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CO₂ geological storage by ECBM techniques in the Sulcis area (SW Sardinia Region, Italy)

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Abstract:

An ECBM (Enhanced Coal Bed Methane as evolution of CBM techniques) pre-feasibility study started for the *Sulcis Coal Province* in December 2004 on the basis of the experience gathered: 1) by INGV, from ongoing and past projects dealing with CO₂ geological storage, i.e., Weyburn test-field (Canada) by EOR techniques and from the studies of “CO₂ analogues” in Italy; 2) by the coal industry of the Sulcis Province (Sotacarbo S.p.A. & Carbosulcis S.p.A.); 3) by ETH – Zurich, specifically on the coal adsorption properties, and 4) by IES S.r.l. reservoir engineering and gas storage industrial activity.

This paper discusses the state of art of the project in the frame of the worldwide ECBM projects as a whole, on the basis of the yet acquired information and available experimental data. Environmental impact considerations are highlighted on the basis of the available Italian legal tools, giving hints for future EU, Italian and new regional legislation and strategies. A new concept of CO₂ as “no waste” product in the coal/hydrocarbons provinces for ECBM/EOR exploitation is depicted, defining CO₂ a “*natural climate-alterant factor*”.

Geochemical, structural-geology, stratigraphic and reservoir engineering considerations are discussed. The first newly gathered experimental data, including CO₂/CH₄ coal adsorption capacity data are showed, even if they are preliminary.

Starting from the geological and logistical available data, a MapInfo GIS structure was built up, to be jointed later to other EC “CO₂ storage” data-GIS as the GETSCO EC project structure. The most important objective of this Phase I is the selection of the best for a ECBM test-pilot site, which will be followed (Phase II) by scaled up site and possibly by a future network (Phase III); these phases are foreseen to be accompanied by the selection of the progressively added CO₂ industrial sources (inserted in the Map-info GIS) to be used within the project economic spreadsheet model.

CO₂ geological storage in Sardinia is evaluated as a whole, considering the seismotectonic framework and the CO₂ industrial sources available or foreseen in the next years.

1. Introduction

Broadly speaking, all ways of converting fossil fuels, *Clean Coal Technologies* (CCT onward), including the “*Hydrogen Carrier*” from fossil fuels produce a waste stream containing variable quantities of CO₂.

The potential storage of CO₂ in Italy has never been fully evaluated, but we are convinced that a general Italian survey could be helped by test-sites studies, as ECBM ones, and the two research activities could be parallel (Quattrocchi, 1999; Pizzino et al., 2002; Quattrocchi et al., 2003, 2004 a; Angelone et al., 2004; Miller et al., 2004; Voltattorni et al., 2005).

Soon after the first challenging scientific results (Law et al., 2001; Wong et al., 1999, 2001; Mavor et al., 1999; 2002; 2004 a,b; Mac Donald et al., 2003; Gunter et al., 2004) coming from the ECBM scientific Community, strongly busy for the proximal ratification of the *Kyoto Agreement* (occurred

in February 2005), as presented mostly at the GHGT international conferences since 1999 (*Green House Gas Control Technologies*), ECBM production (Fig. 1) and some challenging pilot-test projects and feasibility studies on ECBM built-up worldwide (Krooss et al., 2002; Busch et al., 2003, 2004; NOVEM, 2001, 2003; Yamaguchi et al., 2004; McIntyre et al., 2004; Reeves, 2004; Carroll and Pashin, 2004; Groshong et al., 2004; Gunter and Chalaturnyk, 2004; Su et al., 2005).

Using technologies as EOR and ECBM (Fig. 2), it is possible to capture this stream, inject it underground and effectively store it (Srivastava et al., 2000; Walik & Islam, 2000; Gunter et al., 1993; 1997 a-b, 2000; 2004; Emberley et al. 2003, NOVEM 2003, Riding et al. 2003; Wilson & Monea, 2004; White et al., 2004; IPCC Report 2005 in press;). NOVEM (The Netherlands) coordinates the European strategy of ECBM, assisted by TNO (NOVEM, 2001). In Europe, the most important ECBM project is RECOPOL (coordinator: TNO-NITG) aimed at the reduction of CO₂ emission by means of CO₂ storage in coal seams of the Silesian Basin, Poland; while other feasibility studies are starting (Allison Unit, USA by Burlington Resources, Upper-Silesian Basin and Slask, RECOPOL by TNO & partners; Red Deer and Fenn Big Valley by ARC Canada, Quinshui Basin, by ARC-CUCBM, etc....).

Coal has enormous advantages over all the other potential CO₂ repositories because it is present worldwide (there are reserves in almost one hundred countries), it maintains stable prices, and it is a resource to be exploited in order to avoid the dependence from other fuels.

In Italy, significant coal reserves are not present with the exception of the *Sulcis Coal Province* (Sardinia), which is not yet exhausted. The Sulcis region occupies the southwestern end of Sardinia, from the valley of the Cixerri River to the Gulf of Palmas in front of which the isles of San Pietro and Sant-Antioco are located.

The Sulcis Coal Province is yet exploited since the end of the last century (160 years of activity) by mining shallow coal beds at the beginning. In the last months of 1936, the Italian Coal Firm (A.Ca.I) started to exploit the Sirai-Serbariu coal field. After an initial period of intense extractive activity during the second World War, production slowed remarkably. In the 1950's and 1960's, there was renewed activity, as the Sulcis Tertiary coal represented the only coal available in Italy for the renewal of the national industry. *The Sulcis Coal Province* and in particular the *Gonnesa Basin* (as minable around 100 Km²) was managed in the past, before the *Carbosulcis S.p.A.*, by *AGIP Carboni* and *ENEL Carbone* (the first 500 m deep strata, foreseen as 60•10⁶ tonn minable, actually by the *Carbosulcis S.p.A.* facilities). Nowadays the interest for the Sulcis coal is rising again and also the reservoir data were reworked (Carbosulcis, 1994). The reservoir data, available at the *Regional Minerary Office*.

ECBM techniques (suitable for un-minable coal beds, as *Enhanced Coal Bed Methane*) may provide net storage of CO₂, if applied in a coal province such as Sulcis (SW Sardinia Region): it could have very interesting CO₂ storage potential, as high as tens of Million tons of CO₂ stored in a single reservoir. At the same time the CBM production could be not insignificant.

Since November, 2004 a consortium of private companies (*Sotacarbo S.p.A.*, *Carbosulcis S.p.A.*, I.E.S. S.r.l. and other minor contractors) as well as public research institutions, like INGV, ETHZ and University of Cagliari, jointed together to start a feasibility study of the *ECBM Sulcis PROMECAS* Project. The jointed consortium, is a good example of cooperation between a coal industry (*Carbosulcis S.p.A.*), a coal exploitation promotion company (*Sotacarbo S.p.A.*), a gas-storage reservoir-engineering little enterprise (IES. s.r.l.) and research & monitoring public institutions (INGV in Italy, ETHZ in Switzerland and universities). INGV started to model and monitor CO₂ storage test-sites since 2000 (Riding et al., 2003; Strutt et al., 2003, 2004; Jones et al., 2005; Quattrocchi et al., 2004 a, 2005), while ETH Zurich (Swiss) started during '90 to study in details the adsorption-desorption processes on different solid materials, including silica gel, zeolites, activated carbon and coal (Di Giovanni et al. 2001, Rajendran et al. 2002, Hocker et al. 2003).

The project has the main objectives: *i*) to evaluate the ECBM technique throughout the *Sulcis Coal Province* as a whole (SW Sardinia Island, Italy, Sulcis Basin, more than 1400 Km² wide totally divided in 725 Km² in-shore and 730 Km² off-shore), adjacent to the *Carbosulcis S.p.A.* coal mining concession of 550 Km². It is N-S oriented, limited westward by the sea. Apart the CO₂ storage final

Tests, analysis and procedures (Lab and Field) for characterization of Sulcis' Coal Bed

Table 1: Lab Tests:

<i>Test</i>	<i>Objectives</i>	<i>Equipment</i>	<i>Sample</i>	<i>Features</i>
A) Moisture Equilibrium	To know the moisture content equilibrium and use this value in the calculations	See ASTM D 1412 - 93	Crushed coal	Carried out w/ standard test (30° C an 96-97% humidity) ASTM D 1412-93
B) Moisture content	To determinate the actual coal moisture content, so that the test are carried out under more accurate conditions	See DIN 51718	Crushed coal (from core samples or drill cuttings)	Carried out w/ test DIN 51718 as soon as possible after sampling.
C) High pressure adsorption and desorption	To calculate the Langmuir Isotherms. To determinate the excess sorption capacity of the coal (for different gases). To know the hypothetical desorption and verify hysteresis effects.	- Stainless-steel cell - Set of actuator – driven valves - A high precision pressure transducer - A 24 µm filter - Thermostatic oven	Dried or moist (at equilibrium) powdered coal. Mined or surface fresh coal can be used (Only if it represents truly the coal bed). Long storage produces oxidation that could reduce sorption capacity.	Desorption is measured immediately after the corresponding sorption isotherms. Usually Langmuir model is used. It is necessary to correct the obtain Absorbed Volume with the density of the sorbed phase. Finely ground coal particles are typically used in order to reach the equilibrium in a practical amount of time. Isotherms for CH ₄ , CO ₂ and mixtures are calculated.
D) Desorption by direct methods	To know the amount of gas spontaneously released in the time (desorption rate – gas diffusivity). To estimate the gas in place	- Gas-tight container (Stainless-steel) - Graduate Cylinder or burettes - Pressure transducer	Conventional core samples or drill cuttings. In order to know the real gas content in the coal, pressure cores is preferred (even if more expensive).	The more useful method in industrial activities is the USBM method. Pressure cores are samples sealed downhole. Cores as large as possible (preferably 7.6 to 10.2 cm). With pressure samples lost gas is largely less.
E) Core-flooding (CO ₂ injection test)	To determine the swelling behavior, CO ₂ -CH ₄ real sorption-desorption ratio, dewatering rates, production of CH ₄ .	- Stainless – steel cell (internal radius at least 1.5 times the core radio). - Thermostatic oven - Rubber sleeve - Pumps	Conventional core samples.	It is a physical simulation of the coal bed that allows to know the actual process occurring at reservoir conditions.

