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Combining Geothermal Energy and CCS: From the Transformation to the Reconfiguration of a Socio-Technical Regime?

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Abstract

Combining geothermal energy and CCS (Carbon Capture and Storage) is a technological solution that uses the same aquifer to provide heat and to store CO_2, after dissolving it into the brine, leading to a close loop, as proposed in the CO_2-DISSOLVED concept. This technology is more relevant for small-scale emitters - such as biorefineries - than CCS with postcombustion and storage at a supercritical state, which requires larger scale effects i.e., most power generation plants using fossil fuels. Based on a techno-economic analysis, we provide insights on the role of CO_2-DISSOLVED in the sustainable transition. Contrary to conventional CCS on fossil fuels, CO_2-DISSOLVED appears as a bridge towards renewable energies, and acts as a complementary technology, enlarging the potential of CCS for small or medium industrial emitters. This innovation enriches the portfolio of CCS combinations with renewable energies, like BECCS (BioEnergies and CCS). It helps then to overcome the current debates CCS versus renewable energies, showing a large gradient of situations. According to the Multi-Level Perspective (MLP) of sustainable transition, CO_2-DISSOLVED could contribute to the transformation of the existing socio-technical system, and to its reconfiguration towards renewable sources of energy. As other competing technologies, it could play a rising role in the modification of the energy system. Then, focusing only on CCS implemented on large-scale emitters constitutes a narrow vision of CCS potential in the sustainable transition.

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1. Introduction

Combining geothermal energy and Carbon Capture and Storage (CCS) is a promising technological solution that can enrich the large portfolio of mitigation solution helping the transition through a new energy regime. At a first sight, this solution could create a conflict in the use of the subsurface, when technologies would be implemented in saline aquifers (with temperatures between 50°C and 150°C) located at the same depth (800-3500m), with similar properties (IEA, 2013) [1]. Geothermal energy production could be disturbed by the CO_2 injection that hinders an increase of the hydrostatic pressure and brine displacements. For this reason, the EGEC (European Geothermal Energy Council) considers that there is an "*obviously conflicting potential*", and so that the priority should be given to geothermal energy rather than on CCS (EGEC, 2009) [2].

The CO_2-DISSOLVED technology concept provides a solution to this conflict of use, first by dissolving the CO_2 stream into the brine, then injecting it in a saline aquifer by an injection well. The hydrostatic pressure of the aquifer does not increase because a second well - i.e. the production well - pumps the brine and use it for recovery heat purpose. A comprehensive description of this technology is available in Kervévan et al (2014) [3].

The aim of this paper is to explore the role of the CO_2-DISSOLVED concept in the sustainable transition, not only as an innovative combination of geothermal energy and CCS but also as an example of a bridge between renewable energies and CCS. The academic literature on CCS is generally focused on CCS applications on fossil fuels, considered sometimes as a way to continue their use. As a consequence, CCS and renewable energies could be perceived as opposed mitigation technologies, and the potential synergies could be underestimated or neglected. Our first contribution is then to show the benefits and limits of CO_2-DISSOLVED compared to conventional CCS, i.e. CCS with capture through postcombustion, e.g. MEA capture system, and storage at a supercritical phase. In particular, it appears that CO_2-DISSOLVED is more designed for relatively low or medium emitters, and do not directly compete with conventional CCS. These results are derived mostly from a techno-economic case study, see Royer-Adnot and Le Gallo (2017) [4]. Our second contribution is to compare the role conventional CCS and CO_2-DISSOLVED as two different tools to modify the current energy system. This is done by using the Multi-Level Perspective (MLP) approach, designed by Geels [5], that explains transition as a complex interplay between macroeconomic and social changes (named the landscape), the current regime (here energy production) and the emergence of technological niches (such as renewable energies). CO_2-DISSOLVED is not only an innovation coming from the actors of the regime, which could be seen as a way to reinforce the current energy regime based on fossil fuels. It shows that a large portfolio of CCS technologies could also contribute to the creation of an energy system mostly based on renewable energies. Considering its current technological diversity, we show that CCS variants are possibly more than a temporary technology designed to wait for the switch towards renewable energies. The structure of this article is the following: First, we review some forecasts about CCS deployment pathways, with a focus on CCS implementation on coal plants (Section 2); Then, CO_2-DISSOLVED is described and its techno-economic features discussed (Section 3); the role of CO_2-DISSOLVED in the transition is debated through the prism of the MLP (Section 4). Eventually, some main conclusions are set out (Section 5).

2. CCS deployment pathway : Forecasts and role in the sustainable transition

2.1. Current roadmaps and forecasts about CCS

CCS deployment has been documented through many reports and roadmaps, coming from its different proponents: international institutions (IEA, 2013; IPCC, 2014) [6,7], government and non-government organizations, including the European Union, companies and consultant firms, think tanks, and so on. If we refer to the IEA roadmap [6], this deployment should follow a progressive pathway, first focused in the power generation sector, then to other industrial sectors, and to the bio-energy sources. This change will be accompanied by a progressive shift from industrialized to emergent countries, the share of these countries increasing with the growth of the non-OECD countries.

