

# Coal Bed Methane Decarbonization via CO<sub>2</sub> Capture and Storage and Blue Methane Production

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**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<sub>2</sub> tons. To compensate all CO<sub>2</sub> 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<sub>2</sub> to be captured and stored locally with the objective of reaching decarbonized methane. The CO<sub>2</sub> capture process used in this setup is the Cryo Pur CO<sub>2</sub> capture process, using only electricity; its related CO<sub>2</sub> 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<sub>2</sub> capture and Storage (CCS), Decarbonized methane, Blue Hydrogen, energy efficiency.

## LORRAINE GEOLOGY FOR CO<sub>2</sub> 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<sub>2</sub> and between 3 and 140 Mt CO<sub>2</sub>.”

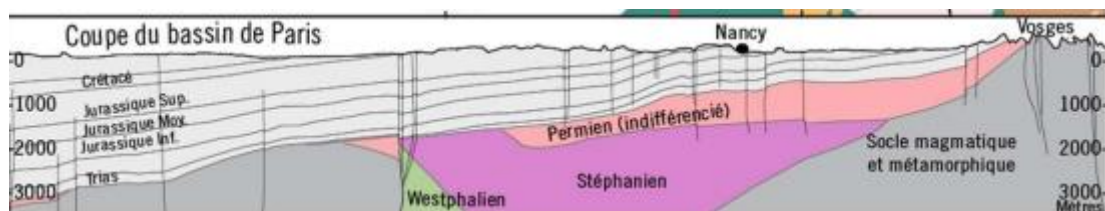


FIGURE 1. Paris Bassin geological section (Hemelsdael).

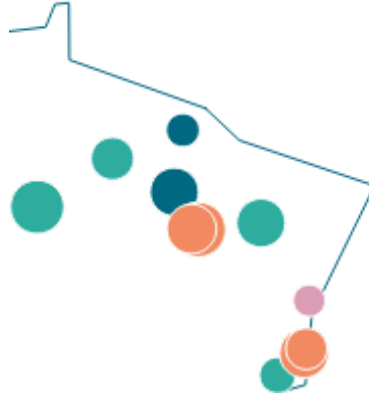
Those CO<sub>2</sub> storage capacities need additional studies to shrink the lower and the higher thresholds. This evaluation does not consider the potential additional storage in coal seams and in saline aquifers which are not negligible at all.

## Coal Seams In Lorraine

It is estimated that the average methane content in Lorraine coal seams is about 20m<sup>3</sup> 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<sup>3</sup>/ton. Coal presents a larger affinity of CO<sub>2</sub> 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<sub>2</sub> by the enhanced recovery of methane. Several studies establish how CO<sub>2</sub> 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<sub>2</sub> adsorption implies Coal swelling and limits CO<sub>2</sub> adsorption in the first injection phase. We will see in the next section how to decarbonize methane with the minimum CO<sub>2</sub> injection.