		- Pressure transducer		
F) Coal characterization	To identify the main properties and parameters of coal	Depending on kind of experiment.	Core samples or powdered coal.	Carried out after sorption/desorption test. These test include: Maceral and rank analysis, NMR pore size distribution, Hg capillary pressure. These experiments deliver fundamental knowledge about, for example, the permeability, cleat orientation and swelling behavior.
Table 2 Field Procedures and Tests:				
Test	Objectives	Equipment	Sample	Features
G) Coring	To retrieve representative samples of coal reflecting in situ conditions.	Core barrel Field equipments	Pressure, drilling or wall cores (pressure coring is better even if expensive)	- Use a non reactive drilling fluid (pH 5.5 – 7.5) - Retrieving samples as large as possible, preferably 7.6 – 10.2 mm (better for determining cleat permeability effects in the lab tests). - If possible, use a wireline retrievable split core barrel, so that reduce time trip.
H) Logs	To collect information about the coal bed, such as water and gas saturation, permeability, geology.	Logs devices	N/A	
I) DST	To obtain data about water and gas permeability, skin, pressures, composition and flow rates.	DST string	N/A	Usual sequence: 1. Initial flow 15 min 2. Initial shut-in 30 min. 3. Intermediate flow 60 – 90 min. 4. Intermediate shut-in 120 – 240 min. 5. Stop/Slug test injection 60-120 min. 6. Final shut-in 120 – 240 min.
Modeling:				
J) Numerical simulation	To represent the reservoir behavior and to match lab results	Conventional or applied reservoir simulators (STARS, GSM, Eclipse, etc)	Model grid	It is carried out with the collected data from lab test, coal characterization and field test. The process permits forecasting the gas production, the pressure drop and the CO ₂ amount to be stored.

objective, the project have in mind to help the initial project economics by producing industrially CH₄, also, if necessary, starting with the CBM techniques as a whole, injecting different proportions of CO₂ and N₂ respectively or, if it is possible the real flue-gas from power plants (foreseen as 17,35% CO₂, 3,35 % O₂, 75,02 % N₂, 0,89 % Ar, 3,38% H₂) for the Sulcis SU3 which will be the most candidate CO₂ source of the project, Pettinau & Meloni, 2005)

The project, at least three years long, foresees: *i*) the complete feasibility study for CBM at different depths (500-1000 mt) but mostly for ECBM techniques development for the coalbed methane strata deeper than 800 m (in continuity below the sea arm which separate the Sardinia island from the S. Pietro island), as requested to inject CO₂ at supercritical conditions. Around 10⁸ tons of coal are foreseen useful for the ECBM exploitation and *ii*) the first test wells drilling (a single set of CO₂ injection and CH₄ production wells, see the figure after). Scaled test-sites and ECBM network will be provided by a further “operative” project, foreseen starting on 2008 just in correspondence of the coal-SULCIS Power plant exploitation (see paragraph and Pettinau and Meloni, 2005).

The anthropogenic sources of CO₂ of the Sardinia Island and in particular those close the *Sulcis Coal Province*, operative within 2009 in the frame of the *CCT* exploitation (Pettinau & Meloni, 2005) are inserted in the MapInfo GIS and discussed in the frame project to allow economic evaluations by an optimization of distances/flue gas quality/compression devices as well as pipelines optimization: CO₂ is very sound to be transported by dry CO₂ pipelines, being the the catalogued plants located only at around 100 Km from the *Sulcis Coal Province*.

The overall project intends both to create the first large-scale European ECBM operative site, and to reduce the GHG emissions in a strategic touristic and clean coal area. In the mean time the project could re-pay the first investments by producing coalbed methane (CBM) from un-minable coal beds. In case of CBM exploitation only, the methane extraction could be very useful to avoid *grusù* problems, in some sectors of the coal province before future deep mining activities.

At the end of the ECBM exploitation (i.e. 20-30 years foreseen), the *Sulcis Coal Province* deeper strata will remain available for further CO₂ geological storage (“saline aquifer” modality, Gunter et al., 1993; 1997 a-b; 2000; Angelone et al., 2005), if the storage potential and WRI conditions will be sound, as deepened by this feasibility study. At the moment the known litho-stratigraphy (up to -800 m from the s.l.m.) and fluid geochemistry data seems to be good as regards the CO₂ buffer capacity for long term CO₂ geological storage.

2. The CBM and ECBM techniques

The most important example of ECBM production is the Allison Unit CO₂ enhanced coalbeds methane recovery pilot project (Shi et al., 2004, Fig. 1 and 3), located in Northern New Mexico portion of the San Juan Basin, USA (242 MI m³ of CH₄ per Km²), operated by Burlington Resources, a little but dynamic reservoir engineers industry. Production from the Allison Unit started in 1989 while ECBM began in April 1995 and suspended in 2001 (Fig. 1). The CO₂ source was from McElmo Dome in Colorado, through a Shell pipeline at 10.4 MPa (6.4 Bcf of CO₂ injected in 6 years with a net storage volume of 277,000 tons of carbon dioxide, www.coal-seq.com). The increase of methane recovery from estimated 77% of original gas in place to 95% of the original gas in place, within the affected area. The average production arrived to = 3,7 MI m³ in 6 years corresponding to 1630 m³/day (around 10 times less than a natural gas reservoir in production).

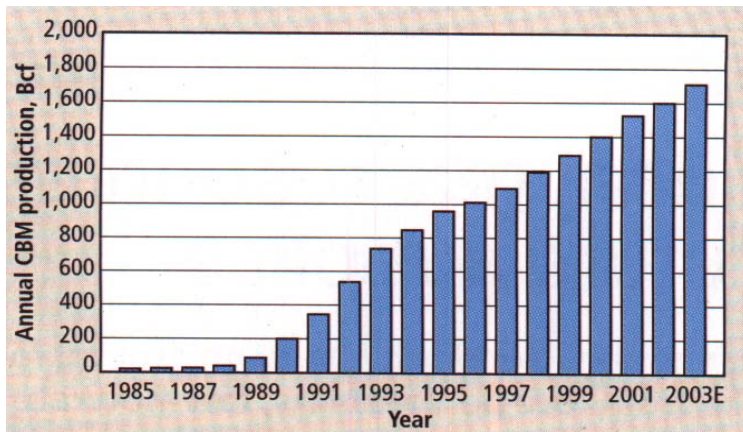


Fig. 1: United States CBM production from 1985 to 2003.

	Storage mechanism	Benefits	Limitations
EOR	physical & mineral trapping	0.33-0.42 t oil/t CO ₂	<ul style="list-style-type: none"> ▪ oil gravity at least 25° API ▪ primary and secondary recovery methods have been applied ▪ limited gas cap ▪ oil reservoir at least 600 meters deep ▪ local CO₂ availability
EGR	physical & mineral trapping	0.03-0.05 t CH ₄ /t CO ₂	<ul style="list-style-type: none"> ▪ depleted gas field ▪ local CO₂ availability
ECBM	physical & chemical binding	0.08-0.20 t CH ₄ /t CO ₂	<ul style="list-style-type: none"> ▪ coal that cannot be mined ▪ sufficient permeability ▪ maximum depth 2 km ▪ local CO₂ availability
Depleted oil fields	physical & mineral trapping	none	
Aquifer storage	physical & mineral trapping	none	

Source: D. Gielen, 2003: Uncertainties in relation to CO₂ capture and sequestration. IEA/EET Working Paper, nr. EET/2003/01.

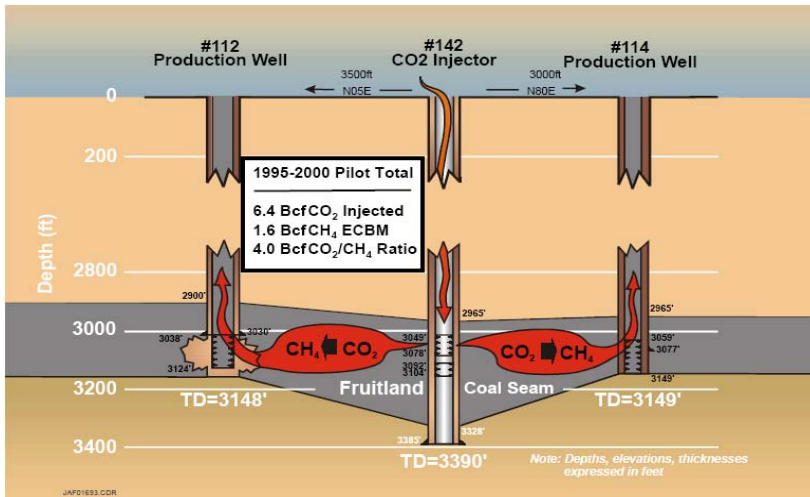
Fig. 2: table of CO₂ geological storage options

The newly exploited field techniques are very well outlined by NOVEM, 2001, 2003 and Gunter et al., 2004, as outlined also by the RECOPOL Project final results (Fig. 4, Kross et al., 2002; Pagnier et al., 2004).