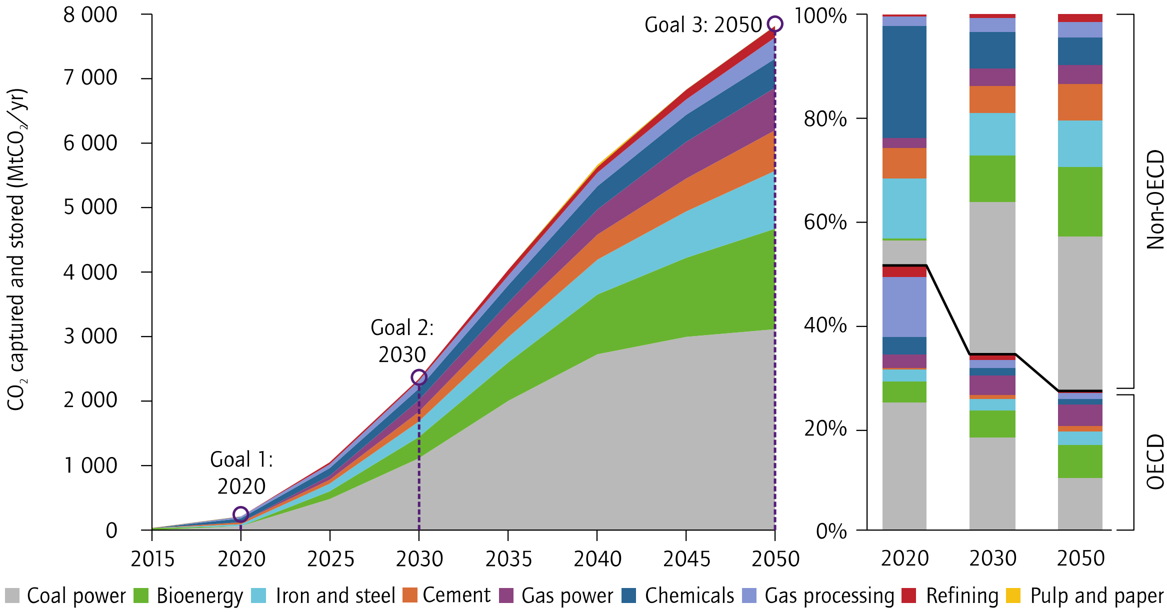

Figure 1: CCS in power generation and other sectors, coming from IEA [6]

As an emerging technology, CCS presents a large portfolio of different technologies, depending on the emitting sector, namely power generation, but also other industrial emitters, and bioenergy sector. The most prominent technology is by now focused on post-combustion on coal plants, with storage in a saline aquifer, but other options are still available although at a lower development step or for relatively small commercial niches. Most of these technologies are focused on the use of fossil fuels, but it is important to point out they could also be implemented on the production of energy from bio-source (Biomass, BioFuel, Biogas) in BECCS technologies. As carbon is captured on an alleged carbon neutral process, the carbon footprint could become negative, leading to an artificial carbon sink [8]. It is important to point out that BECCS technologies are at a more infant development step than conventional CCS, with a still large portfolio of technologies, some using conventional CCS technologies, some others using specific new technologies (for a recent survey, see [9]).

2.2. The commercial CCS deployment: not an easy economic model to define.

The progressive deployment of CCS is considered by the IEA as the IPCC as a cost minimizing scenario for a sustainable transition scenario, in order to comply with the IPCC goal of a 2° global warming scenario [6,7]. However the avoided carbon cost of the different available technologies is still too high to look after a development on a commercial stage, far higher than the prices attained on the different carbon markets, like on the EU ETS (Emissions Trading System) , with carbon prices lower than 10€/tCO_2. In addition, even a progressive rise of the carbon price won't automatically lead to CCS deployment. For example, in the power generation sector with European energy mix conditions, the rise of carbon prices should first promote a switch from coal plants without CCS to gas plant without CCS [10]. This switch is indeed more competitive than towards coal plants with CCS, despite a far lower carbon avoided price for CCS on Coal (60€/tCO_2) than on Gas (115€/tCO_2): at a 60€/tCO_2, electricity produced by a coal plant with CCS will still be more costly than on a gas plant without CCS. In the European context, the switch is going to happen from coal plants to gas plants without CCS, then with CCS, at the very high carbon price of 115€/tCO_2 in this later case.

Results are quite different for China, which could implement CCS on coal plant at a lower avoided price (around 30€/t in 2030 in a "best case" situation) thanks to different cost conditions and to its largely coal-dominated energy mix [10].

Other carbon emitting industries, (chemistry, waste, paper and wood, petroleum, mechanical, and mineral) account for 80% of declared emissions sites in France, 55% in Germany, and 37% in the USA. So they are another important stake for the CCS deployment. These emitters have variable sizes, from small to large, but are in average lower emitters than large fossil fuel electric plants. CCS appears to be the prevailing mitigation solution because these industrial sectors are highly dependent on fossil fuels for technical reasons: it would be more difficult (even impossible most of the time) for some of them to switch to renewable sources, and the energy efficiency gains are also limited. According to the IEA CCS Roadmap [6], the deployment of CCS on industrial sources will be done alongside its deployment in power generation and will account for a growing part of the mitigation gains.

