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Abstract

To achieve the objective of the Paris Agreement to limit global warming to well below 2ºC, there is a growing need to reduce drastically greenhouse gases emissions and even better to set up also negative emissions. Capturing and storing or valorizing carbon dioxide from biomass origin is a way to obtain negative emissions. The CO2SERRE project investigates techno-economic and environmental feasibility of implementing a "BCCUS" (i.e. CCUS for CO2 of biomass origin) pilot in France, in the Centre-Val de Loire Region. The concept consists in capturing CO2 from a biomass cogeneration plant in Orléans, valorizing it in local greenhouse farms, and storing the unused CO2 in geological reservoirs in the region. In addition to generating negative emissions, this concept promotes local and circular economy. To feed the techno-economic and environmental feasibility assessment, each stage of the CCUS chain is considered and assessed (capture, transport, geological storage, and use in greenhouses). Work carried out so far provides useful insights on technical feasibility of the process. However, the key challenge is the viability of the project on both economic and environmental sides. The LCA and TEA analyses, taking into account the whole CCUS chain, are under development and their outputs will address conditions for feasibility of the CO2SERRE concept. A preliminary assessment of geological storage capacity in the region have shown that targeted reservoir would be able to store the equivalent of the total emissions of the region Centre-Val de Loire. Thus, a longer term perspective for CO2SERRE project is to create a new technical and economic network in the region with platforms gathering CO2 emitter, users and storage.

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Keywords: CO2; CCUS; BCCS; carbon from biomass, geological storage; biomass energy; negative emissions; CO2 valorization; greenhouse crop; circular economy

Nomenclature

BCCS	biomass origin carbon capture and storage
BCCUS	biomass origin carbon capture, use and storage
CCS	carbon capture and storage
CCUS	carbon capture use and storage
DBO	Dalkia Biomasse Orléans
GWP	global warming potential
LCA	life cycle analysis
MEA	monoethanolamine
TEA	techno-economic analysis

1. Introduction

To achieve the objective of the Paris Agreement to limit global warming to well below 2ºC, there is a growing need to reduce drastically greenhouse gases emissions. CCUS, for Carbon Capture, Use and Storage, stands among mature technological options which enable large-scale reductions of carbon emissions. According to the Global CCS Intitute, which tracks CCS projects around the world, there are 26 CCS facilities currently in operation and around 40 Mt of CO_2 is stored every year.). However, only two of them are located in Europe (Sleipner and Snøhvit, both Norway).In 2017, the International Energy Agency (IEA) considered CCUS did not grow fast enough. Experts from the Intergovernmental Panel on Climate Change (IPCC) go further by insisting on the need for setting up negative emissions and promoting technologies which can reach this objective, such as direct air capture and storage or CCS for CO_2 of biomass origin. Indeed, CO_2 of biomass origin, such as biomass combustion or fermentation, is considered carbon-neutral as biomass previously captured atmospheric CO_2 for growing. By capturing and storing these neutral emission, we can obtain negative emissions. In France, the National Low-Carbon Strategy (SNBC2) encourages the development and implementation of pilot, and possibly commercial, CCS and CCU projects. It especially targets CO_2 from biomass energy in a negative emissions perspective, and considers capturing 10 $MtCO_2$/year by 2050, while objectives for CCUS for industries are around 5 $MtCO_2$/year by 2050.

The CO2SERRE project fits in this framework of negative emissions. It is an on-going three-years study (2019-2022), led by BRGM (French Geological Survey), which investigates techno-economic and environmental feasibility of implementing a “BCCUS” (i.e. CCUS for CO_2 of biomass origin) pilot in France, in the Centre-Val de Loire Region. The concept consists in capturing CO_2 from a biomass cogeneration plant in Orléans, valorizing it in local greenhouse farms, and storing the unused CO2 in geological reservoirs in the region. In addition to generating negative emissions, this concept promotes local and circular economy. To feed the techno-economic and environmental feasibility assessment, each stage of the CCUS chain is considered and assessed:

Capture: The studied CO_2 sources is the Dalkia Biomasse Orléans facility. Data on the emissions of the plants are collected – quantity, rate, frequency and composition - and the existing capture technologies are evaluated in order to optimize capture costs for this plant, as well as for a wider specter of CO_2 emitters.

Transport: The aim is to plan a local transport network for CO_2 between emitting, storage and use sites. It bases on existing or planned infrastructures in the region, mapping of the different transport options (pipelines, trucks) and their optimization regarding to costs and distances. Special attention is given to the timescale: plans concern as well the short-term with the actual project sites, as the longer term considering a network expansion to other emitters or users.

Utilization: CO_2 injection in greenhouses is a common practice as it allows to boost plant growth and improve outputs. In the region, a number of producers already use either exhaust gases of their gas furnaces – but CO_2 quality is not guaranteed – or pure liquid CO_2 – with higher costs. In both case, CO_2 has a fossil origin. The potential and the technical feasibility of using CO_2 from biomass to feed the greenhouses is assessed, based on the current practice of

CO_2 consumption in greenhouses and the needs of the producers of the region in terms of quantity, period of consumption (mainly winter/spring), and requested quality.