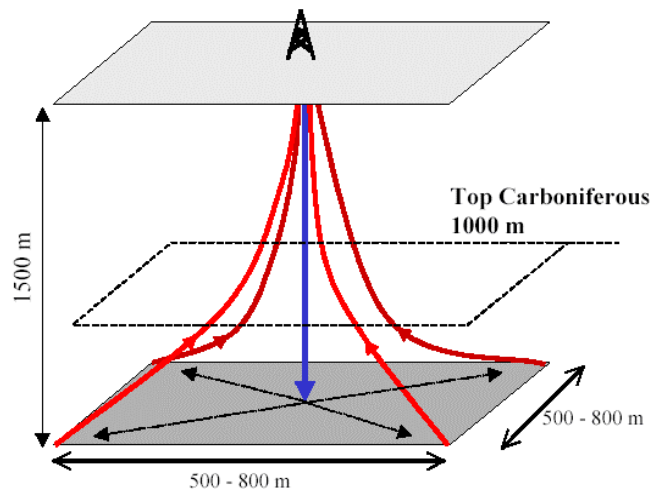
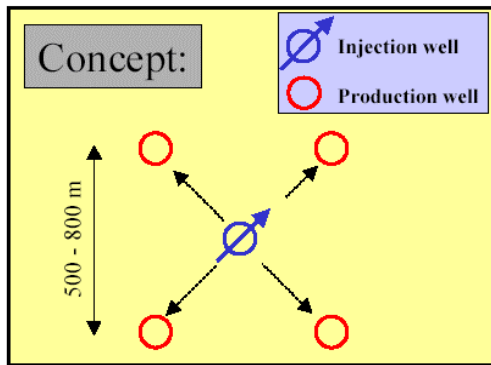
The criteria for selecting a future ECBM sector of the field are:

- reservoir homogeneity
- minimal presence of faults and folds;
- depth range of the coal beds at 600-1500 mt up to 2000 in peculiar cases;
- geometry and frequency of the coal beds
- coal composition (rank, macerals, ash, moisture, etc...)
- saturation in gases and CBM content (after Law and Rice, 1993 ; Yee et al., 1993);
- moisture content;
- aquifer/groundwater saturation and circulation;

good permeability conditions (see Gunter et al., 2004 for an intriguing discussion).



(a)



(b)

Fig. 3: (a) San Juan Basin, New Mexico, US, Allison Unit, New Mexico, CO₂ injection operated by Burlington Resources, like the Tiffany Unit, operated by BP America by N₂ injection. ECBM scheme. (b) concept of injection-production well geometry after Allison Basin ECBM exploitation: 16 CH₄ production wells, 4 CO₂ injection wells (modified from; <http://www.netl.doe.gov/>).

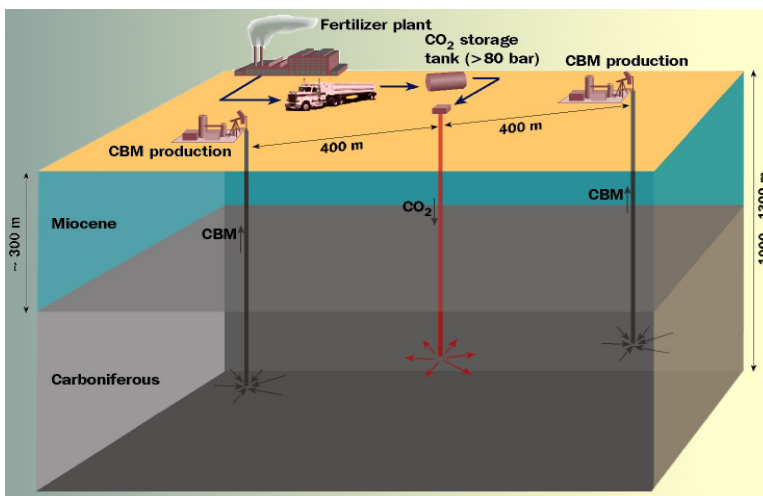


Fig. 4: RECOPOL Project, Upper Silesian Basin, Poland, CO₂ injection in coal bed methane (courtesy of RECOPOL Project partnership).

These criteria arise mainly from the nature of CBM as summarised below for the CCT scientific community as well.

The coalification (Fig. 5, 6) produce naturally hydrocarbons, oil and natural gas, as detailed in Law and Rice, (1993). CBM is the methane naturally contained inside the coal beds structure during and after its burial and structural geology history. Coal contains a natural system of fractures called cleat which increase the possibility to store CH₄ and which impart some permeability to the system.

Coal could physically adsorb many gases and may contain up to 25 Nm³ of CH₄ per ton of coal at coal seams pressure. It has higher affinity to adsorb gaseous CO₂ than methane. Volumetric ratio of adsorbable CO₂ versus CH₄ ranges from around 1 for mature coals, such as anthracite, to as high as 10 for younger coals, mainly if not altered. Gaseous CO₂ injected underground flow through the cleat system of the coal, diffuse into the coal matrix and be adsorbed through the coal micropore surfaces, freeing up gases as CH₄ with lower affinity to coal.

Coals can be systematically described and classified, for CBM and ECBM purposes, according to three compositional criteria:

- **grade**: relative proportion of organic matter vs. inorganic constituents;
- **type**: represents different classes or categories of organic constituents;
- **rank**: represents the level of physico-chemical alteration of coal composition and structure occurring during coalification not divided by sharp thresholds; it consist of *Diagenesis* 1) *Peatification*, 2) *Dehydration*, *Catagenesis* 3) *Bituminisation*, 4) *Debituminization*; *Metagenesis* 5) *Graphitization*. These processes may allow to distinguish: peat, lignite-sub-bituminous coal, high volatile bituminous coal, medium-low volatile bituminous and anthracite (ASTM, 1991, D-388, Tissot and Welte, 1984 and references inside Law and Rice, 1993).

The **rank** assume concrete meaning only when measured in terms of a “rank parameter”, which might be any one of a variety of physical and chemical properties that change with coalification such as:

- fixed carbon yield;
- vitrinite reflectance;
- heating value;

For CBM and ECBM purposes, the rank (Fig. 7) is very important: although *vitrinite reflectance* is now the most widely used parameter to define the coal rank that is applicable to all coals, there is no single coal rank parameter that is applicable to all coals or is free of complications relating to type and grade. During the '70 various authors proposed the rank scale termed *Level of Organic metamorphism* (LOM) arisen by the evidence that no property universally applicable as a rank parameter. ASTM, 1991, D-388 has various deficiencies e.g., the lack of applicability to inertite-rich coals and its reliance solely on rank for classification (new proposed ICCS = International Coal Classification System, Alpern, 1989).

Van Krevelen diagram reports the H/C and O/C ratios. For sorption capability H/C and O/C are lowering during coalification through the expulsion of low molecular weight hydrocarbons such as methane. During this “de-bituminization” process, which continues through medium-low volatile-bituminous ranks, all previous evidence for bituminisation begins to reverse (fluorescence properties disappear, molecular concentrations and mean molecular weight of molecular constituents of the coal decrease and, eventually, the molecular structure “reopens” with associated increase in sorbate accessibility). Most coal properties pass through maximum or minimum values during the transition from bituminisation to de-bituminization.

The CBM problem/techniques include *a*) a modern view of coalification that incorporates the two-components model (matrix/molecular fraction); *b*) tracing the compositional evolution of coal during coalification, especially as it relates to the generation of oil and gas; *c*) discussion of the

geologic context in which these changes occur, including peat formation, burial history and tectonic history.

The *two component model* (details in Law and Rice, 1003) has been proposed in various forms since the turn of the century but has only recently gained wide popularity and acceptance as a consequence of its strength in the utility in reconciling compositional parameters with observed coal behavior. Virtually every measurable property of coal can be interpreted (or reinterpreted) in light of this model, including gas sorption capacity (Fig. 8 and our data in the results paragraph), diffusion rate, optical properties, liquefaction behavior and coking characteristics.

The CH_4 is a gas of small size, non-polar character, low polarizability, free to enter and exit from the coal structure, even in water-saturated coal; weak but significant attractive forces between methane and other coal constituents giving rise to very high concentrations of methane in some coals at moderate reservoir pressures (“equivalent methane porosity” can approach to 100%).

The methods for rank characterization and distinction of molecular component/macro-molecular component are all addressed to distinguish a fraction of coal that is relatively loosely bonded to the coal structure (mol) respect to the fraction more strongly bound and therefore more resistant to removal by thermal treatments or solvents (vacuum distillation; mild thermal treatment; solvent extraction; flash pyrolysis; H-NMR spectroscopy). Methane usually is present in three states: *adsorbed* in the coal micropores (~95%); *dissolved in water* in the cleats; *free* in the cleats, very rare.

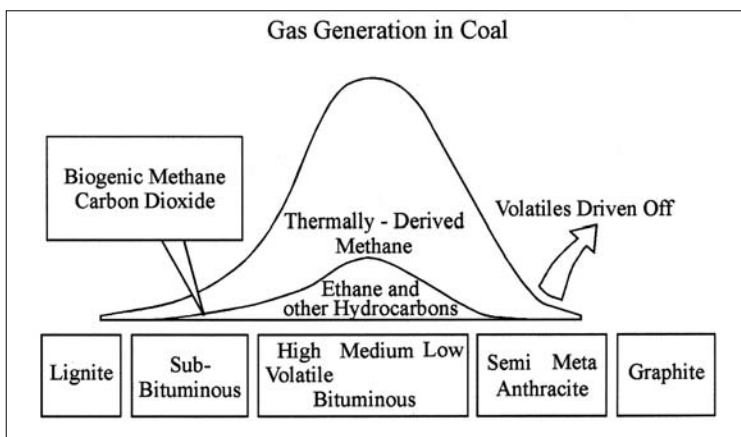


Fig. 5: Methane usually is present in three phases in the coal beds rock: *adsorbed* in the coal micro-pores (~95%); *dissolved in water* in the cleats; *free* in the cleats, this last situation is very rare $CBM\ in\ situ = A \times h \times \rho \times G_c$, A = productive area, h = net coal thickness (only beds > 3 m), ρ = coal density, G_c = methane gas content in coal (for weight units).