Evaluating the feasibility of CCS on industrial sources is more difficult than on power generation. CCS on industrial sources uses a wider variety of technologies than on power generation, and these techniques are moreover also highly site specific. This technological variety prevents an overall comparison of carbon switch prices as in power generation, which could be directed by the availability of other energy sources (e.g., nuclear or renewable energies) and their energy efficiency potentials. Therefore, it is only possible to compare the CO_2 avoidance costs. Another important point is linked to the capture rate, which can change with the sector and technology used. The IEA gives overall estimations of avoidance costs for different archetypal industrial sites, which can be ranked from 20$/t$CO_2$ to higher prices, till 120$/t$CO_2$, this price rising generally with the capture rate , that can be ranked from 45%, 70% and 90 % on power plant [10] and from 60% to 99% on industrial sources [1].

In contrast to the fossil fuel power generation sector, bio-energy production plants are generally small or medium sources of carbon, so they cannot benefit from economies of scale, which are a key component of supercritical CCS deployment. As a consequence, the avoided carbon costs are generally higher, with large differences according to their source and technologies, ranging from €30/tCO_2 to 250€/tCO_2. These differences are explained by the large diversity of available technologies [10], and some improvement must be obtained by the development of new technologies, better adapted to the specificity of these carbon sources.

2.3. Limitations of CCS on fossil fuels and the role of renewable energies

CCS raises other critics as an alleged energy transition tool. It is clearly an end-of-pipe technology, that doesn't suppress a source of externality but on the contrary, try to offset it. As it enables to conciliate the use of fossil fuels with the reduction of Green House Gas Emissions (GHG), it could contribute to the "carbon lock-in" in which our societies are trapped, according to the expression coined by Unruh (2000). Not only CCS will help to continue the use of fossil fuels, but it will increase their consumptions because of CCS energy penalty, which can reach 25% in the case of CCS on coal plant [10]. Hence the energy transition with CCS will require extracting *more* fossil fuels than without CCS. The following table, adapted from McGlade and Ekins [11], shows a comparison of the fossils fuel reserves that should not be extracted (unburnable) with their total fuel reserve in 2050, in a 2° degree global warming scenario. This ratio decreases for each category of fossil fuels if CCS is deployed: it means for example that unburnable coal reserve would decrease from 88% to 82% with CCS, a decrease of 6% of the overall coal reserves.

Table 1 Unburnable Fossil Fuel Reserves to 2050, adapted from McGlade and Ekins (2015).

Unburnable fossil fuel reserves to 2050	Oil		Gas		Coal	
	Billions of barrels	%	Trillions of m^3	%	Gigatons	%
With CCS	431	33%	95	49	819	82
Without CCS	3	35%	100	52	887	88

The notion of technological lock-in is mainly related to technologies that appear resistant to change in the larger context of the coevolution of institutional, political, social and cultural systems. It can be the result of the action of different stakeholders that benefit from the technological regime because they seek to maintain their roles and to protect their interests (resistance to change), or simply because the shift to the optimal technology is too complex (path dependency). There is then a risk that the sociotechnical regime does not change (or not quickly), even if the technology is suboptimal or if a new situation requires adaptation. From this point of view, CCS is well adapted to the former regime, based on the use of fossil fuels. It requires the use of highly capital-intensive units, in a centralized energy system. This compatibility with the former energy regime could help its deployment in a transition process, but it can also contribute maintaining this regime rather than promoting a new one. It could also divert financial resources that could be better used in promoting a new, decentralized energy system using mostly renewables [12]. The following table sums up the sources of lock-in, according to Unruh [13].

Table 2 Lock-in sources, adapted from Unruh (2002), [13]

Lock-in sources	Examples
Technological	Dominant design, standard technological architectures and components, compatibility
Organizational	Routines, training departmentalization, customer-supplier relations
Industrial	Industry standards, technological inter-relatedness, co-specialized assets
Societal	System socialization, adaptation of preferences and expectations
Institutional	Government policy intervention, legal framework, department ministries

The lock-in phenomenon is not limited to technologies but can also affect institutions and even society as a whole. In the case of climate change, the difficulties associated with the shift towards a low-carbon society could be perceived as techno-institutional lock-in mainly regarding the energy and transport sectors [13].

These arguments are less relevant for BECCS technologies, which are implemented on renewable energy sources. As it concerns mainly small or medium carbon sources, it is better adapted to a new decentralized energy system. If this characteristic doesn't allow BECCS to benefit from the scale economies of conventional CCS technologies, it will incite to develop technologies better adapted to small size carbon sources. It will moreover be mobilized in order to comply with more stringent GHG reduction goals. So BECCS can be considered as a bridge in the energy transition, appearing at first as a complement to CCS, then as a substitute. But it is important to point out that its benefits should be balanced with the drawbacks of the massive use of Bioenergy, mainly in the land use.

3. Combining geothermal energy and CCS: the CO_2-DISSOLVED project

3.1. Description of the CO_2-DISSOLVED technology

As already mentioned, CO_2-DISSOLVED is a system that associates the storage of CO_2 with the recovery of geothermal heat, see Figure 2. A comprehensive description is available in Kervévan et al. [3].

