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Coal Bed Methane Decarbonization via CO_2 Capture and Storage and Blue Methane Production

Clodic Denis[1, a)] and Moulin Julien[2, b)]

[1]*Cryo Pur and La Francaise de l'Energie, 4 rue du Vaulorin Wissous 91320 France.*
[2]*La Française de l Energie (FDE), Avenue du District, 57380 Pontpierre, France.*

[a)] *Corresponding author: denis.clodic@cryopur.com*
[b)]*jmoulin@francaisedelenergie.fr*

Abstract. Lorraine underground contains deep coal seams that cannot be mined for regulatory and economic reasons. These coal seams contain methane but are also part of a sedimentary basin (Lorraine basin) able to store millions of CO_2 tons. To compensate all CO_2 emissions related to methane recovery in the deep coal seams, including transport and usages, a Life Cycle Analysis (LCA) is performed to evaluate the CO_2 to be captured and stored locally with the objective of reaching decarbonized methane. The CO_2 capture process used in this setup is the Cryo Pur CO_2 capture process, using only electricity; its related CO_2 emissions are included in the Life Cycle Analysis. Decarbonized methane is a fuel of great interest to produce low carbon blue Hydrogen. An analysis is done in terms of energy efficiency and carbon balance for the production of decarbonized methane and blue hydrogen.

Keywords: Life Cycle Analysis (LCA), CO_2 capture and Storage (CCS), Decarbonized methane, Blue Hydrogen, energy efficiency.

LORRAINE GEOLOGY FOR CO2 STORAGE AND METHANE RECOVERY

The Ademe EVASTOC Lorraine report (Hemelsdael) states that: "Ten zones were delimited within the "Westphalian" and "Stephanian" units by a buffer zone of two kilometers on either side of the major faults. Each zone represents a storage unit with a thickness of between 900 and 3000 meters deep. The average effective porosity is approximately 4 to 7%. Methods 1 and 2 give average storage capacities per sector of between 13 and 620 Mt CO_2 and between 3 and 140 Mt CO_2."

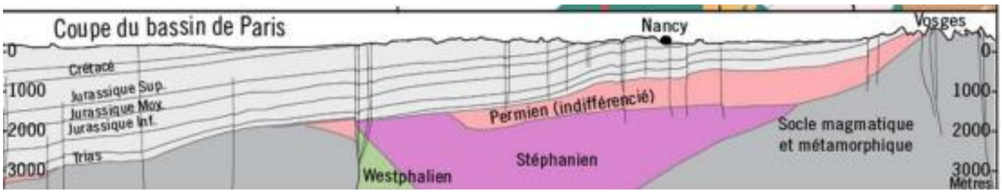

FIGURE 1. Paris Bassin geological section (Hemelsdael).

Those CO_2 storage capacities need additional studies to shrink the lower and the higher thresholds. This evaluation does not consider the potential additional storage in coal seams and in saline aquifers which are not negligible at all.

Coal Seams In Lorraine

It is estimated that the average methane content in Lorraine coal seams is about 20m^3 per ton of coal (Bonijoly) in a more recent study (Amoih) the methane content in Lorraine coal seams is evaluated with a wide variability from 6 to 20 m^3/ton. Coal presents a larger affinity of CO_2 compared to methane, at least 2 to 3 times expressed in mole meaning an affinity of 5 to 8 times when expressed in mass. Enhanced Coal Bed Methane recovery (ECBM) is a technology which gives a value to CO_2 by the enhanced recovery of methane. Several studies establish how CO_2 has a higher affinity with coal compared to methane (Pan et al. 2017, Liu et al, 2022; Li et al.2022) and insist on CO_2 adsorption implies Coal swelling and limits CO_2 adsorption in the first injection phase. We will see in the next section how to decarbonize methane with the minimum CO_2 injection.

POINT SOURCES CARBON CAPTURE IN LORRAINE BY CRYO PUR CRYOGENIC SYSTEM

A national study on the 50 largest industrial CO_2 emitters has been published in 2023, 11 of those are installed in region Grand EST (see FIGURE 2).