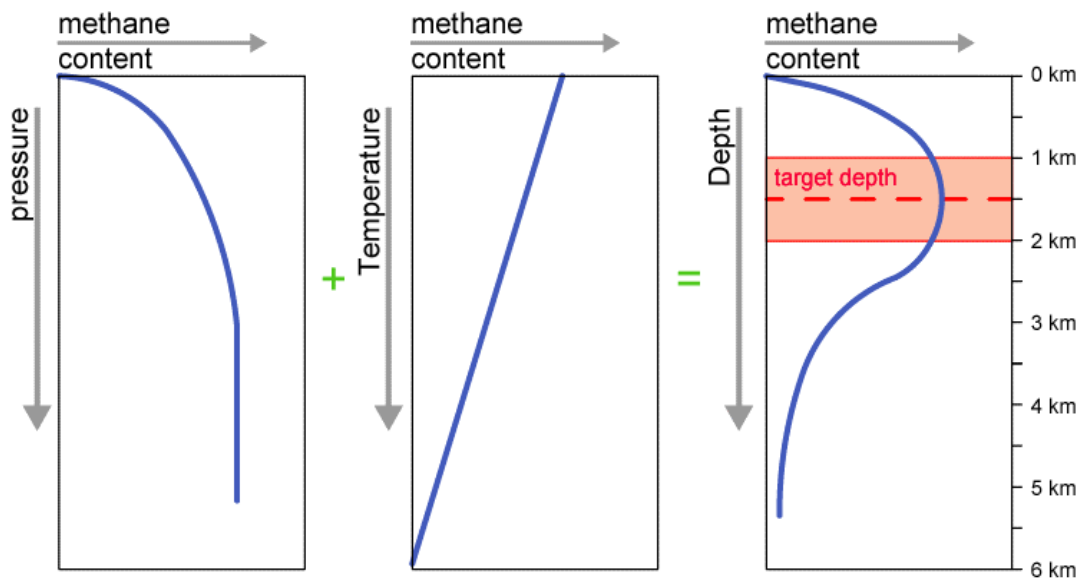


Fig. 6: Methane presence as a whole as a function of depth. Hydrocarbon production is maximum at 1500 mt depth (after Law and Rice, 1993).

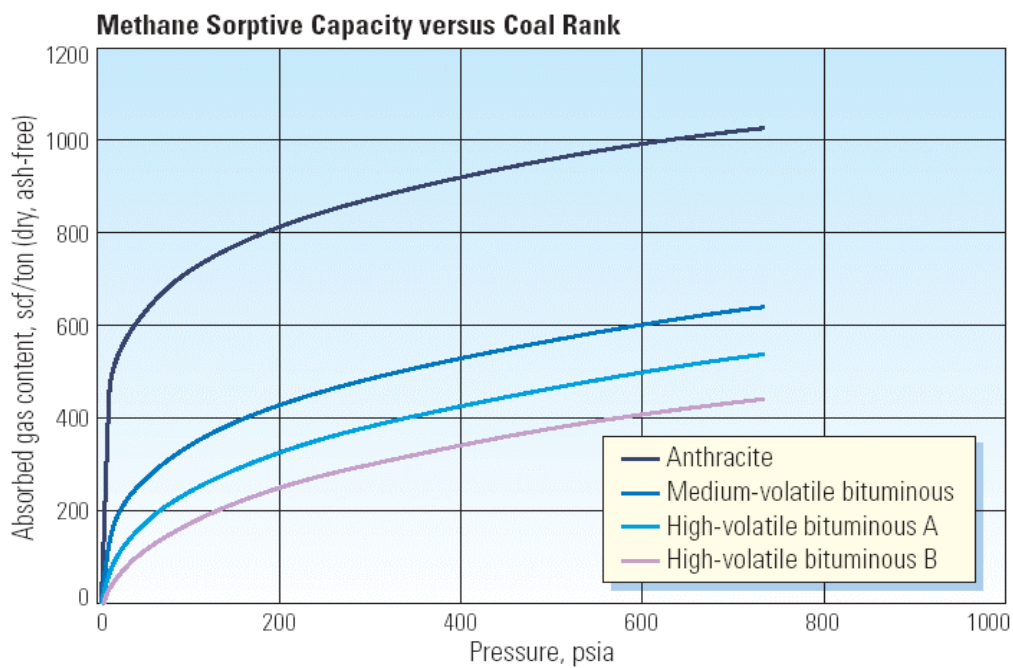


Fig. 7: Methane presence as a whole as a function of rank, 500 mt depth is around 700 psia. (after Law and Rice, 1993).

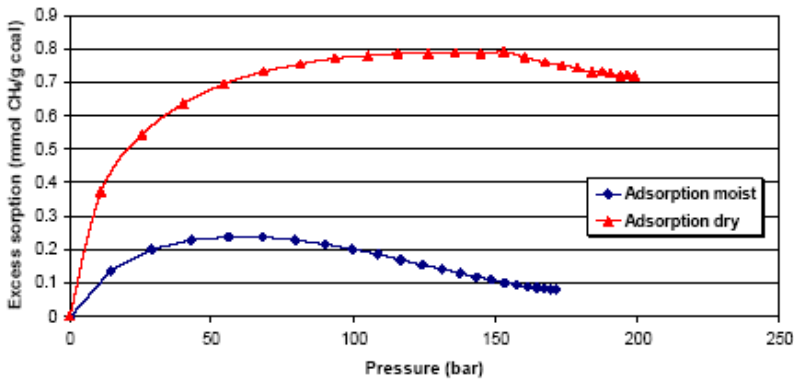


Fig. 8: Different sorption capacities for CH₄ of dry and moisture Upper-Silesian Basin coal (RECOPOL data) coal at T= 45°C Krooss et al. (2002). Swelling behaviour of coal during the CO₂ storage is foreseen: this reduce the permeability as a whole (details in Gunter et al., 2004 and in Shi and Durocan, 2004). Direct measurements of swelling are requested.

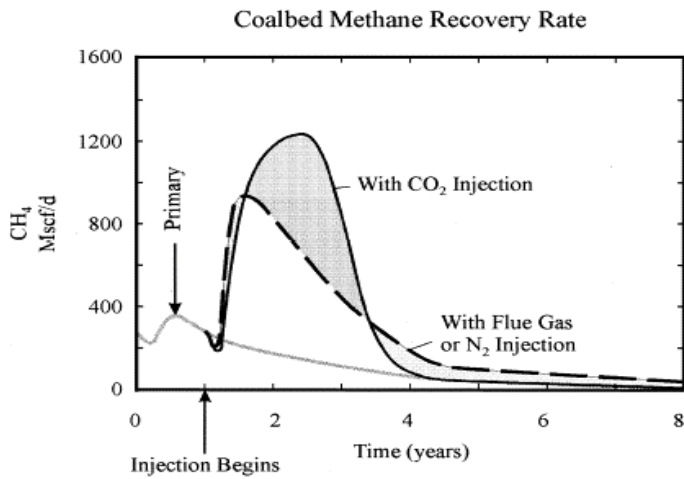


Fig. 9: Synthesis of the results of the first tests throughout the San Juan Basin, New Mexico (Burlington Resources published data).

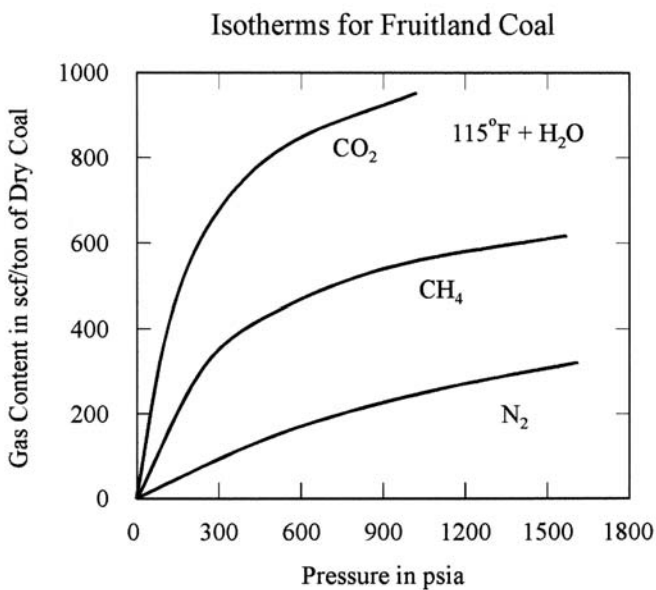


Fig. 10: Adsorbed gas content in a coal. The adsorption ratios are CO₂:CH₄:N₂ = 4:2:1 (after Marroquin et al, 2004)

The Krevelen diagram normally is used (Law and Rice, 1993 for details).

Less is the moisture of the coal, greater is the CBM and ECBM potentiality of a coal (Law and Rice, 1993 and references herein). At 1 km of depth (normal geological gradients of 20 °C/km and 10 MPa/Km) the CH₄ gas content could be higher of 2 times if the moisture is 1% with respect to 6% (Sulcis coal at – 500 mt depth), passing from 10 to 20 Std. m³/tonn daf.