More precisely, for the geothermal part, the system requires the drilling of two wells to form a geothermal doublet; i.e. a brine injection well and a brine production well. The production well extracts the hot brine from the saline aquifer so that heat can be recovered through a heat exchanger located at the surface between the two wellheads. The cooled brine is injected back into the same aquifer through the injection well. For the CCS part, two cases must be distinguished: with or without the need for separating the CO_2 from other gases emitted by the plant. If the outflow is sufficiently pure in CO_2, the flue gas can be compressed directly and CO_2 is dissolved in the injection well. Conversely, if the CO_2 needs to be separated from other gases, the choice was made to rely on the 'Pi-CO_2' technology (property of Partnering in Innovation Inc., [14]). This would necessitate drilling a third well into which the outflow from the plant is injected, beneath a column of water providing a hydrostatic pressure of about 60 bars at depth; such a pressure naturally enhances CO_2 solubilization in water. Having preferentially dissolved the gaseous CO_2 into the water which is the only physical solvent used (because CO_2 is more soluble than other components of the flue gas such as N_2, O_2 , and so on), the CO_2-laden water is then returned to the surface, where CO_2 is recovered by simple degassing [14]. This technology could be an interesting alternative to the current post-combustion capture systems that use solvents such as monoethanolamine (MEA) and that are very energy-intensive.

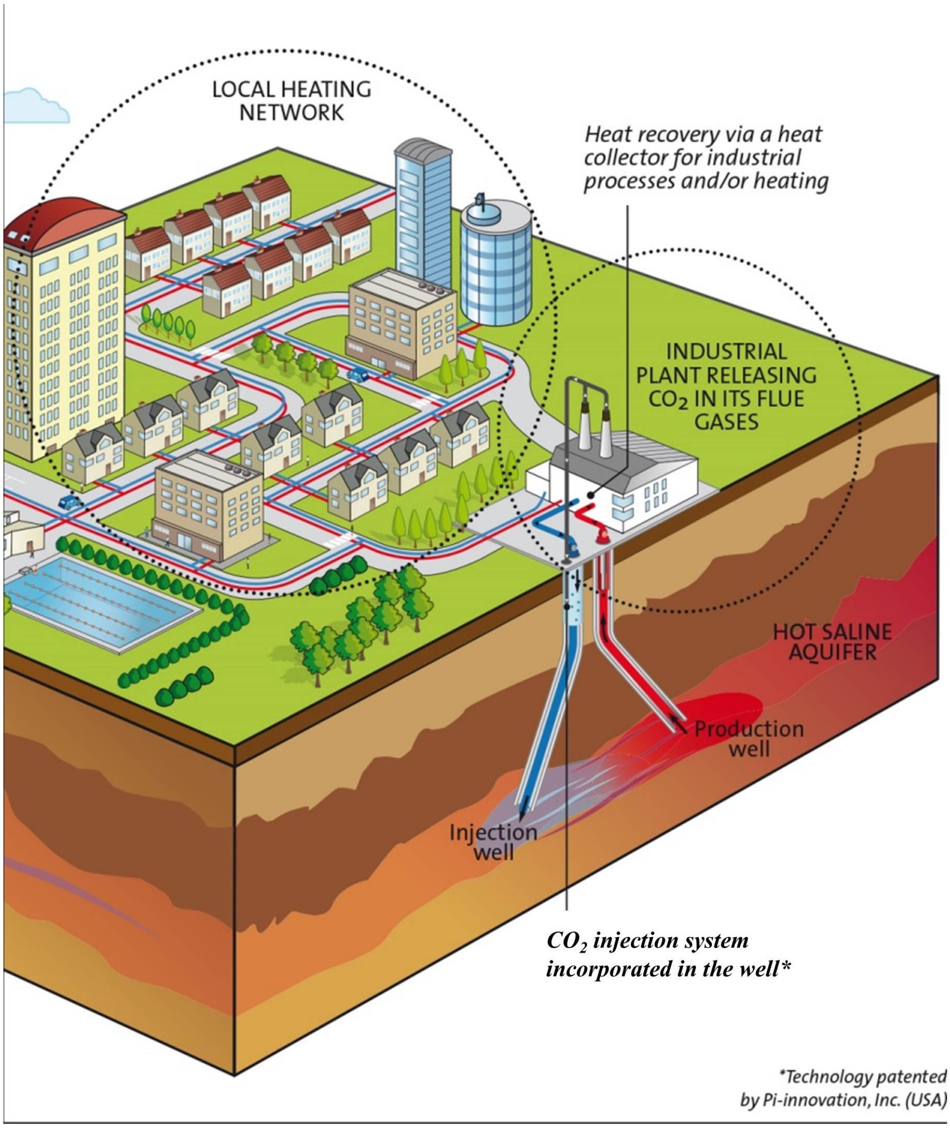

Figure 2 : Schematic view of the CO_2-DISSOLVED concept [4]

3.2. Economics of CO_2-DISSOLVED: First results for the implementation on a biorefinery

A techno-economic analysis of CO_2-DISSOLVED has been performed, on a specific case study, i.e. a factory producing bioethanol from sugar beets, in France [4]. In a nutshell, the production of bioethanol emits CO_2 during the beet fermentation, giving the possibility of recovering and storing 45,000 t CO_2/year. The CO_2 gas flow being sufficiently pure as to not require gas separation, the drilling of a third well for gas purification would not be necessary. The bioethanol plant has a second source of emissions, which is the natural-gas boiler that feeds the plant. The corresponding emissions are around 60,500 t CO_2/year. However, these emissions are not sequestered in this analysis.

