**Coal Bed Methane Decarbonization via CO2 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 CO2 tons. To compensate all CO2 emissions related to methane recovery in the deep coal seams, including transport and usages, a Life Cycle Analysis (LCA) is performed to evaluate the CO2 to be captured and stored locally with the objective of reaching decarbonized methane. The CO2 capture process used in this setup is the Cryo Pur CO2 capture process, using only electricity; its related CO2 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), CO2 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 CO2 and between 3 and 140 Mt CO2.”

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**FIGURE 1.** Paris Bassin geological section (Hemelsdael).

Those CO2 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 20m3 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 m3/ton. Coal presents a larger affinity of CO2 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 CO2 by the enhanced recovery of methane. Several studies establish how CO2 has a higher affinity with coal compared to methane (Pan et al. 2017, Liu et al, 2022; Li et al.2022) and insist on CO2 adsorption implies Coal swelling and limits CO2 adsorption in the first injection phase. We will see in the next section how to decarbonize methane with the minimum CO2 injection.

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

A national study on the 50 largest industrial CO2 emitters has been published in 2023, 11 of those are installed in region Grand EST (see FIGURE 2).

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**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 CO2. Each company is developing its own CO2 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 CO2 capture technologies, Cryo Pur is the only pure electricity process with no heat, leading to a low carbon footprint especially with the French CO2 content of electricity (15 g/kWh). During the 1st Quarter 2026, Cryo Pur will install a CO2 capture demonstrator supported by the French Agency Ademe in North of France able to capture 10 000 tons/year of CO2. In parallel Cryo Pur with its mother company La Francaise de l’énergie (“FDE”) studies in region Grand Est several options to **capture CO2 and store** it locally in the Lorraine sedimentary basin itself. Cryo Pur CO2 capture process has more than twenty years of experience and industrial operation on recovery of CO2 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 CO2 in liquid state.



**FIGURE 3**. Cryo Pur Cryogenic CO2 capture diagram

Both for water removal and CO2 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 CO2 frost on the fins of a frosting heat exchanger.

Close-up of a metal ventilator

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**FIGURE 4.** Beginning of CO2 frosting

A close-up of a wall

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**FIGURE 5.** Maximum CO2 frost thickness

When the pressure loss due to the growth of CO2 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 CO2 sublimation and so, the rise of temperature and pressure inside the enclosure. When the pressure of 5,2 bara is reached, CO2 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 CO2 accumulated at the bottom of the enclosure to the CO2 storage tank placed below the enclosure. CO2 is ready to be transported in liquid phase either by trucks for small quantities or by CO2 pipeline to be injected into the proper wells where CO2 is stored for long term geological times.

The specific energy consumption for a CO2 concentration of 15% (v) is 0.52 MWh/ton CO2, with no need of heat or water and a recovery of CO2 in liquid state at 99.9% purity.

CO2 capture and storage is performed locally in order to recover methane (CH4) trapped in coal seams, producing decarbonized methane as the following LCA (Life Cycle Analysis) will demonstrate. This LCA includes all CO2 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 CO2 to recover 1 mole of methane meaning 44g of CO2 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 CO2 avoided by capture and CO2 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 |  |
| CO₂ capture efficiency | 95% | Mass % |
| Specific power consumption of Cryo Pur Pocess | 0,53 | kWh/kCO₂ |
| Specific emission CO2 emission of French electricity | 10 | gCO2/kWh |

The results on CO2 emissions are presented in Table 2.

## **TABLE 2.** % of CO2 emissions for CO2 recovery transport and injection.



Let’s take the example of 1kg of methane (CH4) recovered by CO2 injected in a coal seam. This CO2 has been recovered from the flue gases of a natural gas boiler. One kg of burned CH4 produces 2.75 kg of CO2 (ratio of the molar mass MCO2/MCH4). The CO2 recovery efficiency is 95%, 2.61 kg of CO2 are so recovered. o recover 1 kg of methane, 2.75 kg of CO2 must be injected into the coal seam, for 1 by mole replacement. As presented in Table 2, the CO2 emissions related to this injected CO2 is 4,95% of recovered CO2 i.e. 0.0495 kg/kg or **0.136kg CO2/kg CH4.** Considering CH4 leaks of 0,02% due to the short distance between the CH4 wells and the gas grid, the CH4 leaks represents 0,0056kgCO2/kgCH4 the total CO2 content of decarbonized fossil methane is **0,14 kgCO2/kg CH4**. Referring this 0.14 kg CO2/kg CH4 emissions to the PCI of CH4 (13,9 kWh/kg). The resulting emission of ECBM methane is **10 kgCO2/MWh** instead of **248 kgCO2/MWh[[1]](#footnote-1)** for natural gas delivered in the gas grid, **a gain of 96%**.

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.CO2 / kgH2**.

Taking reference [Howarth 2021] as a guideline, CO2 emissions per kg of H2 and per MWh are calculated for the current standard process of Steam Methane Reforming (SMR). The overall equation for H2 production from methane is:

CH4 + 2 H2O 🡪CO2 + 4H2

Independently of the required energy, based on this reaction, the amount of CO2 produced during the SMR process is 38,5 gCO2/MJ. The reaction is incomplete, so 14.04 gCH4/MJ are consumed instead of 16 gCH4/MJ. The necessary energy for H2 production by SMR is 2,25 kWh /m3H2 equivalent to 91,3 MJ/kg H2 which requires burning 1,83 kgCH4/kgH2. Table 3 summarizes the mass of CH4 necessary to produce 1 kg of H2.

## **TABLE 3**. Methane consumption for producing 1 kg H2



Those 3,57 kg of CH4 necessary for production 1kg H2 are low carbon content CH4 at 0.14 kgCO2/kg CH4, as presented above. Table 4 presents the CO2 emissions for H2 produced by SMR from decarbonized methane.

## **TABLE 4**. CO2 content of H2 produced from decarbonized Methane



Using locally decarbonized methane leads to producing low carbon hydrogen **at 0,945 kgCO2/kg H2** much lower than the regulatory European threshold of 3,38 kgCO2/kgH2.

### **DISCUSSION**

As stressed in the above-mentioned scientific literature, each type of coal requires a local study to establish the possible CO2 stored quantity as well as the dynamic of the CO2 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 CO2 adsorption potential in coal seams. The Lorraine saline deep aquifers are at pH 9 gives another CO2 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 CO2 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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1. [↑](#footnote-ref-1)