et al. (2013)(19), as the matching between small or medium emitters and relevant storage site for geothermal energy and CCS (19). In France, a total amount of 25.1 millions tons of CO_2 could be stored, which is around 16.9% of national French emissions. In Germany, the estimation is lower with less than 7.95 million tons of CO_2 stored in the North German Basin and some additional sources in the south of the country.

5.2 - Techno-economic analysis of CO_2-DISSOLVED

A first techno-economic analysis has been assessed about CO_2-DISSOLVED. The case study was a bioethanol plant located in France, and feed by a natural gas boiler , see Royer-Adnot and Le Gallo (2016), (20). This factory has been chosen for several reasons: i) an adequate amount of CO_2 (45.000 tCO_2/yr) provided by fermentation ; ii) an almost pure stream of CO_2 ; iii) previous assessment of geological characteristics ; iv) possible comparison with a previous study realized for CCS with CO_2 stored at a supercritical state by Laude et al. (2011) (21). The project has two revenue sources: CO_2 allowances from the EU ETS (European Exchange Trade System), and the savings coming from the reduction of natural gas volumes.

On a technical perspective, the case study shows that CO_2-DISSOLVED can reduce CO_2 emissions by 40% compared to the reference case (meaning without the technology investigated). The energy consumption of natural gas is moreover lower of 15%. The other technology of carbon storage (CO_2 injected at supercritical state) was assumed to store all the emissions. As a consequence, CO_2-DISSOLVED stored less CO_2, with a CO_2 diminution of around 33% of those realized by the other CCS technology. CO_2-DISSOLVED can then be perceived as a partial capture technology. But the energy balance is improved by 13%, meaning that there is no energy penalty.

On an economic perspective, CO_2-DISSOLVED is clearly cheaper than the other storage option: investment costs are halved. The cost of avoided emissions is now of 51€/tCO_2. This is still significant, but the savings on natural gas can make the project valuable, with a positive Net Present Value (8 million euros) over the lifetime of the project (30 years). In addition, CO_2-DISSOLVED is more profitable than a stand-alone geothermal project as soon as carbon prices exceed 12€/tCO_2eq. These results could be improved if the exhaust stream was less seasonable. Most emissions happen indeed during the harvest campaign that occurs only two months by year. CO_2 amounts can then exceed the solubility capacity and the installation has to be oversized compared to a flatter profile of emissions over the year.

5.3 – Business models and the replication/diversity dilemma

The business model of CO_2-DISSOLVED seems well adapted to small or medium emitters in a context of relatively low carbon prices (13€/tCO_2), at least when no gas separation is needed. Additional studies with a capture technology - such as the Pi-CO_2 technology mentioned previously - are needed to assess the profitability of other cases. The case study investigated here could be improved without an emission peak during the year (the harvest campaign) and higher assumptions on ground temperature. But it is important to point out that generalizing these results is uneasy because each project is very high site-specific.

This case study highlights that a trade-off between the amounts of CO_2 captured and the storage project profitability. In other words, the costs increase with the rate of CO_2 avoided. The same phenomenon happens with CO_2 utilization (as an input for industrial purposes) compared with CO_2 geological storage: profitability is assumed to be better, but the mitigation potential is lower, because a part of used CO_2 could be at one or another time be released. In some utilization processes, this potential can even become almost inexistent (14).

However, considering CO_2-DISSOLVED as a competing technology with conventional CCS is misleading, because both technologies do not target the same emitters. We think that it is more a way to enlarge the potential of CCS toward smaller CO_2 sources. CO_2-DISSOLVED provides a new storage process that can open the way to a new capture technology (Pi-CO_2 solution), but it is also innovative because geothermal energy and CCS were generally considered as incompatible. Geothermal energy could be a way to enhance CCS development for small projects, in a context of scarce public funding and low carbon prices. This development regards pilots (for research purpose, e.g. projects focused on capture) but also small commercial projects. Ethanol plants are especially good candidates for this technology since the exhaust stream is assumed to be almost pure.

About the diversity/replication dilemma, CO_2-DISSOLVED shows that there is a need to develop new concepts and solution that could contribute solving technical problems (capture, storage safety), improving business models (by finding additional revenues), and enlarging emitters and sectors considered.

6 - Conclusion

The analysis of the CCS project portfolio provides interesting insights on next CCS development. First of all, there is still a focus on emitters with easier CO_2 recovery and storage by EOR (Enhanced Oil Recovery). This strategy corresponds to the research of low-hanging fruits for CCS. But it is insufficient to enhance CCS expansion. A key issue is to find profitable business models, in the present context of public funding reductions, and low carbon prices.

The CO_2-DISSOLVED project proposes to improve profitability by adding another revenue, i.e. energy savings coming from geothermal energy. This solution is designed for small and medium emitters because of technological constraints, i.e. the solubility of CO_2 into the brine of the saline aquifer. Nevertheless, this kind of emitters is scarcely investigating for CCS whereas there is a significant potential for France, Germany, and the USA at least.