The economic rationales of the project are the followings: Firstly, the stored CO_2 is supposed to be rewarded by the EU ETS (the European Emissions Trading System), even if it is not currently the case. Secondly, the geothermal energy allows reducing the amounts of natural gas consumed. Royer-Adnot and Le Gallo [4] use a probabilistic approach that takes into account a lot of uncertainties, such as the heat of the reservoir, the efficiency of the gas boiler, carbon and natural prices. For the sake of simplicity, we present here only a few results coming from their medium scenario. Compared to the Business As Usual (BAU) case, i.e. the same plant without any capture system, CO_2-DISSOLVED reduces CO_2 emissions of 40%, and the non-renewable energy consumption of 15%. Results are then compared with the conventional method of CO_2 storage in a supercritical state [8]. CO_2-DISSOLVED improves the energy balance by 13%, meaning that there is no more energy penalty due to the capture. The performance of the carbon footprint is still lower for CO_2-DISSOLVED than for CCS. The CO_2 reduction corresponds to 33% of those performed by the conventional CCS. This relatively poor performance results from two main reasons. First of all, as the solubility of CO_2 in the brine is limited, the emissions exceed the capacities of solubility during the harvest campaign, so some amounts of CO_2 are not stored. In addition, CO_2 reductions depend on the assumptions regarding the boiler efficiency: better is the boiler, higher are the prorated amounts of CO_2 saved by geothermal energy. Here, the plant is feed with a not very efficient natural gas boiler.

Nevertheless, it is noteworthy that one of the main drawbacks of the conventional CCS lies in its cost. CO_2-DISSOLVED presents an impressive comparative advantage in this field, 50% cheaper than conventional CCS, with a cost of avoided emissions falling down to 51€/tCO_2. This is still high, but the project benefits from the reduction of natural gas consumption thanks to the use of geothermal energy. During the lifetime of the project (30 years), the Net Present Value would be 8 million euros. Moreover, results show then that CO_2-DISSOLVED is more profitable than a geothermal project alone for a carbon price higher than 12.5€/tCO_2eq.

3.3. Benefits and Limits of CO_2-DISSOLVED : Lessons beyond the case study

Regarding the technological aspect, CO_2-DISSOLVED improves the safety of the reservoir compared to CCS stored at a supercritical state. The dissolved CO_2 does indeed not tend to rise to the top of the reservoir (which requires checking precisely the quality of the caprock), and the hydrostatic pressure in the aquifer remains almost constant since the brine circulates into a close loop.

There is moreover a dilemma between carbon and energy balance in our case study, i.e. a factory producing bioethanol. Conventional CCS has the ability to fully capture the emissions, but it generates a high energy penalty. In [8], it has been shown that if conventional CCS was applied on the fermentation step and on the boiler, the energy balance was so bad that the amount of energy produced (i.e. bioethanol) was almost equaled to the energy required to produce the bioethanol. However, the carbon footprint was then negative (106% of reduction). If conventional CCS is applied on the fermentation step only, carbon footprint declines and energy balance is improved. Here again, the same phenomenon appears: the carbon footprint seems lower, but the energy balance is better. The main point is that energy penalty is reduced for CO_2-DISSOLVED at first by capturing emissions without the need for gas separation (exhaust stream from the fermentation is almost pure), and then by using geothermal energy for lower compression needs.

At the same time, there is a trade-off between the carbon balance and the initial investment cost. The capital costs are indeed reduced if the emissions from the boiler are not captured because of the cost of gas separation for conventional CCS. CO_2-DISSOLVED reduces again the capital cost because the compression costs are lower, and because geothermal energy introduces a novel source of revenues. In other words, it means that the partial capture is more profitable than the capture of all the emissions from the factory.

Regarding the economic aspects, we have still to highlight that the results are highly site-specific. For example, in the case study presented above, the results are improved significantly on each aspect (carbon & energy balance, profitability), if the emissions are distributed equally over the year instead of mostly condensed over the two months of sugar beets harvest. On the reservoir side, the key determinants of profitability are linked to the geothermal capacities, especially the heat of the reservoir. On the emitter side, the key features of profitability are then: i) the amounts of CO_2 that can be stored (rather than amounts emitted), ii) their distribution over the year (to avoid a temporary excess of emissions), and iii) the composition of the exhaust stream because the gas separation could be energy intensive and costly. Because of the solubility limitations, the stream of CO_2 stored per hour is limited, which in turns reduces the whole amounts of CO_2 that could be stored. This is why CO_2-DISSOLVED is assumed to be more adapted to small emitters. Moreover, as mentioned previously, the reference for energy savings calculation is essential. The last point here concerns the way heat is going to be used, directly in the factory or in the neighborhood (another factory or households). In both cases, it is required to optimize the process of heat recovery in order to maximize the profitability. For the sake of simplicity, the previous case study assumed that the heat was used inside the factory, but others possibilities could be envisaged.