Storage: The aim is to assess the location of the injector well and the underground geological storage capacity for a permanent storage and a buffering storage through reservoir simulation studies. Two different brine-reservoir levels of the Trias formation in Paris Basin are studied. One level is deeper and is considered to store excess CO_2 permanently as supercritical phase. The other level is shallower and will work as buffer storage to compensate different time profiles of CO_2 emission and utilization.

Then, a techno-economic analysis (TEA) will first assess the economic viability of the whole concept, in which carbon is considered as an input for growing plants. Its overall capture, transport and storage cost will be compared with the actual price already paid by local greenhouse operators. Along this TEA, a Life Cycle Analysis (LCA) will be performed in order to evaluate the global carbon balance of the project, which mix Carbon Capture Storage and Use. Both TEA and LCA pay special attention to the dynamic aspect resulting from buffer storage option.

We present here the work which has been carried out in the framework of CO2SERRE project, especially results from the first phase of the project on the technical study of the different links in the chain: capture – transport – storage – utilization in greenhouses. First elements of the project second phase about transversal analyses (TEA and LCA) and challenges they will have to tackle will also be presented. However conclusions on techno-economic and environmental feasibility shall be drawn only when these analyses are completed.

2. Carbon capture

2.1. Capture technologies

Carbon capture is the first step of the CCUS chain, but also the most expensive and energy consuming. There are different technologies to capture carbon. Carbon can be removed from smoke from burning (post-combustion technologies), but it can also be separated with other processes, in pre-combustion or in oxyfuel combustion. Post-combustion capture is the most widely used as it does not require any change on the combustion part of the plant. It can be implemented on existing facilities without modifying the process. The main cost of this capture option comes from regenerating the solvent used to extract CO_2. Pre-combustion capture option consists in converting fuel to synthesis gas, then transformed into hydrogen and carbon dioxide in a shift reactor. Both gas are then separated by extraction with a solvent. Hydrogen is used for combustion, while carbon has been removed before combustion. This technology can be more economic than post-combustion if it is implemented since the beginning of the plant building. In oxyfuel combustion option, fuel is burned in pure oxygen instead of air. Thus flue gas contains less impurities (especially NOx) and CO_2 can be collected with a simple condensation. The main cost of this technology comes from the oxygen production unit.

There is a wide range of existing process to capture carbon dioxide from gas streams, in post-combustion or in pre-combustion, with different capture rates: chemical absorption, physical absorption, adsorption, calcium looping, membranes, cryogenics, micro-algae, etc.

Chemical absorption has been used to remove CO_2 from natural gas for decades, thus, it is considered to have a TRL of 9 [1]. This technology bases on an absorption/desorption cycle: an absorption column enables CO_2 removal from the gas stream using a solvent and a stripping column enables recovering CO_2 in gas phase and regenerating the solvent. Choice of the solvent is a key-issue, as it will determine the reactions kinetics and thermodynamics, but also the amount of energy spent for solvent regeneration (which is the most energy-consuming step of capture process) and the impact on environment. Amine-based solutions as chemical solvent for CO_2 capture are most widely used. The solvent can contain a unique alcanolamine or a blend of amines with different features to improve its performances (thermal stability, reaction speed, etc.). The classic solvent for CO_2 separation applications is 20–30 wt% aqueous monoethanolamine (MEA). According to Bui *et al* 2018. review [1], MEA is particularly suited to low CO_2 partial pressure and as a consequence has become the benchmark amine for CO_2 capture. MEA has good capture rates (around 90%), but suffers from moderate rates of oxidative and thermal degradation, and requires high energy for regeneration (around 3.6–4.0 GJ per ton CO_2 captured). New amines and blends has been developed to perform better than MEA in some or all of these characteristics. In pre-combustion for natural gas combined cycle (NGCC) plants, the tertiary amine MDEA (methyl-di-ethanolamine) is most widely used because of its lower heat requirements for CO_2 release from the solvent [2]. Chemical absorption can also use multi-phase absorbents. Aqueous ammonia (NH_3) is the most advanced of the multi-phase absorbent processes [1]. It has a good CO_2 absorption capacity and a low energy demand for stripping (2–3 GJ per tCO_2), but suffers from a high volatility. Aqueous potassium carbonate (K_2CO_3) solutions are less volatile, with very low energy demand for regeneration, but offer poor CO_2 mass transfer (20-25%) [1]. Solvents using ionic liquids are also being developed to propose a green alternative to volatile organic solvents and to reduce energy consumption.

Physical absorption is mostly used in pre-combustion. Carbon dioxide capture using physical solvents is most effective if partial CO_2 pressure is high and temperature is low [2]. CO_2 capture in pre-combustion with physical solvents is mainly implemented on fuel oil- or coal-based integrated gasification combined cycle (IGCC) plants.

Adsorption processes for carbon capture use the adsorption phenomena which consists in the adhesion of atoms, ions or molecules (adsorbate) to a solid surface (adsorbent). The different adsorbents used for CO_2 capture are reviewed in Boot-Handford et al. 2014 [3]. Zeolites (crystalline aluminosilicates) and MOFs (metal-organic frameworks) have high adsorption rates, but are sensitive to presence of water (and of SOx and NOx for MOFs). Carbon-based adsorbents (activated carbon) have good thermal stability but poor capture rate. Mesoporous silicas have low capture rate but potential high affinity with CO_2 at low pressure.