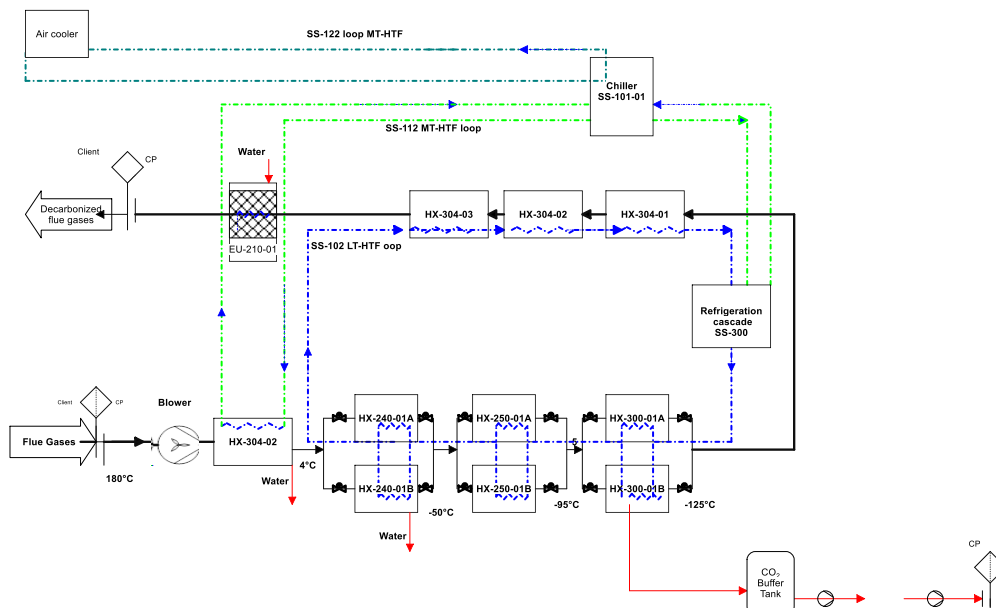
## POINT SOURCES CARBON CAPTURE IN LORRAINE BY CRYO PUR CRYOGENIC SYSTEM

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



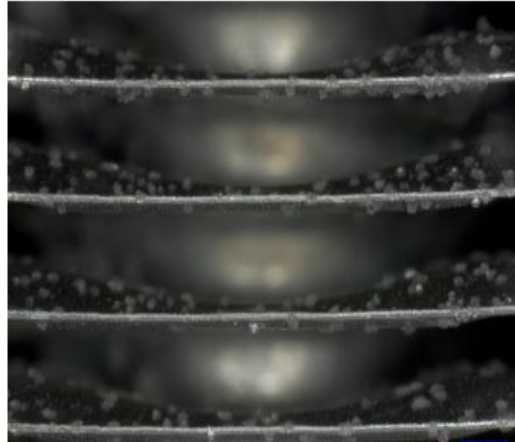
**FIGURE 2.** Large point sources in Grand EST région (Réseau Action Climat)

Those industries are producing Steel, Cement, Chemical products. Each site emits annually between 150 000 and 450 000 tons/year of CO<sub>2</sub>. Each company is developing its own CO<sub>2</sub> 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<sub>2</sub> capture technologies, Cryo Pur is the only pure electricity process with no heat, leading to a low carbon footprint especially with the French CO<sub>2</sub> content of electricity (15 g/kWh). During the 1<sup>st</sup> Quarter 2026, Cryo Pur will install a CO<sub>2</sub> capture demonstrator supported by the French Agency Ademe in North of France able to capture 10 000 tons/year of CO<sub>2</sub>. In parallel Cryo Pur with its mother company La Française de l'énergie ("FDE") studies in region Grand Est several options to **capture CO<sub>2</sub> and store** it locally in the Lorraine sedimentary basin itself. Cryo Pur CO<sub>2</sub> capture process has more than twenty years of experience and industrial operation on recovery of CO<sub>2</sub> mainly on biogas production units, initiated at industrial scale since 2018. The process as shown on Figure 3 cools progressively the flue gases from a typical temperature of 180°C to -125°C and so removes pollutants and water vapor and also recovers CO<sub>2</sub> in liquid state.

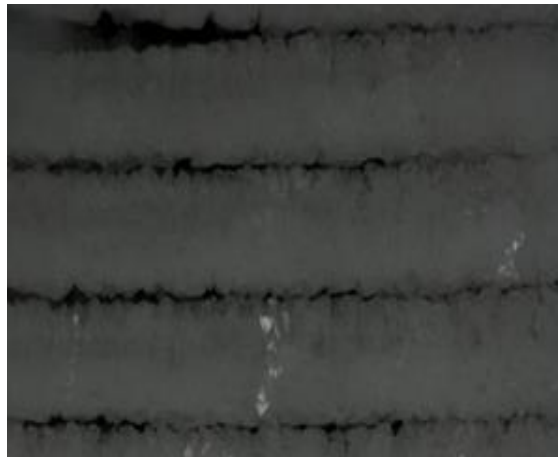


**FIGURE 3.** Cryo Pur Cryogenic CO<sub>2</sub> capture diagram

Both for water removal and CO<sub>2</sub> 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<sub>2</sub> frost on the fins of a frosting heat exchanger.



**FIGURE 4.** Beginning of CO<sub>2</sub> frosting



**FIGURE 5.** Maximum CO<sub>2</sub> frost thickness

When the pressure loss due to the growth of CO<sub>2</sub> 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<sub>2</sub> sublimation and so, the rise of temperature and pressure inside the enclosure. When the pressure of 5,2 bara is reached, CO<sub>2</sub> 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<sub>2</sub> accumulated at the bottom of the enclosure to the CO<sub>2</sub> storage tank placed below the enclosure. CO<sub>2</sub> is ready to be transported in liquid phase either by trucks for small quantities or by CO<sub>2</sub> pipeline to be injected into the proper wells where CO<sub>2</sub> is stored for long term geological times.

The specific energy consumption for a CO<sub>2</sub> concentration of 15% (v) is 0.52 MWh/ton CO<sub>2</sub>, with no need of heat or water and a recovery of CO<sub>2</sub> in liquid state at 99.9% purity.