Generalization of economic results is then hazardous, and the local conditions have to be taken into account. Castillo et al. (2013) have studied the matching between potential emitters and well-adapted geological sites, especially in France and Germany. The emitters considered in this study were small or medium emitters, i.e. emitting 10-150 ktCO_2 by year. For France, the matching between these emitters and geological sites is pretty good and the total emissions that could be stored would be around 25.1 million tons of CO_2, meaning 16.9% of the national emissions. The German potential is lower with an estimation of 7.95 million tons of CO_2. So, there is a real technical potential for CO_2-DISSOLVED. The economic potential is going to depend on the gas separation cost, which could be lowered by the Pi-Innovation technology [14] compared to conventional CCS. However, like in other CCS projects, the current carbon prices are ultimately too low to drive private investment.

4. CO_2-DISSOLVED role in the sustainable transition : towards a reconfiguration pathway

In this section, we first present the Multi-Level Perspective (MLP) approach to study transitions phenomenon (subsection 4.1). Then, we explain how the MLP interprets the role of CCS in the current energy transition (subsection 4.2). Eventually, we present why CO_2-DISSOLVED has a different role.

4.1. The Multi-Level Perspective approach of sustainable transition

The Multi-Level Perspective (MLP) approach seems well adapted for the study of the role of CCS in sustainable transition. This conceptual framework analyses transitions as mutation processes from one sociotechnical regime to another under the pressure of macro-level forces (called the landscape) and the emergence of market niches that could provide the basis for a new regime [5].

The sociotechnical regime could be defined more precisely as a rule set that is "*embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures*" [15]. Regardless of the sociotechnical regime, the MLP assumes that social actors are nested together and tend to maintain and reproduce the regime. Those actors are for instance public authorities (local, national or supranational), industries (firms, engineers), research activities (R&D laboratories), supply chain actors, users, and finance actors (banks, insurance firms, venture capital firms).

The landscape of a socio-technical regime is composed of "*background variables such as the material infrastructure, political culture and coalitions, social values, worldviews and paradigms, the macro economy, demography and the natural environment which channel transition processes and change themselves slowly in an autonomous way*" [16]. An example of an influential landscape change is the case of the emergence of cars as a reaction towards the rising concern about public health (because of horse excrement), longer travel distances due to the urbanization, and the emergence of a middle class and more leisure activities at the end of the nineteenth century.