In the calcium looping process, CO_2 capture is based on the following reversible reaction:

$$CaO(s) + CO_2(g) \leftrightarrow CaCO_3(s) \qquad \Delta H = -178\ kJ.mol^{-1} \tag{1}$$

Lime is used in a reversible cycle to remove CO_2 from flue gases, thus lime can be reused in multiple cycles. In the carbonator, CO_2 from flue gas reacts with lime following reaction (1) at about 650°C. Produced calcium carbonate is then brought to an oxy-fired calciner to form CaO and CO_2, at around 900-950°C, following the inverse reaction. Pure carbon dioxide stream is then captured and lime is put back into the carbonator. Conversion from CaO to $CaCO_3$ is generally limited to 70% for the first cycle and falls to 10% after 30 cycles [4]. The energy penalty can be reduced by using the carbonator and calciner as a heat source for a steam cycle to produce additional power. Lime presents the advantage of being available in high quantities (used for cement production) with a low price. Furthermore, synergies can be made between calcium looping process and the cement industry, as the spent CaO can be reused for cement making.

According to MacDowell *et al.* 2010 [5], technology options that are generally accepted as being suitable for commercial deployment in the near to medium term are post-combustion CO2 capture using amine solvents, oxyfuel combustion and finally calcium looping technologies.

2.2. Carbon capture implementation on a facility

Implementing carbon capture on an industrial facility requires preliminary study of quite a few site-specific technical data, in order to determine the most adapted technology. We developed a work methodology to select most suitable technologies based on analyzing data collected from industrial facilities.

In particular, composition of the facility emissions will be very different according to the type of industry, which could lead to choosing different capture technologies. Carbon content is an essential information for choosing the solvent, since at low partial pressures the absorption capacities of chemical solvents are much higher, whereas physical solvents provide better results at high partial pressures (over 1.4MPa) [2]. Composition of the emissions also indicate the presence of other components which could degrade the solvent. In particular, NOx and SOx cause amine solvents degradation [3].

Energy required for the solvent regeneration in some processes is also a key-parameter to take into account. All types of solvents does not require the same amount of energy for regeneration. Multi-phase absorbents like aqueous potassium carbonate solutions has low thermal energy requirements [1]. New amine blends are developed to lower energy needs for regeneration compared to MEA.

2.3. Dalkia Biomasse Orléans facility

In the framework of the CO2SERRE project, we study the feasibility of capturing carbon from the 25 MW biomass cogeneration plant in Orléans, Dalkia Biomasse Orléans (DBO). The plants provides power and heating for 13000 housing equivalents in the Orléans city. It has a heat production for district heating of 17 MW and a power production of 5,5 MWe in winter and 7.5 MWe in summer. On the same site, there are also two gas-fired boilers of 35 MW and a gas-fired cogeneration facility of 17 MW. These facilities are used to offset high demand (winter) or to bridge heat and power production in case the biomass facility is stopped.

The DBO facility emits around 80 kt of CO_2 per year and uses approximately 90 kt of wood per year, trucked from within a radius of less than 100 km. Temperature in the boiler is comprised between 800 and 1000°C. It produces superheated steam (67 bars, 485 °C) which is then expanded in a steam turbine to produce electricity. Two extractions are performed: the first at 6 bars for the heating network, the second at 2.5 bars for domestic hot water network. On the outlet site of the turbine, the 0.16 bars steam is driven to air coolers for condensing water which then turns back to the boiler.

The flue gas issued from biomass combustion go through a multicyclone to take off fine particles (80% of fine particles are removed) then through bag filters to clean the gas to less than 30 mg/Nm^3 of dusts. Flue gas requires no treatment for SOx and NOx as it meets mandatory emission standards for these components: 200 mg/Nm^3 for SO_2 and 300 mg/Nm^3 for NOx for a 25 MW biomass boiler. In fact, concentration in SOx is very low and concentration in NOx is right below the standards. Concentration in CO_2 is around 10 vol%. Flue gas is emitted at atmospheric pressure at a temperature of approximately 170°C.

For the case of the DBO facility, CO_2 volume fraction and total flue gas pressure lead to a low CO_2 partial pressure. So, chemical absorption processes should be considered for carbon capture on this plant. Pre-combustion capture is excluded, as this technology must be implemented since the building of the plant. Oxycombustion is not considered neither, since flue gas already meets emission standards for SOx and NOx. Carbon capture using amine-based solvents being a mature and commercialized technology, this option should be preferred at short term to capture carbon from DBO. MEA could be considered, or amine blends such as GALLOXOL®. However, amines are sensitive to temperature and require a temperature of 45-60°C. Flue gas emitted at 170°C should be cooled down and this heat could be retrieved.

Energy requested for amine regeneration is a crucial issue. For a 40 wt% MEA solution, amine regeneration requires around 3 Gj/tCO_2. Capturing 90% of the annual carbon emissions would require a large part of the steam produced on the site and, thus, induce a loss in electricity production. Studies are on-going to estimate the quantity of CO_2 to be captured and the source of energy for solvent regeneration, in particular if on-site gas-fired boilers have to be included in the study. This raises economic and environmental balance issues to be addressed as the project goes forward.

