TALLINN UNIVERSITY OF TECHNOLOGY

SAPIENZA UNIVERSITÀ DI ROMA

North Italian CCS scenario for the cement industry

Student: Martina Mariani

Supervisors:

Dr. Kazbulat Shogenov, researcher

Dr. Alla Shogenova, senior researcher

(Tallinn University of Technology)

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1. Introduction

This work was made in the frame of the International Master Course of the Horizon 2020 ENOS project and in cooperation with Horizon 2020 CLEANKER project, as a basic part of Italian CCUS scenario (task 7.2 work package 7).

In 2015, in Paris, a global climate agreement was reached, when world countries agreed to hold the increase in the global average temperature below 2°C and to limit the temperature increasing to 1.5°C by 2100.

Global energy consumption in 2018 increased at nearly twice the average rate of growth since 2010, driven by a robust global economy and higher heating and cooling needs in some parts of the world. As a result of higher energy consumption, global energy-related CO_2 emissions increased to 33.1 Gt CO_2 (for up 1.7%) and hit a new record. Coal-fired power generation continues to be the single largest emitter, accounting for 30% of all energy-related carbon dioxide emissions (*IEA, 2019).* Cement production is responsible for about 8% of global anthropogenic CO2 emissions *(Oliver et al, 2016)* and for about 27% of global anthropogenic CO2 emissions from industrial sources worldwide (*IEA, 2011).* The cement industry is thus a key-sector for the reduction of CO2 emissions *(Fantini et al, 2019).*

The direct CO_2 intensity of cement production increased by 0.5% per year during 2014–2018. Initial estimates suggest that 4.1 Gt of cement were produced globally in 2019. Key strategies to cut carbon emissions in cement production include improving energy efficiency, switching to lower-carbon fuels, promoting material efficiency (to reduce the clinker-to-cement ratio and total demand), and advancing process and technology innovations are necessary *(IEA, 2020).*

CCS is essential to industrial decarbonization. It can provide clean growth opportunities and help ensure a just sustainable transition in industrial regions and communities *(Global CSS Institute, 2019*). By combining energy efficiency, renewable sources with the CCS, global greenhouses gases can be reduced by at least 50% by 2050.

In Italy in October 2011 was promulgated the Legislative Decree n.162 by the cooperation between the Ministry of Economic Development and the Ministry of the Environment. This decree defines the area of the Italian territory where CO_2 storage cannot be performed. Northern Italy, in particular Lombardia Region, seems to have good geological characteristics for the application of CCS technologies.

The CCS technology consists of capture, transport and storage of carbon dioxide. The main storage options for CO_2 are depleted gas and oil fields, which are well known because of the hydrocarbon exploration and exploitation, saline aquifers and unmineable coal seams. CO_2 storage is achieved through a combination of physical and chemical mechanisms that are effective over different time frames and scales (*Bachu et al., 2007; Bachu, 2008*).

The first stage is the capturing of the CO_2 produced during the burning of fuels or produced from the industrial processes such as the production of cement, steel, or chemical industry (*CCSA, 2018*). Carbon capture technologies can be applied to a variety of carbon dioxide emitting processes, where the CO_2 is separated from process emissions by physical and chemical processes. CO_2 could be captured using pre-combustion, post-combustion and oxyfuel combustion technologies.

The pre-combustion capture allows capturing CO_2 in a synthesis gas after the conversion of CO into CO_2. The post-combustion capture permits to capture CO_2 in the exhaust gases once the fuel has been fully burned with air; the capture in oxy-combustion consists of combustion in oxygen with the recycling of exhaust gases and purification of the CO_2 flow, to eliminate incondensable gases (*Kanniche et al.,2010*).

Calcium Looping (or carbonate looping) is recognized as another very promising emerging technology for CO_2 capture in cement plants *(Abanades et al., 2015*). Calcium looping is a regenerative process, which takes advantage of the capacity of calcium oxide-based sorbents to capture CO_2 at high temperatures. The process is divided into two basic steps:

(1) the capture of CO_2 by "carbonation" of CaO to form $CaCO_3$ in a reactor operating at around 650°C; and

(2) oxyfuel calcination in a reactor operating above 900-920°C, which makes the CaO available again and releases a gas stream of nearly pure CO_2.