The permeability requirements (normally in the range 1-5 mD) are strategic. The permeability is changing for the Allison Basin during the first gas injection for mechanism of coal swelling and fracture sealing by CO₂ or N₂ (see Fig. 9 and 10, see details in Gunter et al., 2004).

3. The Sulcis Coal Province

The ancient and actual mining area cover the *Gonnese Basin* (NW sector of the *Sulcis Coal Basin*) which is extended from the *Gulf of di Funtanamare* Northward to Carbonia Southward. Westward, the Tertiary sediments where the coal is trapped are underlying the Oligo-Miocenic covers. The mining concession areas was/are:

- Tedras Collu (1)
- Bacu Abis (2)
- Cortoghiana (3)
- Caput Aquas (4)
- Sirai-Serbariu (5-6).
- Piolamas (7)

The thicknesses of coal beds plus coal black-clays are around 150 m. the coal cumulative thickness is around 20 % < 40 %. Around 250 Mt ton of coal was evaluated in the mining area. Around 1 Bt tonns of coal could be evaluated in the rest of the sectors toward sea for the remaining areas, including the CBM and ECBM prone areas. The cut is 1,40 m high normally and the thickness between two coal beds is > 3,00 m. The volume of coal is > 60 %.

The geology/stratigraphy is very well fitting with the ECBM purposes: a good cap-rock (500-600 m) thickness i.e., is foreseen able to avoid CO₂ flux break-through at surface after the injection. Moreover good pH buffer capacity (Water Rock Interaction as WRI power) of the Miliolidi limestones host rock, is foreseen, able to assure “solubility trapping”, in a first stage, and “mineral trapping” on long periods (Gunter et al., 1993; 1997 a-b, 2000). The stratigraphy from the bottom to the top is:

- 1) Cambro-Silurianian Paleozoic Basement (fillads, carboniosus fillads, quartzites, meta-limestones, meta-conglomerates);
- 2) Eocene, Paleogene Carboniferous (Cuisian-Lutetian) “productive coal strata” (basal conglomerates, Miliolidi limestones, Marly-limestones, Lagoon Marly-dolostones, fresh-water limestones)
- 3) sedimento-clastic *Cixerri Formation* (Pecorini, Pomesano & Cerchi, 1969, clays, sands, 300 m);
- 4) Andesites, Basaltic Andesites and Oligo-Miocene basalts;
- 5) Ignimbrites of the *Formation Unità di Corona Maria*;
- 6) Ignimbrites-dacites of the *Formation Unità Lenzu*;
- 7) Ignimbrites of the *Formation Unità Acqua sa Canna*;
- 8) Ignimbrites of the *Formation Unità di Seruci*;
- 9) Ignimbrites of the *Formation Unità Conca Is Angius*;
- 10) Ignimbrites of the *Formation Unità di Nuraxi*;
- 11) Ignimbrites of the *Formation Commenditi*;
- 12) Ignimbrites of the *Formation Unità di Monte Ulmus*;
- 13) Ignimbrites of the *Formation Unità Paringianu*;
- 14) Ignimbrites of the *Formation Unità Serra Paringianu*.

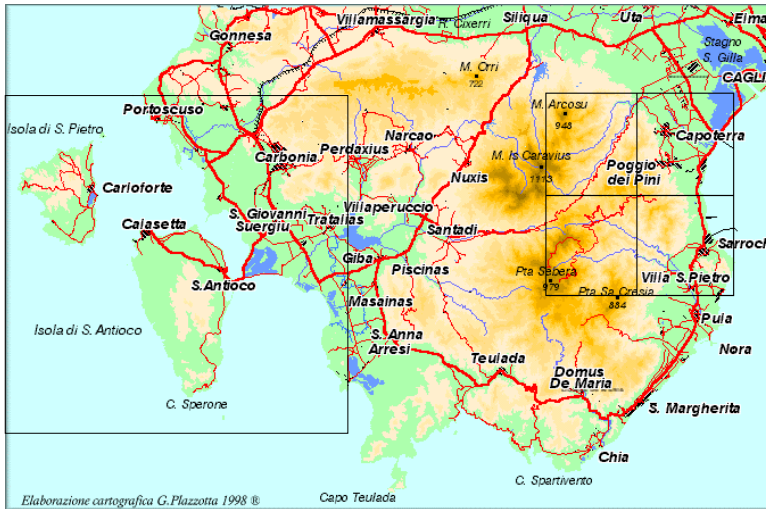


Fig. 11: Square on the left: possible area of the CBM and ECBM exploitation studied in the present paper. Square on the right (divided by sub-square) is the area characterised by environmental laws as park, actually. The location of the test pilot-site will be located in any case either in the North-western part of the basin, west of the *Ponente Fault*, or in the southwester part as a consequence of the ECBM prerequisite that the “coal productive strata” is located under 800 m and because is un-probable that the mining will reach these depth Otherwise in-shore horizontal drillings will reach off shore areas. The precise location of the drillings will be decided after new seismic reflection profiles and explorative boreholes.

The tectonics is characterised by the following main faults (in the mined area)

- *Serbariu-Sirai Fault* (Est of the basin, 50 m dislocation, dip W)
- *Sinni Fault* (NNE-SSW average: N30);
- *Cortoghiana Fault* (NNW-SSE, N170 post-volcanities around 3-18 M years);
- *Maiorchina Fault* (NW-SE, dislocation around 7-20 m);
- *Ponente Fault* (N-S, limited W of Seruci, dislocation of 40-100 m)
- *Acqua Sa Canna Fault* post-vulcanities around Middle Miocene, N80, N dipping, dislocation 50 m, M. Genere block);
- *Paringianu Fault* (E-W, dip N, dislocation 20-50 m).
- *M. Ulmus Fault* (N80E, dislocation 100 m, limited to Permian)



Fig. 12: Available Seismic profiles (Francois private enterprises data) inserted within the Mapinfo GIS under construction. Other seismic profiles are from AGIP, 1990. Other seismic surveys case histories are reported in literature (Marroquin and Hart, 2004).

The foreseen CO₂ geological sequestration area, which details will be deepened by an impending seismic reflection survey (Fig. 11 and 12) could be significant (order of magnitude of tens 10⁶ tons storage foreseen), in the frame of the ECBM cycle as a whole.

Coal-bearing strata, Tertiary in age, dip westward, such that stratigraphically shallower coals crop out in the eastern part of the Sulcis basin and become progressively regular and flat far from the Tertiary-Paleozoic boundary located eastward. The coal strata, increasingly deeper toward the west (around 150 m total thickness, growing westward, with cumulative power of coal comprised among 20 and 40 %), are 8-10% westward dipping.

The coal beds are inside Paleogene clayey sedimentary rocks and over carbonate rocks (Lagoon limestone named “*Miliolitico*”) overlying in angular discordance the filladic Basement. This is reaching the – 800 m sound injection depth in some location in shore (drilling 37/87 at M. Ulmus), but mostly off-shore, where the coal strata thickness tend to be progressively greater and continuous. It involves, very possibly, horizontal wells to be drilled in-shore to pick-up CBM off-shore. This is also to minimize the environmental impact of the project.

The coal composition is very important in the frame of an ECBM feasibility study.

The Krevelen diagram (not shown, but see Law and Rice, 1993) for “humic” coals, rich in *vitrinite macerals*, as the Sulcis coal, is promising for the exploitation of CBM and ECBM in the *Sulcis Coal Province*. The “*sapropelic*”, coals, *alginite* or *sporinite* maceral rich, have an H/C greater and a lower O/C; in this case the conditions are not properly optimal for CBM and ECBM industrial exploitation. The vitrinite reflectance coefficient (R_o) as well as M.V. = Volatile Matter (44.09 % for Sulcis Coal, Method ASTM 5142-02) are normally reported in the Krevelen diagram. The Sulcis coal, located in the *High volatile C bituminous* classification field, (from literature data, while INGV new analyses are ongoing) is characterised by a macerals content of 89.3 % subdivided in Vitrinite: 73.3 %, Exinite: 11 %, Inertite: 5 % and 11% of Mineral Matter (mineral constituents).

Normally the graph Vitrinite reflectance /R_o (%) versus Volatile Matter (V.M. %) is used to estimate the coal pertinence to CBM techniques: among the macerals *inertite* is subject to devolatilization and aromatization well before the maturative history of the coal, with respect to the *vitrinite* macerals (Sulcis, 73.3 %).

The coal *Molecular Fraction* of a coal is dominated by water. At an intermediate rank the hydrocarbons, including oil and asphalts, become the dominant *Molecular Fraction* (Levine, 1992 see inside Law and Rice, 1993).

The CBM maximum potentiality is suggested at around R_o = 0.7 % with bituminization. For a coal with *vitrinite reflectance* % as 0.48 as the Sulcis coal, an estimate of the potential gas generation could be done (after Higgs, 1986): during the coalification up to the anthracite rank, a Carboniferous sub-hydrous coal will generate around 150 mL/g of CH₄ while a per-hydrous Tertiary coal (Sulcis) will generate around 200 mL/g of CH₄ (at 1 atm pressure). The gas generation as a whole, including CO₂, is around the same for the type of coals.

At high rank, the free hydrocarbons are not more present but water newly dominates in the coal structure. Better conditions are expected in Sulcis at 800-1000 m depth with respect to the actual 500 m depth coal, sampled for this study.