CO<sub>2</sub> capture and storage is performed locally in order to recover methane (CH<sub>4</sub>) trapped in coal seams, producing decarbonized methane as the following LCA (Life Cycle Analysis) will demonstrate. This LCA includes all CO<sub>2</sub> emitted due to the necessary energy for CO<sub>2</sub> capture on flue gases, transport, injection, methane

recovery and purification, and usages. The assumption is to inject 1 mole of CO<sub>2</sub> to recover 1 mole of methane meaning 44g of CO<sub>2</sub> to recover 16g of CH<sub>4</sub>. 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<sub>2</sub> avoided by capture and CO<sub>2</sub> emitted by Methane recovery

Production LCA	Assumptions	Units
CO <sub>2</sub> transport leak	0,14	tCO <sub>2</sub> /per year and km of pipeline)
Storage leak	0,002%	Leak per Stored CO <sub>2</sub> volume
CO <sub>2</sub> recovery in liquid stat	No leak	
CO <sub>2</sub> capture efficiency	95%	Mass %
Specific power consumption of Cryo Pur Pocess	0,53	kWh/kCO <sub>2</sub>
Specific emission CO <sub>2</sub> emission of French electricity	10	gCO <sub>2</sub> /kWh

The results on CO<sub>2</sub> emissions are presented in Table 2.

**TABLE 2.** % of CO<sub>2</sub> emissions for CO<sub>2</sub> recovery transport and injection.

CO <sub>2</sub> capture	3,94	% (kgCO <sub>2</sub> /kgCaptured CO <sub>2</sub> )
Transport	0,069	% (kgCO <sub>2</sub> /kgCaptured CO <sub>2</sub> )
Storage	0,13	% (kgCO <sub>2</sub> /kgCaptured CO <sub>2</sub> )
CH <sub>4</sub> ECBM	0,81	% (kgCO <sub>2</sub> /kgCaptured CO <sub>2</sub> )
Total	4,95	% (kgCO <sub>2</sub> /kgCaptured CO <sub>2</sub> )

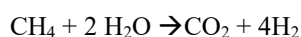
Let's take the example of 1kg of methane (CH<sub>4</sub>) recovered by CO<sub>2</sub> injected in a coal seam. This CO<sub>2</sub> has been recovered from the flue gases of a natural gas boiler. One kg of burned CH<sub>4</sub> produces 2.75 kg of CO<sub>2</sub> (ratio of the molar mass MCO<sub>2</sub>/MCH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

<sup>1</sup> The combustion of natural gas is emitting 199 kg/MWh, and the total emission of 2023 gas grid in, France is 49 kgCO<sub>2</sub>/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<sub>2</sub> / kgH<sub>2</sub>**.

Taking reference [Howarth 2021] as a guideline, CO<sub>2</sub> emissions per kg of H<sub>2</sub> and per MWh are calculated for the current standard process of Steam Methane Reforming (SMR). The overall equation for H<sub>2</sub> production from methane is:



Independently of the required energy, based on this reaction, the amount of CO<sub>2</sub> produced during the SMR process is 38,5 gCO<sub>2</sub>/MJ. The reaction is incomplete, so 14.04 gCH<sub>4</sub>/MJ are consumed instead of 16 gCH<sub>4</sub>/MJ. The necessary energy for H<sub>2</sub> production by SMR is 2,25 kWh /m<sup>3</sup>H<sub>2</sub> equivalent to 91,3 MJ/kg H<sub>2</sub> which requires burning 1,83 kgCH<sub>4</sub>/kgH<sub>2</sub>. Table 3 summarizes the mass of CH<sub>4</sub> necessary to produce 1 kg of H<sub>2</sub>.

**TABLE 3.** Methane consumption for producing 1 kg H<sub>2</sub>

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<sub>4</sub> necessary for production 1kg H<sub>2</sub> are low carbon content CH<sub>4</sub> at 0.14 kgCO<sub>2</sub>/kg CH<sub>4</sub>, as presented above. Table 4 presents the CO<sub>2</sub> emissions for H<sub>2</sub> produced by SMR from decarbonized methane.

**TABLE 4.** CO<sub>2</sub> content of H<sub>2</sub> 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<sub>2</sub>/kg H<sub>2</sub>** much lower than the regulatory European threshold of 3,38 kgCO<sub>2</sub>/kgH<sub>2</sub>.

## DISCUSSION

As stressed in the above-mentioned scientific literature, each type of coal requires a local study to establish the possible CO<sub>2</sub> stored quantity as well as the dynamic of the CO<sub>2</sub> 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<sub>2</sub> adsorption potential in coal seams. The Lorraine saline deep aquifers are at pH 9 gives another CO<sub>2</sub> 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<sub>2</sub> 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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