Today, Horizon 2020 project CLEANKER is focusing to demonstrate the feasibility of the integrated Calcium looping concept at the industrial level in a demo system by the Buzzi Unicem cement plant in Vernasca, Italy (*Fantini et al., 2019*).

Once the CO_2 has been separated from the flue gas, the resulting concentrated CO_2 stream is dehydrated and compressed to make transport and storage more efficient.

CO_2 can be transported by pipelines, ships, trucks and railway. Ship transportation is suitable for offshore storage sites and its economic feasibility depends on the distance from a CO_2 source and amount of CO_2 to be transported. In industrial-scale large quantities of CO_2 are preferably transported by pipelines. There is significant potential for the development of local and regional CCS pipeline infrastructure, leading to CCS "clusters" where CO_2-intensive industries could locate. Developing clusters, where infrastructure can be shared by a number of industrial sources of carbon dioxide emissions, will result in the most cost-effective way to deliver CCS infrastructure development and ultimately lower costs to consumers (*CCSA, 2018).*

After transportation CO2 could be used and/or stored underground. For storing CO_2 underground, a natural process that has trapped CO_2, oil and gas for millions of years is used. Both oil and gas fields and deep saline aquifers have the same key geological features required for CO_2 storage: a layer of a porous rock to absorb the CO_2 in supercritical state and an impermeable layer of caprock which seals the porous layer underneath, trapping the CO_2 (*ZEP, 2020).*

As the storage mechanisms are changed over time from structural to residual, dissolution and then to mineral storage, the carbon dioxide becomes less and less mobile. Therefore, the longer carbon dioxide is stored the lower the risk of any leakage and thus CO_2 could be stored underground for thousands of years.

1.1 North-Italian scenario

Since 2011 Italy has become the second cement producer country in the EU 28, as a consequence of the reduction of clinker production in the last years, which has been confirmed also in 2015. The picture of the cement sector in 2016 includes 24 companies (62 plants of which: 33 full cycle and 29 grinding plants) operating in Italy. Among operating plants 42% are located in Northern Italy, 16% are in the central regions of the country and 42% are in the southern regions and at the islands. The main driver for the reduction of CO_2 emissions is the reduction in emissions observed in energy industries and manufacturing industries and construction (*ISPR*A, 2018).

The EU Horizon 2020 project CLEANKER is aimed at the Ca-looping capture of CO_2 emissions produced by the cement industry (*Fantini et al., 2019*). Italy has a good option for storage CO_2 especially in the Northern Italy (Lombardy Region) (*Civile et al.,2013*). One of the main objectives of the CO_2 Transport, Use and Storage Work Package of the CLEANKER project is to explore local and regional transport, utilization and storage needs, options and solutions in the vicinity of the demo system Vernasca Cement Plant in Italy (Lombardy Region).

Recently ENI has run various studies and preliminary evaluations as part of the design of surface infrastructure for CO_2 injection and monitoring in the Cortemaggiore field (Piacenza). ENI has also analysed the legal and societal aspects linked to storage here. The injection of 8000 tonnes of CO_2 per year was planned over a three-year period, followed by two years of post-injection monitoring. Studies on the utilization of the CO_2 were also planned in order to increase the recovery factor from Italian hydrocarbon fields (*Rütters et al., 2013*). However, these plans were not yet realised and the results of feasibility study made by ENI are confidential and not available to the public. Considering these issues, CO_2 captured at the Vernasca Cement plant (Piacenza) could be stored using other local CO_2 storage and use options (*Shogenova et al., 2018*).