As a whole, the coal sorption capacity of the coal as a function of the methane pressure, i.e. for an high-volatile bituminous B (hvBb) pertinent to the Illinois Basin (after Joubert et al., 1974) is around variable with the moisture content reported as weight %. The dry coal has an adsorption capacity (Gas in Place = GIP) significantly higher. For the Sulcis coal, of similar rank, the cross-check with the Illinois Basin coal suggests around 6 cm³ CH₄/gram of coal at STP conditions, considering 6-7 % of moisture; instead, 16 cm³ CH₄/gram of coal at STP conditions, are expected for the same coal, dry.

Considering all the literature suggestions, the expected GIP of 150-200 ml CH₄/gram of coal at STP conditions as whole, is estimated but it could be changed in the course of the project depending on the intrinsic coal characteristics highlighted in the mean time as:

- absorption capacity
- porosity (free gas)
- structural geology/burial history of the reservoir
- gas generation and migration
- structural geology patterns (fault systems).

Gas sorption of CO₂ for the Sulcis coal rank is foreseen as 300 scf/ton corresponding to 10 m³ CO₂ per ton of coal.

4. New experimental results

An ECBM pre-feasibility study has the aim to perform a first assessment of technical, geological, geochemical, geophysical, environmental, economical and legal aspects involved in the development of CO₂ storage with coal bed methane production, considering that very few case exists in literature after NOVEM (2003). It provides:

- the selection of possible drilling location in the area as test-site considering the geological, structural and geochemical conditions underground.
- The potentials of gas production and CO₂ storage capacity of the reservoir.
- Preliminary technical design for a single test site and cost spreadsheet in details.
- Overall evaluation for up-scaling of that test site as well as for a commercial size network for ECBM exploitation.
- A first reworking of applicable environmental laws and regulations, if lacking.

The work done or in progress up to date (see also table 1 and 2) in the frame of this Phase I of the project is:

- critical reworking of the information and documents available by the *Carbosulcis S.p.A* and collection of literature data on CBM, ECBM and the Sulcis coal province papers (mainly from Carbosulcis, 1994 and references herein, AGIP data, papers cited in the list) We reworked geochemical (fluid geochemistry mainly and compositional data of coal, table 3 and Table 4), structural-geology, stratigraphic and reservoir engineering experimental data;
- critical reworking of environmental impact throughout the Sulcis area on the basis of the existent laws and directivities as well as regional documents;
- experimental study of adsorption of CO₂ on the Sulcis coal to evaluate the adsorption capacity;
- design a new de-sorption experiment to evaluate the rate and quality of gas spontaneously released from the Sulcis coal.
- build up of a Mapinfo GIS structure, adding new CBM and ECBM pertinent strata, including the available industrial CO₂ sources to the geological, idrogeological, geophysical and structural-geological data. Environmental objects and other significant polygons were added too. At the end this GIS will be jointed to other CO₂-storage EC data-GIS as the GETSCO EC project structure to allow a ready picture about where and how store CO₂ from the interested industrial plants. Further software sub-routine will calculate the costs on the basis of the pipeline distances, compressors energy expanses, depth of drillings, etc...., environmental constrains, etc... All this information will be made friendly available inside the MapInfo GIS for the project partners and for the CCT (*Clean Coal Technologies*) community.

	Media %	ASTM	Met.
Umid.	6.91	3302-02	U_i= 5.25
M.V.	44.09	5142-02	R_o=0.48 (old datum)
Ash = A%	31.26	5142-02	
C fix	19.40	5142-02	
C tot	45.96	5373-02	
H	4,04	5373-02	
N	1,21	5373-02	
O	11,93	3176-02	
S	5.60	4239-02	
PCS =	4415	PCI =	4177
	Kcal/ kg		Kcal/kg

Table. 3: Analyses (24/02/05) of the Sulcis “in situ” coal, useful to characterize the coal for ECBM and CBM techniques. Macerals analyses are in progress by INGV.

Groundwater analyses available (from Carbosulcis et al., 1994 and from Piras, 2000) are the baseline to start further INGV analytical work foreseen in the next months on selected sites listed in Table 4.

The available chemical data data are suggesting CBM potentiality as a consequence of the Cl composition of the thermal groundwater circulating in the Miliolidi Limestone Formation (NUF 1 sample, 42 °C) located under the “coal productive strata”. Isotopical analyses are actually completely lacking in literature with the exception of D and H ratios data. Isotopes of C, S, He and Cl are foreseen, as other case histories (Snyder et al., 2003 and references herein) to deepen the origin and circulation patterns of groundwater and WRI processes as done for other CO₂ storage settings (Quattrocchi et al., 2004 a, 2005).

As regards the adsorption experiments on the Sulcis coal, ETH started with high-pressure adsorption of CO₂, CH₄ and their mixtures on coal, needed for the design of ECBM processes (Pini et al., 2005). In literature there is an almost lack of comprehensive adsorption data at high pressure. Competitive adsorption under near critical conditions is even less well understood. A gravimetric method was used to produce the experimental data for the excess adsorption of CO₂ on different commercial adsorbents. The first data highlight clear evidences of *Critical Adsorption* and *Critical Depletion* phenomena. Adsorption behaviour on commercial adsorbents is well modelled using *Lattice Density Functional theory (DFT)*. There is possibility to apply the model to adsorption properties on coal (Rajendran et al., 2002; Pini et al., 2005). The overall applications of these experimental studies are:

- investigation of single component adsorption of CO₂ and CH₄ on coal.
- investigation of binary sorption equilibria for applications in chromatography and in Enhanced Coal Bed Methane (ECBM) for CO₂ sequestration.
- swelling of polymers and coal under supercritical conditions and description of Supercritical Fluid Chromatography (SFC) systems with non-negligible pressure drops (see Pini et al., 2005 for details).

The first preliminary experimental data are showed (Fig. 13). The ETH experimental apparatus to measure the Sulcis Coal adsorption capacity is a *Rubotherm Magnetic Suspension Balance*. The specifications are: T_{max} = 250 °C, P_{max} = 450 bars, Resolution 0.01 mg, Measurements of temperature, density and excess adsorption were performed. The Void Volume measurement is

Name	Site	Type	Flow l/s	Temp. (°C)	pH	Cond. el. (µS/cm)	Cl ⁻		SO ₄ ²⁻		HCO ₃ ⁻		Na ⁺		K ⁺		Mg ²⁺		Ca ²⁺	
							(mg/l)	(meq/l)	(mg/l)	(meq/l)	(mg/l)	(meq/l)	(mg/l)	(meq/l)	(mg/l)	(meq/l)	(mg/l)	(meq/l)	(mg/l)	(meq/l)
NUF 1	Nuraxi Figus	sorgente		41.0	7.40	2500	616.0	17.38	32.0	0.67	432.0	7.08	500	21.75	15.2	0.39	11.3	0.93	27	1.35
NUF 3	Nuraxi Figus	sorgente		14.0	7.90	2310	575.0	16.22	366.0	7.62	87.0	1.43	322	14.01	19.8	0.51	51.2	4.21	110	5.49
NUF 4	Nuraxi Figus	sorgente		18.0	7.40	1990	531.0	14.98	130.0	2.71	219.0	3.59	285	12.40	15.5	0.40	35.7	2.94	106	5.29
2	Funtana Figu	sorgente	0.3	17.8	6.39	1074	18.9	0.53	244.6	5.09	92.8	1.52	152	6.61	11.9	0.30	36.2	2.98	40	2.00
7	Caput Acguas Seddargia	sorgente	50-60	18.9	7.05	1132	226.9	6.40	56.5	1.18	419.8	6.88	109	4.74	3.6	0.09	40.4	3.32	120	5.96
43	Miniera Serbariu	pozzo	50	34.7	6.59	8706	868.0	24.48	2950.0	61.42	649.0	10.64	546	23.75	49.3	1.26	426.0	35.03	682	34.03
44	Miniera Piolas	pozzo		19.2	7.12	3983	691.4	19.50	869.0	18.09	469.9	7.70	423	18.40	6.9	0.18	94.5	7.77	363	18.11
102	Nuraxi Figus vasche	sorgente	2	40.7	7.66	2180	621.0	17.52	18.3	0.38	463.7	7.60	532	23.14	11.5	0.29	11.4	0.94	26	1.27
103	Nuraxi Figus raschino	sorgente	0.11	34.9	8.00	2224	628.0	17.71	30.2	0.63	473.0	7.75	535	23.27	11.7	0.30	12.3	1.01	30	1.50
104	Nuraxi Figus stillicidio	sorgente	0.17	24.5	8.49	2253	644.0	18.17	25.7	0.54	493.0	8.08	532	23.14	13.8	0.35	16.3	1.34	32	1.60
106	Nuraxi Figus venuta principale	sorgente	15-20	42.3	7.82	2224	616.9	17.40	86.2	1.79	430.4	7.06	530	23.05	10.5	0.27	11.4	0.94	21	1.05
107	Nuraxi Figus zona vasche	sorgente	2-3	36.0	7.59	2340	654.3	18.46	119.7	2.49	418.6	6.86	510	22.18	11.4	0.29	22.3	1.83	57	2.84
108	Nuraxi Figus zona vascone	sorgente		41.5	7.60	2166	640.0	18.05	17.6	0.37	463.8	7.60	526	22.88	9.9	0.25	16.8	1.38	21	1.04
109	Miniera di Cortoghiana	pozzo		21.2	7.64	1613	191.0	5.39	394.4	8.21	274.6	4.50	232	10.09	12.4	0.32	45.0	3.70	75	3.72
110	Bacu Abis Pozzo Roth	pozzo		22.4	6.74	3881	414.0	11.68	91.5	1.91	1573.6	25.80	305	13.27	13.8	0.35	180.0	14.80	304	15.17
113	Bacu Abis Pozzo Nuovo	pozzo		20.2	8.02	1352	219.8	6.20	229.0	4.77	292.9	4.80	206	8.96	7.8	0.20	32.5	2.67	72	3.57
114	Miniera di Terras Collu	pozzo		21.5	7.12	1919	283.7	8.00	316.8	6.60	503.4	8.25	212	9.22	7.3	0.19	66.0	5.43	151	7.53

Table 4:

conventionally performed by using helium at ambient conditions assuming helium does not adsorb. Studies show that substantial helium adsorption is possible. Neglecting helium adsorption leads to errors in adsorption measurements. In the present study helium adsorption and thermal expansion were accounted for and corrections incorporated (Rejendran et al., 2002, see inside Pini et al., 2005). Adsorption equilibria are evaluated by the true measurable quantity: $m_{\text{excess}} = m_{\text{adsorb.}} - \rho^b V_{\text{adsorb.}}$

We are waiting the subsequent data gathered by using mixtures too, to give a final interpretation addressed to the ECBM or CBM exploitation in the Sulcis area. De-sorption experiment design (Fig. 14) was completed and it is under construction at INGV.