More generally, this article shows that CCS development needs technological diversity to be adapted to the wide diversity of CO_2 sources and local conditions of transport and storage. Enlarging the portfolio of CCS technologies through different carbon uses and energy sources seems a promising way to find better business models for this mitigation technologies.

Involvement of stakeholders is also a key issue in the implementation of CCS. Implementing more decentralized technologies like CO_2-DISSOLVED requires less capital investment, but the cooperation of different stakeholders is necessary all along the value chain to trigger the large-scale development of this promising technology.

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References

1. S. Russell, N. Markusson, and V. Scott, “What Will CCS Demonstrations Demonstrate?”, *Mitigation and Adaptation Strategies for Global Change,* Vol. 17, 6, p. 651–68, 2012.
2. D. Reiner, and M. David, “Learning through a Portfolio of Carbon Capture and Storage Demonstration Projects” *Nature Energy*, Vol.1, 1, 2016.

3. J. March, “Exploration and Exploitation in Organizational Learning”, *Organization Science*, Vol. 2, 1, p. 71-87, 1991.
4. IPCC, “Mitigation of Climate Change Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change” [Edenhofer O. et al.], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 2014.
5. IEA (International Energy Agency), Technology Roadmap – Carbon Capture and Storage, OECD/IEA, Paris, 2013.
6. IEA (International Energy Agency), Twenty Years of Carbon Capture Storage, OECD/IEA, Paris, 2016.
7. IEA (International Energy Agency), Energy Technology Perspectives 2017, OECD/IEA, Paris, 2017.
8. B. Nikvist, “Ten times more difficult: Quantifying the carbon capture and storage challenge”, *Energy Policy*, Vol. 55, p. 683-689, 2013
9. IEA (International Energy Agency), Technological Roadmap: Carbon Capture Storage, OECD/IEA, Paris, 2009.
10. M. Renner, *The Emergence of Capture Carbon Storage Techniques in the Power Sector*, PhD Dissertation, Paris, 2015.
11. H. de Coninck, J.C. Stephens, and B. Metz, “Global Learning on Carbon Capture and Storage: A Call for Strong International Cooperation on CCS Demonstration” *Energy Policy* Vol. 37, 6, p. 2161–65, 2009.
12. K. van Alphen, M.P. Hekkert, and W.C. Turkenburg, “Accelerating the Deployment of Carbon Capture and Storage Technologies by Strengthening the Innovation System” *International Journal of Greenhouse Gas Control*, Vol. 4, 2, p. 396–409, 2010.
13. Global CCS Institute, CCS Projects Database, https://www.globalccsinstitute.com, 2017.
14. N. Mac Dowell, P. Fennell, N. Shah, and C. Maitland, “The role of CO_2 capture and utilization in mitigating climate change”, *Nature Climate Change*, Vol. 7, 2017.
15. H. Herzog, Lessons learned from CCS demonstration and large pilot projects, MIT Energy Initiative, MITEI-WP-2016-06, 2016.
16. V. Clark, An analysis of how climate policies and the threat of stranded fossil fuel assets incentivize CCS deployment, M.I.T. Master’s Thesis, 2015.
17. C. Kervévan, M.H. Beddelem, and K. O’Neil. “CO_2-DISSOLVED: A Novel Concept Coupling Geological Storage of Dissolved CO2 and Geothermal Heat Recovery – Part 1: Assessment of the Integration of an Innovative Low-Cost, Water- Based CO2 Capture Technology” *Energy Procedia,* Vol. 63, p. 4508–18, 2014.
18. G. Blount, M. Gorensek, L. Hamm, K. O’Neil, C. Kervévan, and M.H. Beddelem, “Pi-CO_2Aqueous Post-Combustion CO_2 Capture: Proof of Concept through Thermodynamic, Hydrodynamic, and Gas-Lift Pump Modeling”, *Energy Procedia*, Vol. 63, p. 286-292, 2014.
19. Castillo C., S. Knopf, C. Kervévan, and F. May., CO_2-DISSOLVED: a Novel Concept Coupling Geological Storage of Dissolved CO2 and Geothermal Heat Recovery – Part 2: Assessment of the Potential Industrial Applicability in France, Germany, and the U.S.A., Proceeding of GHGT13, Forthcoming *in Energy Procedia*, 2017.
20. J. Royer-Adnot and Le Gallo, “Economic Analysis of Combined Geothermal and CO_2 Storage for Small-Size Emitters”, Proceeding of GHGT13, Forthcoming *in Energy Procedia*, 2017.
21. A. Laude, O. Ricci, G. Bureau, J. Royer-Adnot, A. Fabbri, « CO_2 capture and storage from a bioethanol plant: carbon and energy footprint and economic assessment”, *International Journal of Greenhouse Gas Control*, Vol. 5, 5 p.1220-1231, 2011.