1.2 Italian regulations

Italy passed new legislation to regulate the geological storage of carbon dioxide. Legislative Decree No. 162 of 14 September 2011 entered into force on 5 October 2011. CO_2 storage is permitted in Italy except for the seismic areas. Italy is completing a Strategic Environmental Assessment that will allow assessing the available storage capacity (*EC, 2017*). The main regulations for CO_2 storage have been developed in Italy. Additional regulations should be taken for clarification of some specific CCS regulatory issues, especially for transboundary storage. The 2009 amendment to article 6 of the London Protocol, enabling the export of carbon dioxide streams for the purpose of sequestration in trans-boundary sub-seabed geological formations should be ratified. Italian CCS Decree in Article 28 obliges operators of CO_2 transport networks and storage sites to guarantee the connection and free access to its transportation network and storage sites to other operators in a transparent and non-discriminatory manner. However, it is also stated that "transport network operators and operators of storage sites may refuse access for lack of ability or link". Transnational cooperation is regulated only in short by Article 30 of Italian CCS Decree: "For cross-border transport of CO_2 storage sites or transboundary storage complexes, the Ministry of economic development and the Ministry of environment shall fulfil the provisions of this Decree and other applicable Community standards, or promote the conclusion of agreements with countries outside the European Union" (*Shogenova et al., 2018*).

2. Malossa area

2.1 Geological background

The Malossa structure is located in the central part of the Po Valley (North Italy) (Fig. 1). The Po valley subsurface framework resulted from a Mesozoic extensional tectonic phase, followed mainly by the Tertiary collisional tectonic phase (*Bello & Fantoni, 2002*). Seismic areas in the Northern Italy is shown at the Figure 2. The Malossa structure is located between shown seismic areas.

Figure 1. Location of Malossa structure in the central part of the Po Valley in the Northern Italy. From Guandalini et al. (2010).