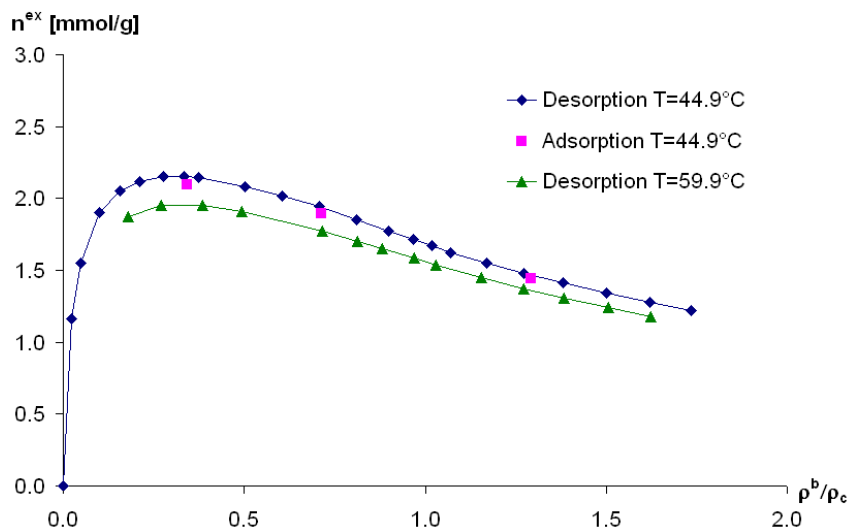


Fig. 13: Sulcis coal experimental results, regarding the absorption equilibria of CO₂ on coal powdered at 0.25-0.35 mm. Different isotherms at T = 44.9-59.9 °C .

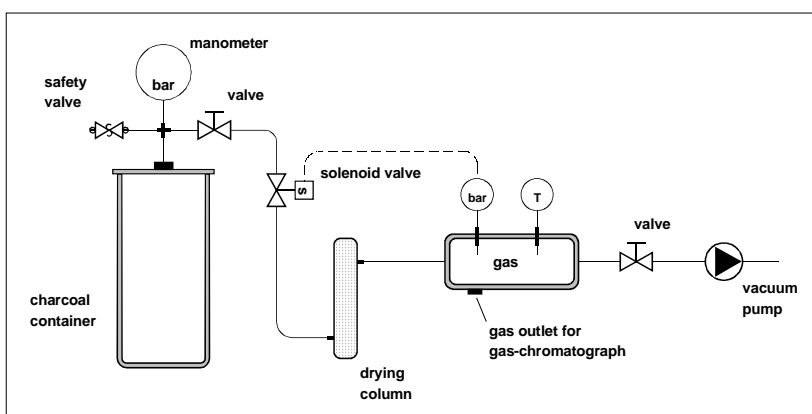


Fig. 14: INGV design to measure the de-sorption quality, quantity and rate to characterize the Sulcis coal for ECBM and CBM techniques.

In literature experiments of kinetics of adsorption of CH₄ and CO₂ where done by TNO (Franck Bergen) and by University of Aachen (Busch Andreas, busch@lek.rwth.aachen.de) on different Upper Silesian Basin coals (Polonia, RECOPOL), 900 m deep with average

vitrinite macerals high as 60% - 72%, as the Sulcis coal, and $R_o = 0.48$ as Sulcis at depth. A simple *semi-empirical model of sorptive transport* for both gases is used. The results highlighted that the equilibrium is obtained faster for CO_2 than for CH_4 . The adsorption rate decreases with the increase of the granulometric sizes, for both gases. The equilibrium is reached well before for the dry coals with respect to the moist coals. The equilibrium period is less if the temperature decreases for each of the gases. The adsorption rate is less if the overall pressure (depth) increases. The implications of this information on CBM/ECBM are that CO_2 exhibits a higher rate of adsorption than CH_4 and this evidence strengthens the hypothesis to store CO_2 in coal beds because also kinetically a preferential adsorption of CO_2 is expected. On the other hand, experiments with mixtures, as approached for the Sulcis coal at the ETH laboratories, highlighted that the selective adsorption is not always favourable to the CO_2 phase.

If industrial flue gas would be directly injected in the Sulcis deep coal beds, it is very important to define the mixtures with N_2 . The University of Tokyo (Toribio M.M., see <http://www.ghgt7.ca/>) used the “*Gibbs Excess Sorption*” to state that N_2 strongly affects (as the CH_4 presence) the CO_2 adsorption on coal, as a consequence of competition of the different gases within the adsorption sites. Gunter et al., 2004 suggested a completely different behaviour of N_2 if injected in the reservoir with respect to CO_2 . High pressure tests are recommended.

5. Environmental risks assessment

Environmental impact considerations for the CBM and ECBM exploitation in the Sulcis area are highlighted on the basis of the available Italian legal tools, giving hints for future EU, Italian and new regional legislation and strategies. A new concept of CO_2 as “no waste” product in the coal/hydrocarbons provinces for ECBM/EOR exploitation is depicted, defining CO_2 a “*natural climate-alterant factor*”.

A list of laws and directivities is given as follows (Italian language):

- Direttiva del Consiglio della CEE del 27/6/1985 - 85/337/CEE
Direttiva 97/11/CE del Consiglio della Comunità Europea del 3/3/1997
Direttiva 27 giugno 2001, n° 42
LEGGE 8 luglio 1986, n. 349 istituzione del Ministero dell'ambiente e norme in materia di danno ambientale
- DPCM 10 agosto 1988, n. 377 regolamentazione delle pronunce di compatibilità ambientale della 349
- DPCM 27 dicembre 1988 norme tecniche per la redazione degli studi di I.A. e la formulazione del giudizio di compatibilità
- Circolare 11/8/1989 pubblicità degli atti riguardanti la pronuncia di comp. amb. della 349, modalità dell'annuncio su quotidiani
- LEGGE 11/2/1994, n.109 (Merloni Ter) Legge quadro in materia di lavori pubblici
- LEGGE 22 febbraio 1994, n. 146 (direttiva 337/85/CEE)
- D.P.R n° 526 del 18/04/1994
- Circolare del 15/2/1996 specifiche in materia di pubblicità – integrazione della circolare 11/8/1989
- DPR 12/4/1996
- Direttiva 337/85/CEE
- Circolare n° 15326 del 8/10/1996, N.GAB/96/15326
- Circolare n° 15208 del 7/10/1996, n. GAB/96/15208
- D.P.R. del 11/2/1998
- decreto del Presidente del Consiglio dei Ministri, 10 agosto 1988, n. 377
- DPCM 3/9/1999
- Capo V, Art. 31 della LEGGE REGIONALE 18/1/1999, n. 1

- DPCM 1/9/2000 – modificazioni al DPCM 3/9/1999 aggiungendo all'allegato B del DPR 96 la lettera (g): attività di ricerca di idrocarburi liquidi e gassosi in terraferma
- DECRETO LEGISLATIVO 20/8/2002
- DECRETO 1/4/2004 del Ministero dell'Ambiente e della Tutela del Territorio
- DPR 12/4/1996 e Legge 6 dicembre 1991, n. 394 e legge regionale 7 giugno 1989, n. 31;
- LEGGE REGIONALE 5/9/2000, n. 17
- LEGGE REGIONALE 25/11/2004, n. 8.

CO₂ since prehistoric times “lives” together with human Beings and it could not be considered like a “waste”; simple considerations allow us to define it as “poisonous gas” if some thresholds are overcome in lived areas. Anyway some urbanistic remediation were adopted in geodynamically active areas (Pizzino et al., 2002; Voltattorni et al., 2005).

As regards the possible industrial CO₂ flux degassing to surface (Strutt et al., 2003, 2004, Jones et al., 2005), after the CO₂ injection, the *Cixerri Formation* and the andesitic-ignimbritic formations that both overlie the “coal beds”, are impervious and thick enough, thus determining an intrinsic safety factor for CO₂ storage in the Sulcis CO₂ coal-bearing beds. The deep geological formations could be the seat of huge “CO₂ solubility trapping” (more than in the Weyburn case, Emberley et al., 2003; Quattrocchi et al., 2005) and “CO₂ mineral trapping”.