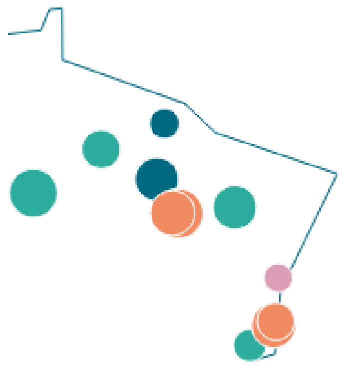

FIGURE 2. Large point sources in Grand EST région (Réseau Action Climat)

Those industries are producing Steel, Cement, Chemical products. Each site emits annually between 150 000 and 450 000 tons/year of CO_2. Each company is developing its own CO_2 abatement policy for most of them, especially for the cement and steel industries, CCS (Carbon Capture and Storage) is one possible option deeply studied. Among the CO_2 capture technologies, Cryo Pur is the only pure electricity process with no heat, leading to a low carbon footprint especially with the French CO_2 content of electricity (15 g/kWh). During the 1st Quarter 2026, Cryo Pur will install a CO_2 capture demonstrator supported by the French Agency Ademe in North of France able to capture 10 000 tons/year of CO_2. In parallel Cryo Pur with its mother company La Francaise de l'énergie ("FDE") studies in region Grand Est several options to **capture CO_2 and store** it locally in the Lorraine sedimentary basin itself. Cryo Pur CO_2 capture process has more than twenty years of experience and industrial operation on recovery of CO_2 mainly on biogas production units, initiated at industrial scale since 2018. The process as shown on Figure 3 cools progressively the flue gases form a typical temperature of 180°C to -125°C and so removes pollutants and water vapor and also recovers CO_2 in liquid state.

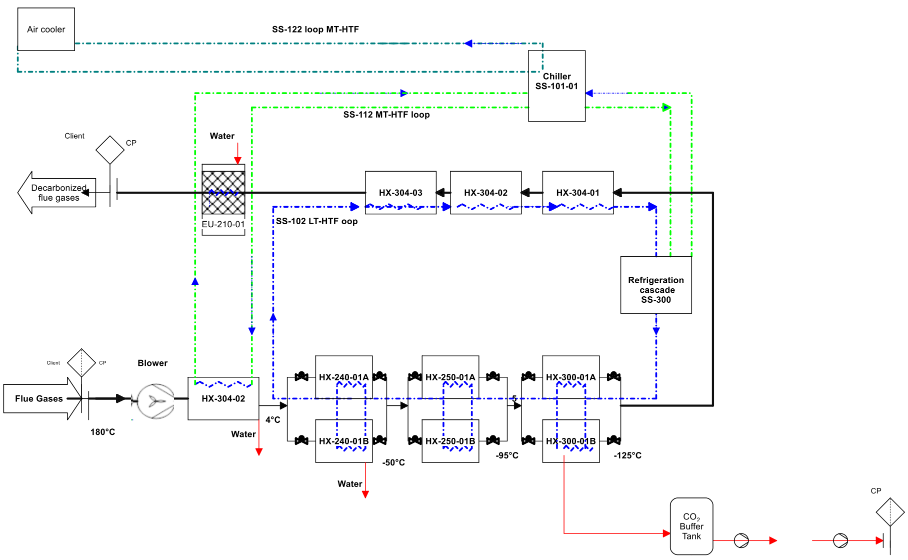

FIGURE 3. Cryo Pur Cryogenic CO_2 capture diagram

Both for water removal and CO_2 capture, the dehumidification and the decarbonization of flue gases is continuous, requiring a swing process where alternately a series of heat exchangers are in frosting mode and the others in defrosting mode. Figures 4 and 5, taken from (Toubassy), show two levels of CO_2 frost on the fins of a frosting heat exchanger.