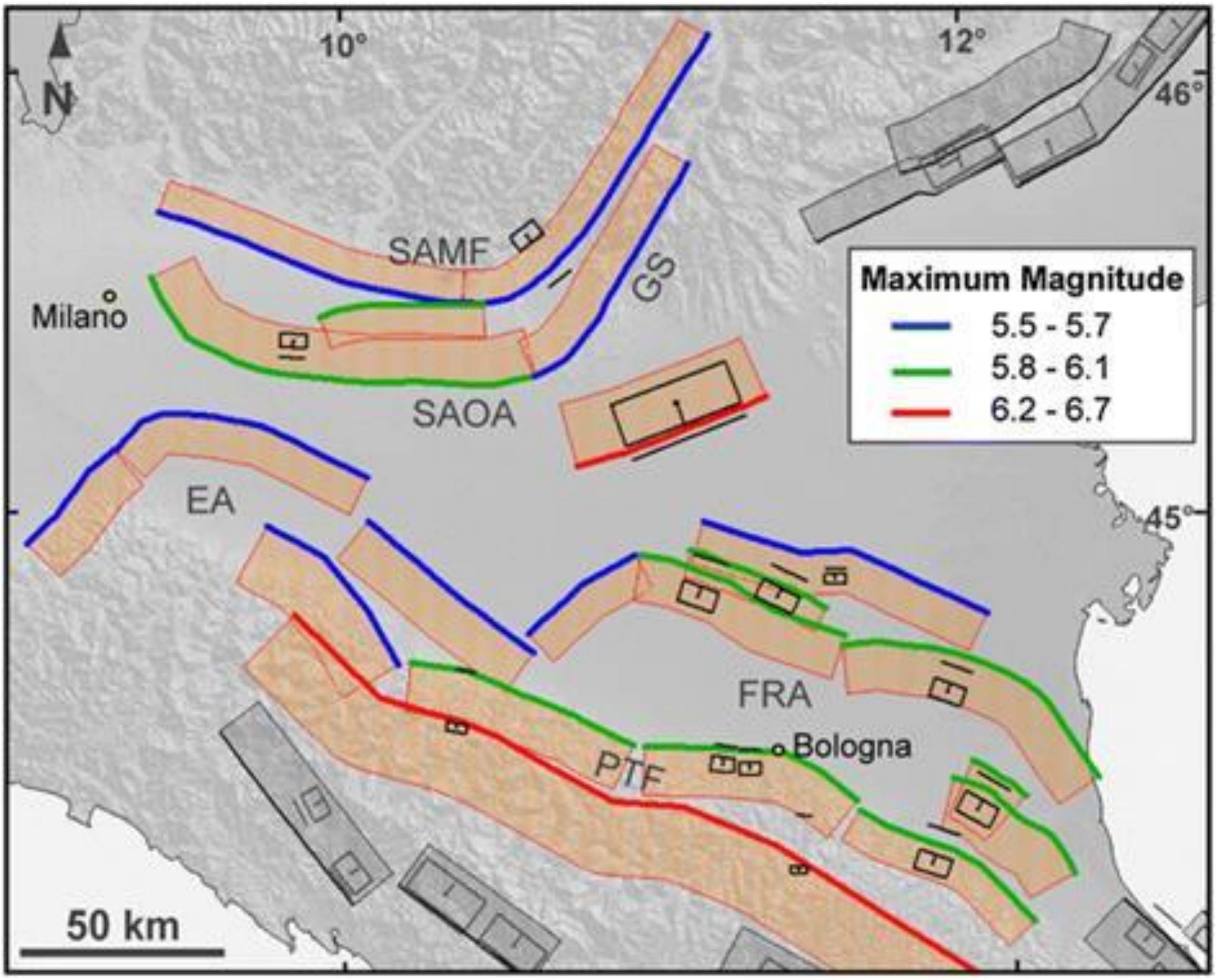

Figure 2. Maximum expected magnitude estimated for all the composite seismogenic sources from the database DISS (Vanolli et al., 2015).

In the lower Triassic the sedimentation started with continental to siliciclastics followed by a carbonate depositional system (Middle Triassic). The maximum basin widening and deepening was achieved, however, only after the late Triassic–Liassic syn-rift phases related to the Ligurian–Piedmontese and Jonian spreading cycle that progressively led to the formation of the 100-km wide Jurassic–Cretaceous Lombardian, Belluno, and Adriatic carbonate basins (*Fantoni & Franciosi, 2010*).

The Po valley, during the alpine orogenic phases (Upper Cretaceous), represented the foreland of the Southern Alps. The foreland was progressively involved in the deformation that involved the carbonate and the overlaying syntectonic siliciclastics. In particular, the pre-Messinian formations have been intensely deformed, displaced and eroded before the Pliocene transgression (*Colucci et al., 2016*). During the Pliocene and the Quaternary, the deposits covered the irregularities producing a sub-horizontal surface, in fact these formations are not affected by relevant deformations or faults. For the aim of the project this information is fundamental since the cap rocks (Santerno's clays) are seemed not to be deformed. On the contrary, Sergnano's gravels might be locally faulted (Fig. 3).