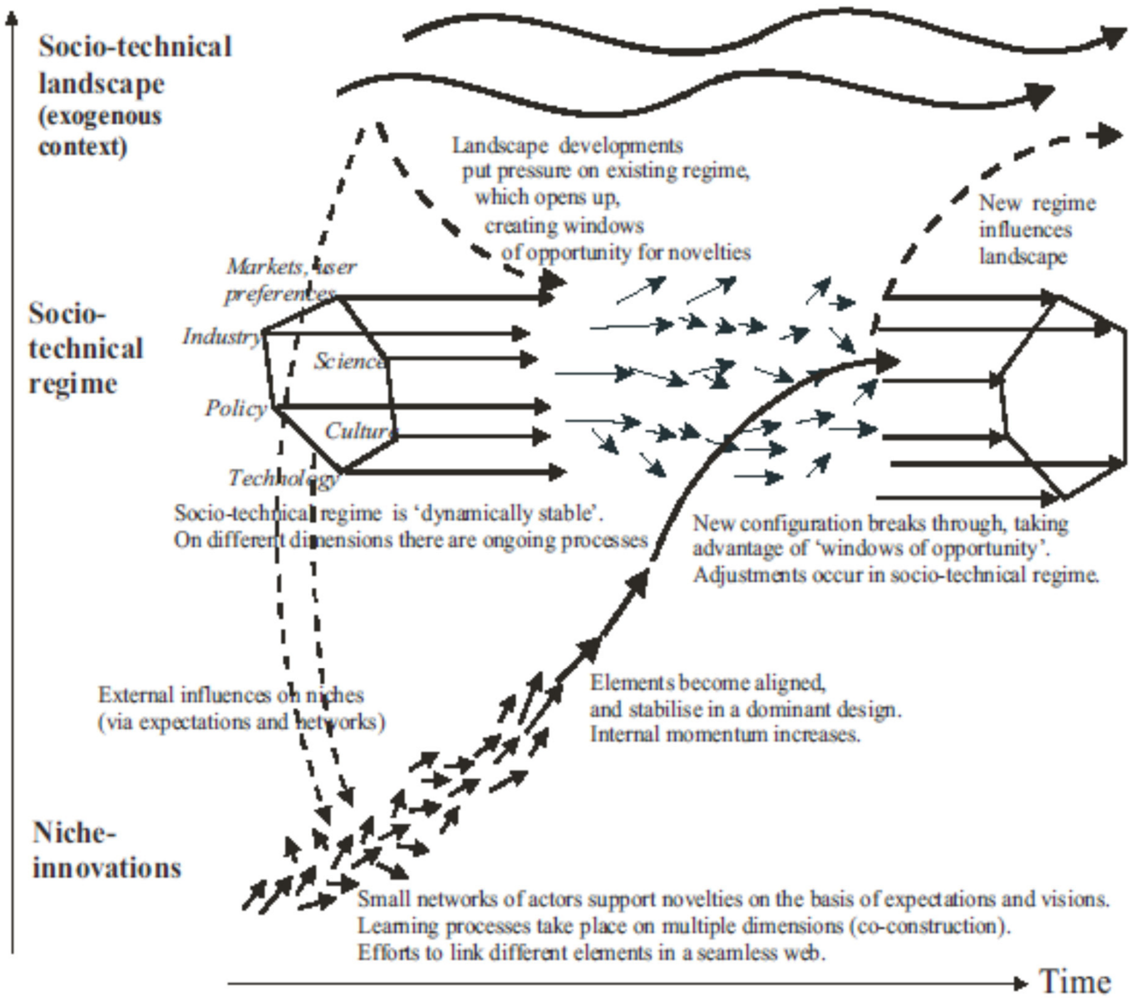

Figure 3: Multi-Level Perspective, according to Geels [5]

The interactions between social and technological concerns are twofold: technologies modify society and vice versa. Most of the time, the regime evolves slowly and through incremental innovation, notably because of path dependency and lock-in effects. However, the landscape could change dramatically. The regime could then be deeply disrupted, leading to a window of opportunity for technologies to come from the niches. Technological niche can appear and survive in protected places (for instance, because of subsidies or because the application is very specific). They allow testing and improving promising technologies without the pressure of short-term profitability. They also have their own internal momentum through effects such as learning processes or lobbying. Radical innovations are more likely to occur in this case than if the innovations were coming from the regime itself. For instance, at the end of the nineteenth century, various methods for moving were discovered (bicycle, electric tram, steam automobile, etc.).

4.2. CCS in the Multi-Level Perspective: driver or barrier to sustainable transition

In the MLP perspective, climate change awareness could be seen as a macro pressure with economic and social aspects that affects the landscape and requires a deep change in the global energy system, i.e., the sociotechnical regime. CCS can be seen as an innovation coming from the regime based on fossil fuel use in order to adapt him to this landscape change. It is then supported by its main actors, i.e. energy suppliers, fossil energy companies, and policy makers (notably at the European level). Geels [18] considers CCS an example of a defensive technology that leads to resistance to change from these actors. He shows how the discourse on renewable, coal, gas and nuclear energies has evolved in the United Kingdom in favour of CCS and nuclear energy. On the contrary, renewable energies appear as market niches assumed to compete with the current sociotechnical regime in the long run that will replace it by the end of the century.

Geels and Shot [17] offer a typology of transition based on two main criteria: first, the natures of the interactions among landscapes, regimes, and niches (reinforcing versus disruptive effects on the regime), and second, the timings of these interactions (mainly the maturities of the niches). Four ideal-typical paths have been described [17, 19]:

1. Technological substitution: Due to the landscape pressure, there is a technological push from market niches. Niche actors can compete directly with regime actors, which potentially lead to technological substitution.
2. Transformation: The regime changes gradually due to pressure from the landscape, but market niches are insufficiently mature to cause major mutations (i.e., radical innovations).
3. Reconfiguration: Niches are more developed than in the transformation scenario. Some innovations are integrated into the regime. The regime is more deeply modified than previously. There are more interactions between the niche and regime actors.
4. De-alignment and re-alignment: Landscape pressure results in major tensions in the regime. Several niches can co-exist for a while.

The four transitions can follow one another, for instance starting with transformation, then reconfiguration, de-alignment and re-alignment, and/or technological substitution. Verbong and Geels [19] use this typology to create scenarios in the case of the electric transition.

In the transformation scenario, CCS plays an important role; as well as nuclear energy, offshore wind power or gasification from biomass. This scenario is compatible with the former centralized energy infrastructures and allows them to continue to work. Current market mechanisms still continue, and small, decentralized renewable energy sources (e.g., photovoltaic power) remain market niches, for instance, in the sector. R&D investments - regardless of the technology, i.e., renewable energies or CCS - are assumed to be limited, which seems quite unlikely if CCS is going to be largely developed.

The reconfiguration scenario goes a step further with the notion of a “supergrid”. More renewable energy sources are implemented in the energy mix, leading to concerns about safety and reliability of the energy supply (because of the variability of renewable energy). The solution should be to bet on centralized renewable energy sources, such as big offshore wind energy, Saharan solar energy, hydraulic energy, and fossil fuels with CCS.

The re-alignment scenario is the largest change in the energy system. Power is then mostly produced from distributed renewable energies, in a decentralized energy system. However, such a scenario could appear only under high pressure from the landscape that deeply destabilizes the regime, e.g., a major energy crisis, fluctuations in oil prices, a climate change emergency, and so on.