Also cap-rock is sound for CO₂ storage as suggested by the main mineralogy (reactions in marly limestones, see Gunter et al., 1993; 1997 a,b, 2000; and reactions as: $KAlSi_3O_8 + Na^+ + CO_2(aq) + H_2O \leftrightarrow NaAlCO_3(OH)_2 + 3SiO_2 + K^+$), if CO₂ leakage and micro-seepage occurs from the deeper strata and from coal where the CO₂ will be adsorbed (Czernicowsky et al., 2001, Le Nidre & Gaus, 2004). Centuries and tens of centuries are foreseen for the CO₂ to reach and pass through this kind cap-rock (Le Nidre & Gaus, 2004).

Future prone sectors for CO₂ leakage from coal beds to surface are evaluated on the basis of tectonic, stratigraphic and hydrogeological considerations. At the moment a “baseline” study is ongoing throughout the Sulcis area, starting from the liquid phase (aquifers, mining groundwater) to quantify the dissolved CO₂ and CH₄, as well as other fault-fractures pathfinder elements (Radon, He, H₂S, etc, Quattrocchi et al., 1999). Natural degassing prone sectors have been evaluated and inserted within the MapInfo GIS, so that soil gases surveys are planned in the impending Phase II of the Project. Micro-seepage processes and buried fault location are outlined and they will be tested by CO₂/CH₄ flux measures before the CO₂ injection. Future discrete survey monitoring is planned to quantify the “Gas Hazard” for livings.

Risks assessment is discussed, considering possible degassing episodes, fault activation, sismotectonics and fluid-transport processes: a positive scenario arises as a whole from the collected preliminary information, mainly from lithological-hydrogeological, geochemical and coal compositional reasons, as well as from logistical reasons, in a densely populated region with tourist attractions.

In general, the first results suggest that the ECBM exploitation in the Sulcis coal province could be different from the RECOPOL, Campine and Zuid Limburg case histories, as well as different from the USA and Canada CBM and ECBM extensive experience, despite the Fenn-Big Valley (Alberta, Canada) approach seems to be the most sound to the Sulcis situation.

As regards the Protected area denominated “*Dell'Isola e Canale di San Pietro*” (Municipalities of Carloforte, S. Antioco, Calasetta, Portoscuso, location centered on 39° 08' lat. N - 8° 17' long. E., area spanning around 50 km²) no actual laws are available, because the Managing Authority must be still defined. There are automatic legal links to the Law 431/85, regarding the respect area around the coast (300 m from the cost line). There is another landscape-Law for the sector of the coast between the Bue Marino grotta and Punta Grossa. There is a proposal for the Natural Botanic Reserve of San Pietro and Isola Piana written by

“Piano Parchi of the Sardinia Region since 1989. In any case the CBM-ECBM exploitation will take in consideration the environmental framework of this protected area.

6. CO₂ sources perspectives

The electricity power ENEL society signed a contract with Carbosulcis S.p.A. on 20/10/2004 for the supply of coal destined to the power plant “*Grazia Deledda*” located inside the Sulcis area. For the next 3 years (2005-2007) *Carbosulcis S.p.A.* will deliver to ENEL around 1.100.000 tons of coal scheduled as follows::

- 300000 tonns during 2005
- 370000 tonns during 2006
- 430000 tonns during 2007

This initiative satisfies in the impending future the electric power needs of the island as a whole. The SULCIS ENEL power plant (SU3 in the tables of Pettinau & Meloni, 2005) is equipped by the environmental quality registration EMAS, allowing to use the Sulcis coal in environmentally sure manner, thank to the best *Clean Coal Technologies* foreseen for the plant, as the de-sulfurization devices, denitrification devices as well as the almost complete cut of the coal powders. This is relative to the 240 Mw section, yet operative, but mostly for the combustion systems and treatment systems of the new 340 MW section AFBC SULCIS which will be operative starting from 2006.

A recent evaluation of the CO₂ emissions in atmosphere was accomplished by a jointed study of Sotacarbo S.p.A: and University of Cagliari (Pettinau and Meloni, 2005), specifically addressed to evaluate the CO₂ sources for the ECBM exploitation in the *Sulcis Coal Province*. Apart the existent and foreseen electricity power plants (ENEL, ENDESA, SARLUX), also Alumina industry is an available CO₂ source in the vicinity of the coal beds. The sites are located at Portovesme, Portoscuso, Sarroch, Fiumesanto and Assemini, while other secondary CO₂ sources are the renewable energy plants located in S. Gavino Monreale, Arborea, Capoterra, Serdiana, Macomer. The industrial auto-producer power plants are small and of scarce interest for the ECBM exploitation (sites of Portotorres – very far-, Saras, and Ottana).

Historical time series of CO₂ emissions in Sardinia, elaborated by ENEA jointed with University of Cagliari highlighted a growing from 12,8 Mt during 1988 to 15,0 Mt of CO₂ during 1995. The punctual termo-electrical power plants with around 10,6 Mt of CO₂ emissions budget during 1999 constitute the 50% of the total emissions while the refineries with around 4 Mt of CO₂ in the same year constitute the 20 % of the total emissions. The ECBM exploitation is addressed towards these concentrated CO₂ emission points, all located in the first 20-100 km from the coal basin. The projections of this study up to 2012, when 13,24 Mt of CO₂ emitted from the old and the new clean coal technologies (CCT Sulcis) are foreseen.

7. Conclusions

Some general conclusions could be drawn:

- CO₂ storage and ECBM is not economical feasible under current circumstances, an incentive will be needed, as stated firstly in Europe by NOVEM (2001, 2003). For example, a CO₂ price of 42-52 Euro/tonn corresponding to around 0.03-0.04 Euro/kWh or, better for the coal industry, an energy tax devoted to clean technologies expenditures and overheads.
- A CBM intermediate exploitation step (first years) could be opportune. ECBM drillings is not economical feasible as natural gas drilling. Around 1/10 is the ratio between CH₄ volume in an CBM well (enhanced of a factor 4 by ECBM) and in a natural gas well respectively. A gas reservoir could have a production rate of 10⁶ m³/day of CO₄ while an ECBM production field could arrive at 5000 m³/day of CH₄.

- the ECBM technique is safe and likely to become economically feasible by using peculiar techniques (i.e., deviated wells foreseen for the Sulcis Coal Province from inshore towards offshore);
- CO₂ storage potential is large by using ECBM techniques also in Italy despite lower than in USA, Canada, Poland and Fiandres.
- A lot of feasibility studies are necessary (after Zuid Limburg, Campine, Upper-Silesian Basin of RECOPOL, Fenn-Big Valley, Sulcis, etc....) to better understand ECBM technique behavior in different geological environments. It will allow progressive test site – scaled up site – networks growing.
- CO₂-ECBM feasibility studies involve multidisciplinary task forces comprising technical & environmental aspects: drilling location test site & network, available coal volumes, thickness coal beds, depth interval logs at preferentially 800-2000 m, sorption capacity CO₂/CH₄, sub-surface conditions, tectonics, hydrodynamic system, groundwater quality/flux, permeability, saline waste water produced, law/regulations, Environmental Impacts Evaluations (VIA in Italy), stakeholders relationships, geochemical & geophysical monitoring plan scheduling etc... In Sulcis the environmental aspects must be more accurate due to the touristic attraction of Sardinia.
- Considering the actually available experimental data, the Krevelen diagram for “humic” coals, rich in *vitrinite macerals*, the Sulcis coal is promising for the exploitation of CBM and ECBM in the *Sulcis Coal Province*. The vitrinite reflectance coefficient (R_o) as well as M.V. = Volatile Matter (44.09 % for Sulcis Coal) allow to locate the Sulcis coal as *High volatile C bituminous*, sound for CBM and ECBM purpose. For a coal like Sulcis with vitrinite reflectance % as 0.48, an estimate of the potential gas generation could be 200 ml/g of CH₄ (at 1 atm pressure). Better conditions are expected in Sulcis at 800-1000 mt depth with respect the actual 500 mt depth coal, sampled for this study.
- The Sulcis Basin could be coupled with other interesting CO₂ storage basins throughout the Sardinia island, as envisaged by us recently (Angelone et al., 2004). CO₂ sources are very near to the ECBM envisaged field area as a whole.
- Economic model spreadsheet & production time scheduling by this preliminary data seems positive for capital costs involvement. A final view is in progress. At the moment it seems intriguing the approach used by Gunter et al., (2004): exploitation of CBM before (i.e., in USA it corresponds to the 9 % of total production of CH₄), followed by ECBM production and finally by “saline aquifer” modality for CO₂ geological storage after ECBM. This multiphase and multi-technique project scenario could have a duration of 30 years (2-5 years ECBM, 5-15 years ECBM and the rest CO₂ geological storage in saline aquifer).
- At the end of the ECBM exploitation (i.e. 20-30 years foreseen), the *Sulcis Coal Province* deeper strata will remain available for further CO₂ geological storage (saline aquifer modality, Gunter et al., 1993; 1997 a-b; 2000; Angelone et al., 2005), if the storage potential and WRI conditions will be sound as deepened by this feasibility study. At the moment the known litho-stratigraphy (up to - 600 m from the s.l.m.) and fluid geochemistry data seems to be good as regards the CO₂ buffer capacity for long term CO₂ geological storage (retention time foreseen for CO₂ injection: 10⁵–10⁶ years).
- In Sulcis high purity CO₂ sources and roads in the vicinity of the ECBM site are strategic, but also power plants with low-CO₂ flue gas (*ENEL Sulcis SU3 unit* at the beginning). The direct flue-gas storage from the existing and foreseen Sardinia power plants, without CO₂ capture, is possible. In this case it is necessary to evaluate the overall costs of N₂ purification from CH₄ at the end of the production, as done for the Fenn-Big Valley (Alberta, Canada; Gunter et al., 2004).

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