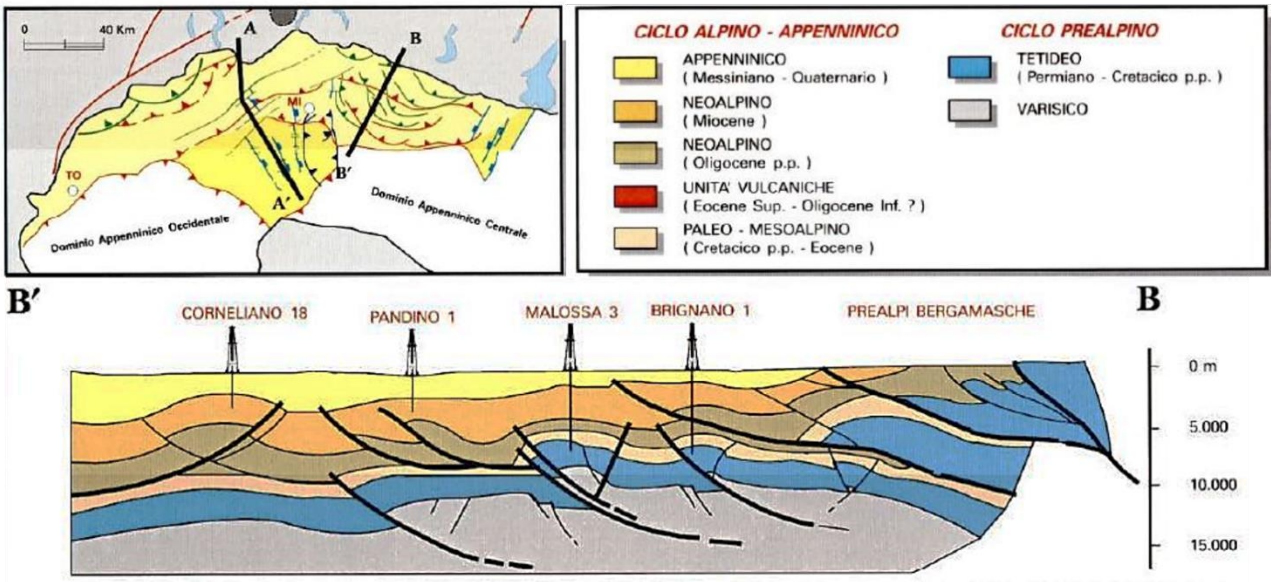

Figure 3. Central sector of the Po valley. Modified after Pieri & Groppi, 1981 (Cassano et al., 1986)

The Sergnano Gravels (Messinian) show different thickness, which varies from few meters (Malossa 11, 13 and 14) to about 210 m (Malossa 2) and declined in Malossa 5 and Malossa 13 wells (Table 4). The Sergnano Gravels are made mostly by polygenic conglomerates with some interbeddings of sand, clay and sandstone (*Mancini et al., 2014*).

Measurements of porosity and permeability are carried out on the core samples with results presented in the table below (Table 1), *Guandalini et al.,2010*). Figure 4 shows an example of porosity estimated from sonic logs (Malossa B well). The Sergnano Gravel porosity has been estimated also from sonic log P-wave velocity measurements by using the Raymer time-average relation (Raymer et al., 1980); porosity ranges from 6 to 39%. (*Colucci et al.,2016*)

The Santerno Clays (Pliocene) present a wide thickness range of about 250-710 m, but is only 62 m thick in Malossa A well (Table 3). In Malossa 2 the Soncino clay replaces the Santerno clay formation. There are not differences between them in the lithology and neither in the time of deposition. The formation is composed of clays with quartz sand interlayers (*Mancini et al., 2014*).

Table 1. Porosity and permeability data (Guandalini et al., 2010).

	Porosity (%)	Permeability (mD)
Sands and Clays	20–30	3–1250
Conglomerates	14–30	0.2–960
Sandstones and Conglomerates	18–30	10–1500
Conglomerates and Clays	18–30	10–1500