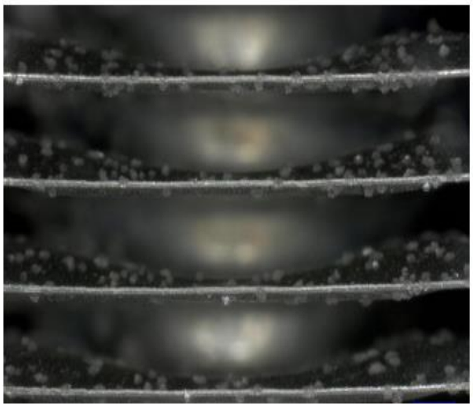

FIGURE 4. Beginning of CO_2 frosting

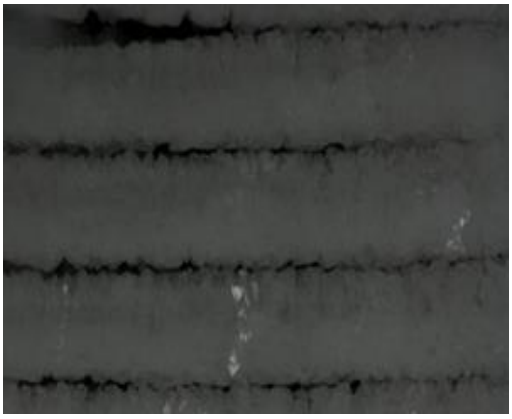

FIGURE 5. Maximum CO_2 frost thickness

When the pressure loss due to the growth of CO_2 ice reaches a predefined level (5 to 10 kPa), the enclosure where the frosting heat exchanger is installed is closed and evacuated to a low-pressure level to eliminate the remaining flue gases. Then "hot" heat transfer fluid at -45°C flows inside the tubes of the fin-and-tube heat exchanger, the delivered heat capacity generates CO_2 sublimation and so, the rise of temperature and pressure inside the enclosure. When the pressure of 5,2 bara is reached, CO_2 begins to melt due to the heat delivered by the heat transfer fluid, melting temperature is constant at -56.6 ° C.

When the melting is achieved, the temperature of the defrosted heat exchanger raises rapidly. So, the control system stops the heat exchanger heating and begins the transfer of liquid CO_2 accumulated at the bottom of the enclosure to the CO_2 storage tank placed below the enclosure. CO_2 is ready to be transported in liquid phase either by trucks for small quantities or by CO_2 pipeline to be injected into the proper wells where CO_2 is stored for long term geological times.

The specific energy consumption for a CO_2 concentration of 15% (v) is 0.52 MWh/ton CO_2, with no need of heat or water and a recovery of CO_2 in liquid state at 99.9% purity.

CO_2 capture and storage is performed locally in order to recover methane (CH_4) trapped in coal seams, producing decarbonized methane as the following LCA (Life Cycle Analysis) will demonstrate. This LCA includes all CO_2 emitted due to the necessary energy for CO2 capture on flue gases, transport, injection, methane recovery and purification, and usages. The assumption is to inject 1 mole of CO_2 to recover 1 mole of methane meaning 44g of CO_2 to recover 16g of cH4. Making the Life cycle analysis of ECBM will assess how deep this fossil methane decarbonization is.

LCA OF DECARBONIZED METHANE AND BLUE HYDROGEN

Blue Methane

This fossil methane decarbonization LCA requires, as said before, analyzing all the steps from the well to its usages, mostly combustion. The following data comes from a BLUNOMY study (Deronzier) performed for FDE.

Table 1 presents the assumptions based on specialized literature.

TABLE 1: Assumptions for CO_2 avoided by capture and CO_2 emitted by Methane recovery

Production LCA	Assumptions	Units
CO2 transport leak	0,14	tCO2/per year and km of pipeline)
Storage leak	0,002%	Leak per Stored CO2 volume
CO2 recovery in liquid stat	No leak	
CO_2 capture efficiency	95%	Mass %
Specific power consumption of Cryo Pur Pocess	0,53	kWh/kCO_2
Specific emission CO2 emission of French electricity	10	gCO_2/kWh

The results on CO_2 emissions are presented in Table 2.

TABLE 2. % of CO_2 emissions for CO_2 recovery transport and injection.

CO2 capture	3,94	% (kgCO_2/kgCaptured CO_2)
Transport	0,069	% (kgCO_2/kgCaptured CO_2)
Storage	0,13	% (kgCO_2/kgCaptured CO_2)
CH4 ECBM	0,81	% (kgCO_2/kgCaptured CO_2)
Total	4,95	% (kgCO_2/kgCaptured CO_2)