3. Valorization in greenhouse crops

3.1. Injecting carbon dioxide in greenhouses

The CO2SERRE study investigates valorization of captured CO_2 in local greenhouse crops. Injecting carbon dioxide in greenhouses is a currently practice, as advantages of CO_2 enrichment of greenhouses are recognized for many years. CO_2 is essential to photosynthesis: plants use light energy to transform CO_2 and water into carbohydrates (e.g. sugars) with dioxygen release. Carbon dioxide concentration in the atmosphere is around 400 ppm. Addition of CO_2 into greenhouses allows to increase productivity by improving plants growth and robustness. Optimum CO_2 concentration depends on crop type, and also on factors such as illuminance, temperature, plants growth stage and nutritional state. It ranges from 600 to 1000 ppm.

Currently, injected carbon dioxide can come from natural gas combustion when producers have boilers for greenhouses heating or gas cogeneration facilities. These flue gases are relatively clean compared to biomass combustion, and are mainly composed of CO_2, water and NOx. Yet, urea injection in the boiler (DeNOx) can eliminate nitrogen oxides. Combustion of 1 m^3 of natural gas produces approximately 1.8 kg of CO_2 and 1.4 L of water. This solution is economic and easy to implement for producers who already own gas boilers. However, CO_2 is produced only when the boiler is operating. This can induce a lack of consistency with CO_2 needs periods (*e.g.* in summer). Moreover, flue gas composition is not controlled and some impurities such as ethylene, sulphur dioxide, nitrogen dioxides, acetylene, propylene, are prone to damage crops.

An alternative is to buy liquid CO_2 to industrials suppliers. Liquid CO_2 is usually transport by truck and stored in tanks leased by the supplier. Tanks capacity ranges from 6,000 to 60,000 L and CO_2 is stored at 20 bar and -20°C. CO_2 is then injected into the greenhouse in gas phase: it is first expanded, then vaporized to use pressure and ambient temperature and finally injected under control in the greenhouse. The advantage of liquid CO_2 is its purity (food grade), which ensures absence of impurities and no humidity addition in the greenhouse atmosphere. Price of liquid CO_2 is around 100€/ton. Liquid CO_2 production originate from various processes, a large part of them using fossil fuels (*e.g.* steam methane reforming for hydrogen production). The use of liquid CO_2 also induce a dependency to suppliers. In particular, temporary closure of main CO_2-producing facilities (*e.g.* maintenance period) reduces the amount of available liquid CO_2 and greenhouse growers face the risk of not being supplied.

Other innovative carbon supply options have been developed in the Netherlands, principally. Since 2005, project OCAP (Organic Carbon-dioxide for Assimilation of Plants) allows CO_2 supply of 580 greenhouse farms, totaling 1,900 ha, between Rotterdam and Amsterdam. Carbon is captured on two industrial facilities: a refinery and a bioethanol plant. It is then compressed and distributed to the greenhouses through a 97 km-long pipeline network. The trunk pipe is a former oil pipeline, unused for 25 years, converted to CO_2 transport. This network supplies 400 kt CO_2 per year. The OCAP carbon is particularly interesting for the growers during summer, when the needs for CO_2 are high, while the gas-fuel boilers and cogeneration facilities should be off.

Still in the Netherlands, the DES (Duurzame Energie Sirjansland) facility is a biomass boiler which produces heat and CO_2 for 3 greenhouse farms in Sirjansland, totaling 25 ha of crops (tomato and eggplant). The biomass boiler capacity of 7 MW (Vincke) has been designed to meet the 25 ha greenhouses needs for CO_2. Extra heating needs are met by complement gas cogeneration facilities. The biomass boiler operates 24h/24, 7000 h/year, and consumes 2t/h of biomass. It produces pressurized superheated water at 145°C. This high temperature (classical boilers produce 90°C water) is requested for CO_2 desorption (minimum 120°C). Flue gases need cooling down from 850°C to 50°C for the capture process (heat is recovered). Urea injection in the boiler enables to lower NOx content to 145 mg/m3, in order to prevent solvent degradation. The solvent used is an amines blend developed by Frames, Galloxol®, which captures 90% of the CO_2 of the gas stream, i.e.50 tCO_2/day (or 2.2 tCO_2/h), with a 99.7% purity. The CO_2 is then transported by pipeline to the greenhouses (the maximum distance is 3 km). This installation of direct valorization in greenhouses of CO_2 captured from biomass combustion represents an interesting experience feedback for the CO2SERRE study.

3.2. Current practice in Centre-Val de Loire Region

The French region Centre-Val de Loire has an important number of greenhouse vegetable crops, especially around Orléans, where greenhouse growers essentially produce cucumber. A preliminary investigation was conducted among a few local producers members of the CVETMO association, gathering vegetable growers of the Orleans area, in order to draw a first overview of the CO_2 injection practice in the region. Half of the producers use CO_2 enrichment in their greenhouses. The reasons why the others do not use CO_2 are either because they do not heat the greenhouses and cannot afford liquid CO_2, or because their facility is too obsolete to implement CO_2 injection. The period when CO_2 consumption is higher is from January to April, when greenhouses are closed and when the climate conditions are most unfavorable. The rest of the year, CO_2 is only injected in the morning when temperature is not too high and vents are not open yet. Half of the producers who inject CO_2 use flue gases from their boiler, and thus have no information on the quantity of CO_2 injected or on its purity. Yet, all CO_2-enriched greenhouses have carbon monoxide analyzers (very toxic for plants) and at least one CO_2 sensor. Growers who buy liquid CO_2 pay around 100-110 €/tonCO_2.