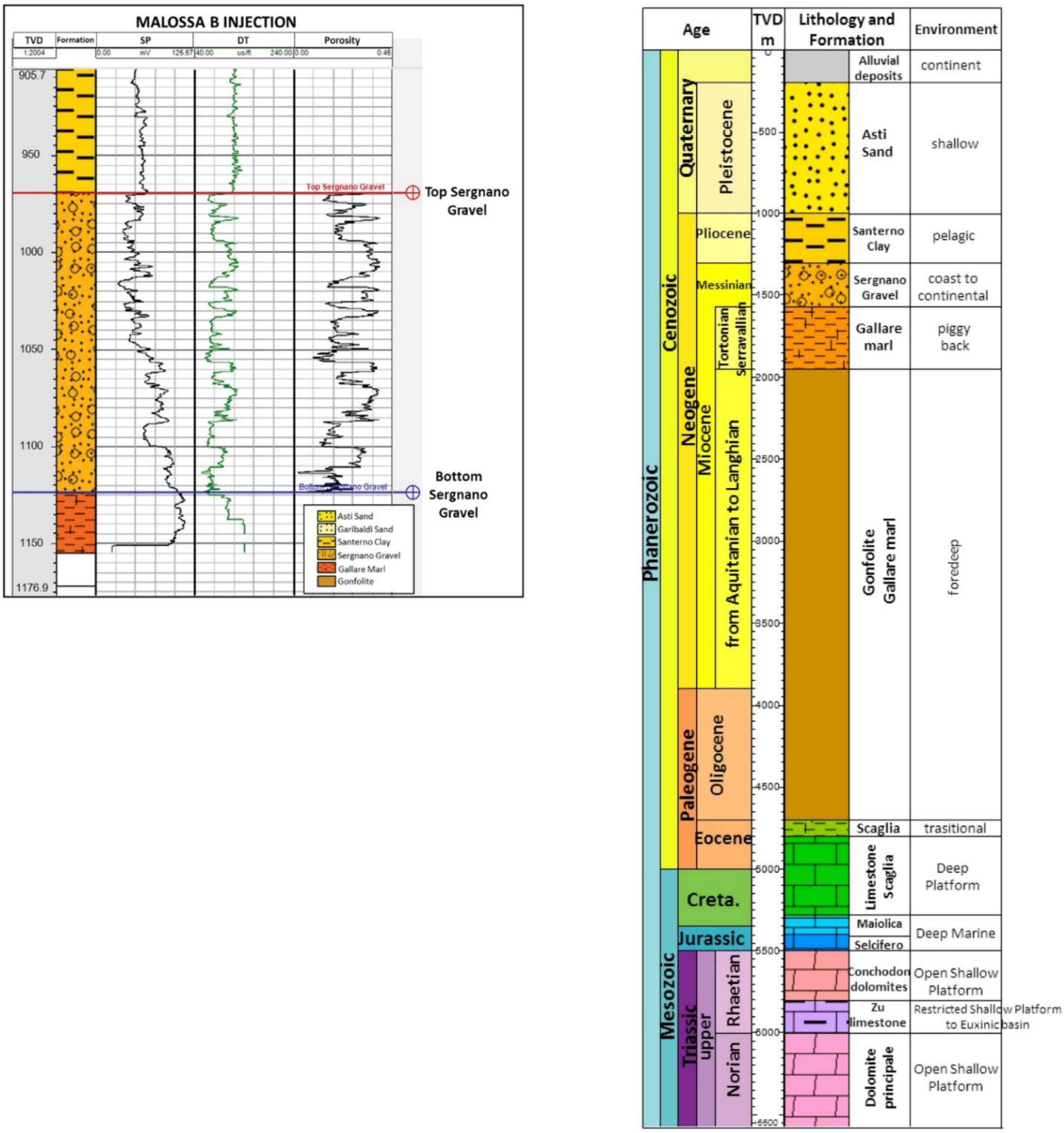

Figure 4. Lithological section of the Sergnano gravel reservoir with sonic log, spontaneous potential and porosity from Malossa B well. Stratigraphic chart on the right side (Colucci et al., 2016).

3. Methods and data

This work is based on the analysis of the data collected in the ViDEPI database (https://www.videpi.com/videpi/videpi.asp). This database includes various documents such as well logs, which have been used to reconstruct the stratigraphy and to highlight the caprock-reservoir system. In particular, to define thickness and depth of the caprock and of the reservoir.

The geological formations suitable for CO_2 storage must fulfil particular criteria, as established in the framework of the EU FP6 Geocapacity (*Vangkilde-Pedersen et al., 2009*).

The essential parameters are (1) the presence of a reservoir with adequate characteristics of porosity and permeability, (2) the presence of an impermeable caprock with suitable thickness that prevents the possible migration of the CO_2, (3) the presence of structural traps such as anticlines, pinch out that can control the extent of the CO_2 migration, (4) a thickness less than 20 m is not safe whereas greater than 100 m is preferable, (5) a location of the reservoir should be at least 800 m because temperature and pressure are high enough to reach the CO_2 in the supercritical phase, it means maximizing the quantity stored. In supercritical condition, the CO_2 density is about 500 kg/m^3, in sedimentary basins where the geothermal gradient is about 25/30°C/km the supercritical condition is reached at about 800 m of depth.

All the available geological data have been evaluated to create the 3D static model of the Malossa structure.

The analysis of the contour maps of the reservoir top and the thickness contour map, taken from the study "A feasibility study for CO_2 geological storage in the Northern Italy" (*Colucci et al., 2016*) allowed to reconstruct the different geological formations.