Let's take the example of 1kg of methane (CH_4) recovered by CO_2 injected in a coal seam. This CO_2 has been recovered from the flue gases of a natural gas boiler. One kg of burned CH_4 produces 2.75 kg of CO_2 (ratio of the molar mass MCO_2/MCH_4). The CO_2 recovery efficiency is 95%, 2.61 kg of CO_2 are so recovered. o recover 1 kg of methane, 2.75 kg of CO_2 must be injected into the coal seam, for 1 by mole replacement. As presented in Table 2, the CO_2 emissions related to this injected CO_2 is 4,95% of recovered CO_2 i.e. 0.0495 kg/kg or **0.136kg CO_2/kg CH_4.** Considering CH_4 leaks of 0,02% due to the short distance between the CH_4 wells and the gas grid, the CH_4 leaks represents 0,0056kgCO_2/kgCH_4 the total CO_2 content of decarbonized fossil methane is **0,14 kgCO_2/kg CH_4**. Referring this 0.14 kg CO_2/kg CH_4 emissions to the PCI of CH4 (13,9 kWh/kg). The resulting emission of ECBM methane is **10 kgCO_2/MWh** instead of **248 kgCO_2/MWh**[1] for natural gas delivered in the gas grid, **a gain of 96%**.

[1] The combustion of natural gas is emitting 199 kg/MWh, and the total emission of 2023 gas grid in, France is 49 kgCO2/MWh because 60% of the natural is coming from LNG which consumes a high level of energy.

Blue Hydrogen

The European parliament has defined as of December 2021 *low carbon Hydrogen* as "*hydrogen which meets the greenhouse gas emissions reduction of 70% compared to fossil fuel* [production]" Directive EU 2024/1788]. This means that the threshold is set at **3.38 kg eq.CO_2 / kgH_2**.

Taking reference [Howarth 2021] as a guideline, CO_2 emissions per kg of H_2 and per MWh are calculated for the current standard process of Steam Methane Reforming (SMR). The overall equation for H_2 production from methane is:

$CH_4 + 2\ H_2O \rightarrow CO_2 + 4H_2$

Independently of the required energy, based on this reaction, the amount of CO_2 produced during the SMR process is 38,5 gCO_2/MJ. The reaction is incomplete, so 14.04 gCH_4/MJ are consumed instead of 16 gCH_4/MJ. The necessary energy for H_2 production by SMR is 2,25 kWh /m^3H_2 equivalent to 91,3 MJ/kg H_2 which requires burning 1,83 kgCH_4/kgH_2. Table 3 summarizes the mass of CH_4 necessary to produce 1 kg of H_2.

TABLE 3. Methane consumption for producing 1 kg H_2

Reaction CH4 consumption (kg)	14,04
H2 production from CH4	8,06
kg CH4 /kg H2 (reaction)	1,74
kg CH4 /kg H2 (Heat)	1,83
Total kg CH4/kg H2	3,57

Those 3,57 kg of CH_4 necessary for production 1kg H_2 are low carbon content CH_4 at 0.14 kgCO_2/kg CH_4, as presented above. Table 4 presents the CO_2 emissions for H_2 produced by SMR from decarbonized methane.

TABLE 4. CO_2 content of H_2 produced from decarbonized Methane

Reaction CO2 emissions kgCO2/kg H2	0,244
Heat CO2 emissions kgCO2/kg H2	0,701
Total CO2 (kgCO2/kgH2)	0,945
kgCO2/MWh	35,67

Using locally decarbonized methane leads to producing low carbon hydrogen **at 0,945 kgCO_2/kg H_2** much lower than the regulatory European threshold of 3,38 kgCO_2/kgH_2.

DISCUSSION

As stressed in the above-mentioned scientific literature, each type of coal requires a local study to establish the possible CO_2 stored quantity as well as the dynamic of the CO_2 adsorption in the coal seam. Currently the Geologists: J. Pironon and Ph. De Donato of GeoRessources (University of Nancy) are developing a new campaign of measures in Lorraine to assess the methane resources and CO_2 adsorption potential in coal seams. The Lorraine saline deep aquifers are at pH 9 gives another CO_2 storage capacity associated with long term mineralization.

CONCLUSION

Decarbonized methane recovered by ECBM (Blue Methane), is combustible which can be burned as usual, but its low carbon value presents a significant interest for all industries aiming at lowering their carbon footprint such as the steel, cement and chemicals industries. Its low carbon value should be recognized by rule makers as one of the solutions for industry CO_2 abatement. Blue methane is also an economic advantage for producing blue hydrogen, the decarbonization being made upstream. Blue methane will become a decarbonized commodity with multiple usages and so acceptable cost. Moreover, ECBM gives value to geological storage and not only cost, ECBM could be the basis for the development of CCS strategy in Europe.

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