Estimating the potential for captured CO_2 use in greenhouse in the Orléans region is one of the objectives of the CO2SERRE project. We identified so far a total surface of 46 ha of greenhouse crops in the region. It is a first estimate, as all these farms may not be suitable for CO_2 injection, and as additional farms may have not been considered. Scarce data on liquid CO_2 consumption by local growers indicate values from 30 to 136 t/ha/year. It is probably a conservative value as growers limit liquid CO_2 consumption because of its cost. Information from OCAP project in the Netherlands states a CO_2 supply of approximately 210 t/ha/year. This value excludes the additional injection of CO_2 from growers' own gas boilers. Yet, this provides interesting insights for CO2SERRE project. Applied to the greenhouse surface in the region, this leads up to a potential of 10 $ktCO_2$/year. Finally, the DES facility also provides useful information. The daily capture rate could lead up to an annual consumption of 600t/ha/year. This would be an upper value, as carbon may not be captured and injected into greenhouses during the whole boiler operating period. This leads to a maximum potential of 30 $ktCO_2$/year for CO_2 use in the region. Studies are still on-going to provide a more accurate analysis of the region's potential for valorizing CO_2 in greenhouse crops.

4. Storage

The proposed storage site, between Orléans and Paris cities, has a strategic geographical location. The site is in a low demographic zone, land use is mainly for agriculture, relief is flat and is easy to connect with highway, pipelines and railroad. This area is an important transport corridor between Centre-Val-de-Loire Region and Paris-Ile de France.

This site was previous assessed in the CPER Artenay project [6]. CPER Artenay project (2008-2010) evaluated the technical-economic feasibility of storing the CO_2 issued from the bio-ethanol distillery, and also quantified the environmental benefits of the CCS chain. Dynamic simulation carried out in the CPER Artenay study performed 30 years of CO_2 injection with a maximum flow rate of 200 kt of CO_2 per year.

Geological and reservoir models designed in the CPER Artenay project are being re-used in the CO2SERRE project. These models were built from the reprocessing of 13 seismic lines representing 342 km, acquired in the 80's. Eleven stratigraphic surfaces were calibrated with wellbore data and properties such as: K, Phi, net thickness, salinity, T, P came from regional data and wellbore data. The structural schema was completed with secondary faults pattern.

The geological model covers an area of 125 km by 142 km. The preliminary appraisal of storage capacity considers 2 different locations for injection: the Point4 in the North and the Point5 in the South (Fig. 1). The reservoir thickness at the Point4 is 60 m-thick and at the Point5 is 340m-thick. The initial average size of the grid-block of the geological model is 1.5km x 1.5 km x 16m (X x Y x Z directions). The grid was refined around the injector wells given an average size of the grid-block of 75m x 75m x 5m (X x Y x Z directions).

The vertical profile of porosity and permeability of reservoir at Point4 is homogeneous, whereas in Point5, the reservoir is more heterogeneous with shales and coarsed sandstones interbedded. The scenario of porosity and permeability distribution is pessimist for the considered reservoir, the TRIAS. Porosity in the area around both injector wells varies between 7-16% and permeability between 0.1-100 mD.

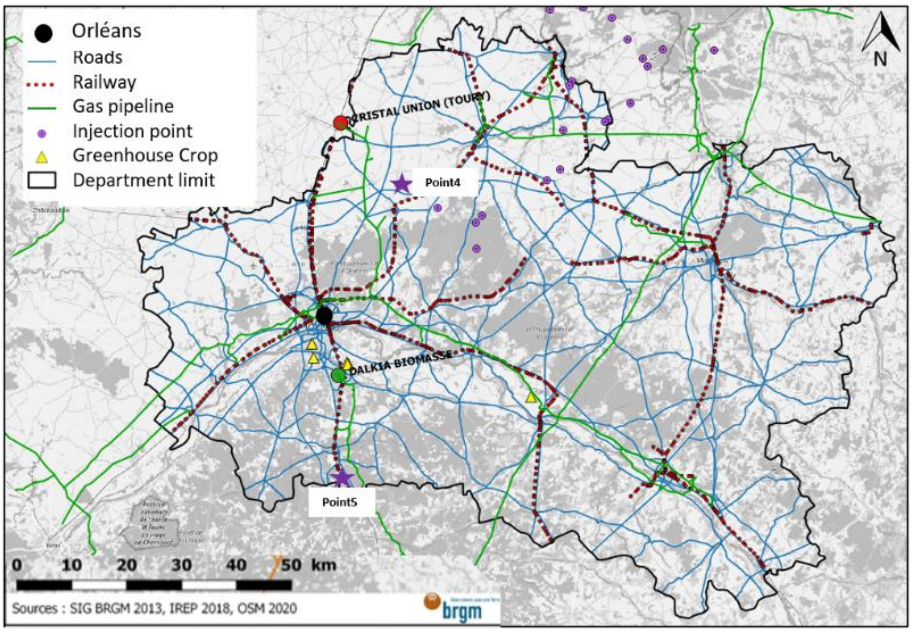

Fig. 1: Transport options and location of the studied injection points for emission from Dalkia Biomasse (DBO)

The DBO facility emits up to 85kt/year and represents one of important emitters in the Centre Val de Loire Region. The most important emitters is a cement plant, which emitted up to 300kt/CO_2 in 2018 [7]. The optimal location of the storage site should allow to store all emission of the Centre Val de Loire region for a long-term solution. Therefore, the assessment of storage capacity consider the storage of total emissions of the region.