It is important to note that CCS plays a decreasing role in these different scenarios; it is prominent in the transformation scenario but more marginal in the reconfiguration and substitution scenarios. The question of the role of CCS in the de-alignment and re-alignment step remains open and depends on the deepness of the fossil fuel lock-in but also on the ability of renewable energies to replace fossil fuels in all of their uses, especially intermittent use.

4.3. Combining renewable energy and CCS: CO_2 DISSOLVED as an example of a reconfiguration pathway

As discussed before, conventional CCS can be considered as a niche coming from the sociotechnical regime itself, so it could be suspected to be a form of resistance to change. In contrast, CO_2-DISSOLVED appears as hybridization with renewable energies, which are niches that are assumed to come from outside the regime. This kind of project could contribute to the sustainable transition following the transformation and reconfiguration pathways for the energy transition, described in [19].

At first, CO_2-DISSOLVED could contribute to the transformation scenario as a niche innovation that will be implemented on small CO_2 emission sources. At this step, it does not interfere with the existence of large energy infrastructures, which are still dominated by the centralized use of fossil fuels, but often with the implementation ofwithCCS. CO_2-DISSOLVED does not contribute to change the energy production system as a whole: habits of the actors and previous infrastructures are largely maintained. For instance, CO_2-DISSOLVED does not contribute to the construction of a network of pipelines for CO_2 transportation, because heat has to be used locally. Nevertheless, it appears as a complementary technology that is well adapted to small CO_2 sources and so enlarged the potential of CCS in direction of industrials.

Regarding the reconfiguration pathway, the role of renewable energies is increased, but with a focus on centralized renewable energies. Geothermal energy with high enthalpy could contribute to that aim, especially when power generation is concerned, since large amounts of energy are produced in one location. Because CO_2-DISSOLVED is concerned by low enthalpy heat, the energy production (through heat) is lower. Then, the contribution is close to the one of the transformation pathway. However, Geels et al. (2016) argued that this reconfiguration scenario seems better adapted to manage the sustainable transition than the previous transformation scenario, as there are more changes in consumption practices and production technologies, driven by the interactions between new entrants and incumbents, in a changing institutional framework [20].

In the case of realignement/alignement transition pathway, the energy production systems is deeply changed to take into account all the sources of renewable energies, including the local energies produced in large amounts. The role of CO_2-DISSOLVED is then increased since the use of the geothermal energy is a way to create a local energy, while energy penalty of the CCS is offset. Geothermal energy is not sufficient by itself to feed the factory of our case study, but other energies – such as bioenergies – could be then used for this purpose. In this situation, the new design of the energy system will lead to new alliances between incumbents and new entrants, and to a shift from limited to more substantial institutional change [20].

In the case of a complete substitution towards renewable energies (which a long-term perspective, maybe the end of the century), a technology such as CO_2-DISSOLVED could still to be used, especially is combined with other renewable energies. Because it can use fossil fuels and bioenergy as carbon sources, it could be used as a conventional CCS plant or as a negative emissions provider. However, the place of CO_2-DISSOLVED in the mitigation technologies should rise with the stringency of each scenario.

5. Conclusion

CO_2-DISSOLVED is an innovative technology that overcomes some of the major economic and environmental drawbacks of CCS in a supercritical state and gives in the same time a new application of geothermal energy. The energy penalty of the whole process is dramatically reduced by the heat recovery coming from geothermal energy and by the CO_2 injection in dissolved form. As a consequence, storage costs are lower than CCS with CO_2 in a supercritical state notably because of reduced compression costs and no need for a CO_2 transport infrastructure. An additional benefit of this technology is that the hydrostatic pressure is almost constant in the aquifer, leading to a better mechanical stability of the reservoir. The absence of a gas phase also strongly reduces the risks of CO_2 escape to the surface. The storage potential of CO_2-DISSOLVED is nevertheless limited by the solubility of CO_2 into the brine that prevents to store large amounts of emissions. In our case study, there is no need for gas separation because the exhaust stream of CO_2 is almost pure. An additional case study with capture could extend our economic results, and enriches the comparison between CO_2-DISSOLVED and conventional CCS. The innovative “Pi-CO_2” capture technology would provide a cheaper capture solution than current post-combustion purification technologies with MEA membrane.

CO_2-DISSOLVED is then mostly dedicated to small or medium emitters, which are currently not well targeted by CCS technologies. These technologies are then complementary rather than competitive, and CO_2-DISSOLVED enlarges the potential of CCS technologies. Its role in the sustainable transition could also be seen as a bridge between renewable energies and CCS, because of its use of geothermal energy. CCS is sometime criticized as a way to reinforce the current carbon lock-in into fossil fuel, whereas a quick switch to renewable energies could be seen as beneficial. Energy penalty of CCS is also a big concern because it means that additional energy has to be produced to feed CCS installations. On the contrary, combining geothermal energy and CCS allows moving beyond a simplistic opposition between CCS on fossil fuels and renewable energies, as other promising technological solutions like the implementation of CCS on Bioenergies (BECCS), or its combination with hydrogen production. CCS technological diversity should be maintained and even more explored, in order to promote the transformation or reconfiguration of the current energy production system.

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