Two injection rates were studied: an injection rate of 1 kt/day of CO_2 over 10 years with an accumulated total of 0.3 Mt/year, corresponding to the total emissions in 2016 of an important cement factory in the area; and other injection rate of 3 kt/day of CO_2 over 10 years with an accumulated total of 1.09 Mt/year corresponding to almost the total emissions of the region Centre Val de Loire in 2016.

Injection at the Point5 located in the South area of the geological model dissolved ~75% more CO_2 than at the Point4 for an injection rate of 1 kt/day of CO_2. For an injection rate of 3 kt/day of CO_2 at the Point5, 30% more CO_2 was dissolved in water phase than at the Point4 (Fig. 2).

The plume extension for the injection of 1.09 Mt/y at the Point4 is higher because the thickness of reservoir is limited, and extends around 600 m² from the injector well. The bottom hole pressure does not exceed 10% of initial hydrostatic pressure in every scenario for both injection locations.

The location of the injector well at the Point5 allows the storage of total CO_2 emissions in the Centre Val de Loire Region, at least for 10 years without important overpressure in the reservoir; further this location enhances the dissolution of CO_2, which is the safest way to keep the CO_2 in the reservoir.

Long-term simulation of CO_2 injection are ongoing to estimate injection feasibility on time scales exceeding 10 years (up to 40 years).We will also investigate the possibility of having a buffering storage at upper reservoir layers. This storage buffer would store CO_2 as gas phase (density of ~300 kg/m^3) in order to prevent dissolution, allowing CO_2 availability for a future withdrawal. The reservoir should have enough working gas capacity to allow several cycles of injection and withdraw.

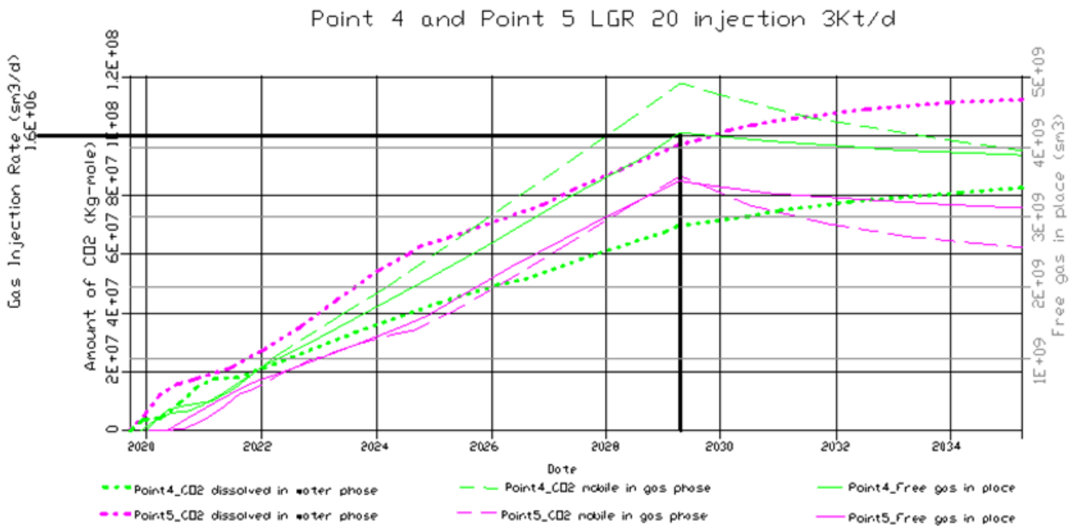

Fig. 2: CO_2 partitioning at Point4 and Point5 for the injection rate of 3 kt/d

5. Transport

5.1. Carbon dioxide transport technologies

Technologies for carbon transport are well established. CO_2 can be transported by pipelines in supercritical phase, or by truck, train or ship in liquid phase. Pipelines are considered as the only onshore option to transport large quantities of CO_2. There are 6,300 km of CO_2 pipelines in the United States, transporting 50 MtCO_2/year [8]. CO_2 is transported in supercritical phase at a pressure over 73 bar and a temperature over 31°C. In order to maintain this state, compressor stations have to be installed along the route. CO_2 purity is an important factor. However, CO_2 with 1% H_2S is currently transported between USA and Canada.

For transport by truck, rail or ship, CO_2 is in liquid phase with a pressure from 10 to 15 bar and a temperature between -40 and -30°C. A liquefaction facility is thus necessary close to the CO_2 source, and this process is highly energy-consuming and expensive. Besides, as these transport options are discontinuous, a buffer storage is required at the loading point. For road transport, truck capacity is around 40-44t. However, this option is the most flexible and can be interesting for temporary solution.

For on-shore transport, pipeline is more cost-effective for long distances [3]. Conditioning CO_2 to supercritical phase requires less energy than conditioning to liquid phase for truck or train transport. Although pipelines require re-compression along the route, it remains more profitable than truck transport for long distances.

5.2. Building a regional Geographical Information System tool

Public data were collected and implemented into a GIS tool :

- Localization of DBO facility and of other CO_2 emitters in the region
- Localization of potential injection wells
- Localization of identified greenhouses
- Digital Elevation Model
- Land cover
- Protected areas
- Networks: roads, rail, existing pipelines (natural gas)

For CO2SERRE project, the study area is exclusively onshore. The selected transport options are, thus, truck, rail and pipelines (Fig. 1). Reuse of existing and unused pipelines will be considered as long term option, since currently no abandoned pipeline has been identified.

5.3. Planning a CO_2 transport network

Two step of the transport planning were assessed:

- CO_2 transportation from emitter to the storage sites (injection wells)
- CO_2 transportation from emitter to the utilization sites (greenhouse crops).

A plugging on QGis calculated distance between 2 selected points using an algorithm to optimize it. Different options of transport were considered for a single pathway.

- Transport to the greenhouses: the truck option is chosen because greenhouse farms are scattered, but distances are short. A liquefaction facility is required to have CO_2 as liquid phase at P=10-15 bar and T=-40-30°C.
- Transport to the storage site: the pipeline option is more suitable to transport CO_2 from DBO to the injection well4 (point4 in Fig. 1). CO_2 should be compressed to supercritical phase (P>73 bars, T>31°C), but no compressor station is required along the route since distances stay below 50km.

The area including storage and emitters is relatively flat and comprises large areas of intensive crop farming. Pipelines already exists to transport gas at the scale of the region. Roads and railway could support the CCUS development at short scale as the area has a good network. Attention should be paid for some protected areas in the Southern of the region.

6. Environmental evaluation

As part of the CO2SERRE project, the objective of the Life Cycle Analysis (LCA) is to compare the environmental impacts of biomass transformation activities with and without CCUS. By seeking to achieve negative emissions for global warming mitigation, the implementation of carbon capture, transport, storage and utilization may also have adverse repercussions, for example on ecosystems, resource availability or human health. In particular, aspects relevant to carbon accounting in LCA have been intensively discussed by the Intergovernmental Panel on Climate Change (IPCC), paving the way for ongoing research, part of which is presented hereafter [9].

The main feature of LCA is its holistic approach, which is reflected in its internationally standardized methodological framework [10, 11]. All life cycle steps of the supply chain are taken into account, namely raw material extraction, manufacture, transport, use and end of life. Multiple environmental impacts are also considered: climate change, water use, human toxicity, eutrophication, to name a few. Possible burden shifting between life cycle steps and environmental impacts can thereby be identified, allowing for a comprehensive environmental assessment.

6.1. Existing LCAs on BCCUS

Over the past decade, several reviews have compiled LCAs on carbon capture coupled with either storage or utilization [12-15]. A large majority of these LCAs take fossil-fuel power plants as CO_2 emitters. As regards bioenergy with carbon capture, biomass is either the sole fuel or co-fired with fossil fuels for the production of electricity only. In the former case, LCAs focus on comparing power generation technologies and fuels [16-20], whereas the influence of the co-combustion ratio is studied in the latter case [21-23]. Hammar and Levihn's [24] work is an exception in that the influence of a new cogeneration plant is investigated. As in the other bioenergy LCAs, only permanent storage of CO_2 is considered, excluding carbon utilization and temporary storage from the study scope.

To the best of our knowledge, none of the LCAs available in the scientific literature fall within the specific scope of the CO2SERRE project. In order to address the methodological issues raised by the bioenergy–CCUS supply chain and then actually perform the LCA, it seems necessary to draw on the development and application of LCA in other sectors (e.g. crop cultivation, bioenergy).

6.2. Accounting for temporary carbon storage

A key LCA methodological issue raised by the CO2SERRE project is the accounting of temporary carbon storage. It concerns carbon sequestration by trees before their harvest for biomass combustion, by greenhouse crops before human consumption and in buffer reservoirs after carbon capture. Different accounting methods exist. The International Organisation for Standardization considers temporary carbon storage accounting as optional, whereas the International Reference Life Cycle Data System (ILCD) handbook recommends to credit any delayed CO_2 emission by 1 wt% per year of storage to the IPCC Global Warming Potential (GWP) [10, 11, 25]. Carbon dioxide released after 100 years is considered permanently stored. As for the British Standards Institution, its Publicly Available Specification 2050 calculates the credit based on the weighted time average of carbon storage over a 100-year assessment period [26]. Although differences exist in the conceptual framework, the same value as with the ILCD handbook method is obtained.

The major limitation of these institutional recommendations and provisions is the poor integration of CO_2 flow dynamics in the accounting, which has led researchers to develop new methodological tools. The two most advanced ones are dynamic GWP and GWPbio. The dynamic GWP suggested by Levasseur et al. [27] is comprised of an inventory of annually differentiated emissions and a time-dependent impact assessment. The GWPbio developed by Cherubini et al. [28] more specifically estimates the climate impact of CO_2 emissions from biomass combustion. The dynamics of CO_2 sequestration during biomass growth is notably considered via the biomass rotation period.

Considering the lack of consensus on this issue among the LCA community, it seems relevant under the CO2SERRE project to carry out a sensitivity analysis on the accounting methods mentioned above. The robustness of LCA results can thereby be evaluated and contribute to inform decision-makers.

6.3. Ongoing work

LCA methodological issues have so far been raised and addressed, a key one of which is the accounting of temporary carbon storage, as previously discussed. Other issues concern biogenic carbon accounting, multi-functionality and system boundary definition. Work is still ongoing to define the scenarios that will be compared to the business-as-usual scenario (without CCUS) and collect the corresponding data, in particular on the energy source used to power the CCUS supply chain.

7. Techno-economic analysis

The techno-economic analysis (TEA) aims to complement the life-cycle assessment, providing sound economic elements on the project according to the technical scenarios considered. The key results will be an estimation of capital and operational expenditures. Moreover, the introduction of exogenous parameters such as actualization rate or price index tries to address a prospective standpoint and to contribute to a benchmarking of mitigation options, either for states or companies. In this case, the TEA aims to compute abatement cost of CO_2 or net present values.

Although TEA are routinely conducted in many industries, one particularity of BCCUS (capture, use and storage of CO_2 of biomass origin) projects assessments is to evaluate mixed indicators, combining physical flows and economic data. Since LCA is a standardized method and is usually more comprehensive, the TEA has to adapt to its perimeter to produce coherent and comparable results.

7.1. Main economic results on CCS

By now, the economic viability of CCS in its different versions CCUS [31] and BCCS has been largely documented [29] [30], as its ability to drive to negative emissions [32]. They tend to prove that (i) CCS on fossil fuels is a cost minimizing solution in order to conciliate the energy transition with the decay of fossil fuels use[33], (ii) BCCS appears as a way to reach the carbon neutrality of the economies, through its ability to obtain negative emission [32] and (iii) CCUS could contribute to this decarbonation, although on a limited scale [31].

The necessity of CCS is underlined by the IPCC and the IEA, as 14% of the cumulative emissions in the period up to 2060 should be captured to meet the 2 degree scenario [34]. This result is confirmed by several integrated assessment models [35]. Multiples technologies of capture are implemented or in development in various industries (power, iron, cement, paper…).

The impact on the levelized cost of energy for biomass power production is estimated between 30 and 60 \$/MWh, with an abatement cost between 60 and 250 \$/tCO2 [36]. This variability depends heavily on the purity of CO_2 sources, the capture technology and the scale effects of transport and storage.

7.2. Valuing the economic viability of CO2SERRE as a BCCUS project

The techno-economic analysis of the CO2SERRE project will give a new appraisal of this BCCUS project viability, which combines BCCS with the use of carbon as an input for growing plants. It will be the economic counterpart of the LCA which evaluates the global carbon balance of the project. Its overall capture, transport and storage cost will be compared with the actual price already paid by local greenhouse operators.

The first specificity of the CO2SERRE project lies in the use of captured CO_2 for agriculture in greenhouses. Such use already exists wide-scale (OCAP-CO2, Netherlands) but relies on nearly pure streams of CO_2, for which no capture but only compression is required and is carried through former oil pipelines. In our case, the ATE will be useful to assess the competitiveness of biomass power plant carbon.

Given the energy penalty of carbon capture, the second issue is to choose the cost-minimizing technical option for the power producer, who runs 24/7 all year and must meet contractual engagements in terms of productivity with the electrical and heat networks operator.

Notwithstanding these particularities, the TEA shall also give insights on the generalization of negative emissions technologies at a broader scale. It will evaluate the sensibility of the avoided carbon price to the different technical hypothesis of the LCA and to some economic hypothesis, which will be defined by comparison with other prevailing studies in the field of BCCS and CCUS [31]. It will by the end be able to determine at which avoided carbon price could the CO2SERRE lead to negative carbon emission, and in which economic and technical conditions this could be made.

7.3. Comparison with other BCCUS projects

The TEA results will be compared with other BCCUS projects, carried out in other contexts and fields. This comparison will help to determine the possibility of extending the CO2SERRE concept to other local and topical fields. Moreover, benchmarking the CO2SERRE TEA with other case studies will be an insightful way not only for its economic viability, but also to determine the conditions of its economic implementation.

8. Conclusion and perspectives

The CO2SERRE project aims to valorize CO_2 from biomass industries to provide greenhouse growers with a cheap, good-quality and “green” CO_2, with a negative emission balance as this CO_2 is captured from bioenergy sources and the exceeding is stored permanently in saline aquifer. Work carried out so far provides useful insights on technical feasibility of the process for the different steps (capture, transport, geological storage, and use in greenhouses). However, the key challenge is the viability of the project on both economic and environmental sides. The LCA and TEA analyses, taken into account the whole CCUS chain, are under development and their outputs will address conditions for feasibility of the CO2SERRE concept.

A preliminary assessment of geological storage capacity in the region have shown that targeted reservoir would be able to store the equivalent of the total emissions of the region Centre-Val de Loire. Thus, a longer term perspective for CO2SERRE project is to create a new technical and economic network in the region with platforms gathering CO_2 emitter, users and storage. So its design could also be compared with other CCUS or BECCS projects, and be used as a benchmark for future pilots in this promising field.

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