After that, the 3D static geological model has been elaborated by $Petrel^{TM}$, the most popular software for modelling. The $Petrel^{TM}$ code, is manufactured and marketed by the multinational Schlumberger. It is a cutting-edge code that allows:

• management and cross-comparison of a variety of geological and geophysical data/information;

• effective graphic support for 2D/3D representations;

• various operations such as 3D visualization of well profiles, insertion of stratigraphic and structural surfaces, representation of fault surfaces, visualization and processing of seismic data for both geological and structural modelling purposes.

In this work, the two geological surfaces, previously digitalized in QGIS *(Qgis, D. T. (2015).* have been imported in Petrel, where the 3D model has been created. This operation is done in the section called "Geological and Structural Modelling" available in Petrel. This module allows obtaining, in 3D, accurate structural models of the potential reservoir to be investigated, as well as a precise representation of the stratigraphy. All with the ability to view the model with a high resolution. Inside this module there are commands for modelling of well logs, surfaces, faults and structures connected to them, fractures and petrophysical modelling.

Three surfaces have been considered: the Caprock, top and bottom of the Sergano Gravel reservoir Formation. I focused on the reservoir since the aim was to evaluate the storage capacity of the structure. The 3D grid has been created and it has been populated with the petrophysical properties. Since the lack of data, I simplified the model using just one facies. Successively, log data were imported into the model, in particular the porosity data that have been acquired from Colucci et al. (*2016*). After that, thanks to the layering function, these data from one well has been exported to all the other wells. Later, the 3D petrophysical model has been populated with porosity data, using the modelling algorithm called "Sequential Gaussian Simulation".

3.1 Calculation of CO_2 storage capacity

The knowledge of the available CO_2 storage capacity is required for the implementation of CCS technology.

The calculation of the CO_2 storage capacity can be done at different scales in order to increase or decrease the resolution (from country level to the local site), it depends also on the type of field where the CO_2 storage would be implemented (oil and gas field, CO_2-EOR (enhanced oil recovery), coal beds methane, or saline aquifer).

Other important parameters that should be evaluated are the techno-economics aspects. For that reason, the *Techno-Economic Resource-Reserve Pyramid for CO_2 storage capacity* has been proposed (*Bradshaw et al., 2007*). The various storage capacity is nested within the pyramid, and their size and position vary in time as data, knowledge, technology, policy regulatory framework and economics of CO_2 geological storage change (*Bachu et al., 2007*).

In this work, the method used for the evaluation of the CO_2 storage capacity is based on the well-known formula for estimation of the capacity of the structural trap (*Bachu et al., 2007*) and some additional approaches proposed by the EUGeoCapacity project (*Vangkilde-Pedersen et al., 2008*). This method involves the concept of "total affected space" which is the total space influenced by the injection of CO_2. This parameter depends not only on the storage potential of a specific site but also on the porosity and permeability of the reservoir rocks. Furthermore, this method provides the estimation of the "effective storage capacity" based on the bulk volume, since detailed knowledge of the reservoir itself is often unavailable. The formula is:

$$\mathbf{MCO_2 = A * h * NG * \varphi * \rho CO_2 * S_{Eff}} \quad (1)$$

where the effective storage capacity (MCO_2) is the product of the area of the region or the basin occupied by the aquifer (A); h is the effective thickness multiplied by the net to gross ratio (NG) (net to gross ratio has been estimated from ViDEPI database well logs. It is 50% because of high presence of clays in the reservoir); φ – the average porosity of the reservoir formation; the CO_2 density (ρCO_2) should be calculated at the reservoir conditions (the density of the CO_2 is estimated according to the www.energy.psu.edu/tools/CO2-EOS/ website, knowing the pressure and the temperature. The temperature was provided by the ViDEPI database. In particular, from Malossa B well. To evaluate the pressure, two wells on the anticlines have been considered: Casirate 001 and Malossa B. The sum of both average pressures, is the pressure that has been considered for the calculations); storage efficiency factor (S_{Eff}) is a parameter that reflects a fraction of the total pore volume that can be filled by CO_2 during the injection (*Bachu et al., 2007, Van der Meer & Egberts, 2008*). This factor normally ranges between 1% and 4% for the "Conservative" estimation (*U.S. Department of Energy, 2008*). While for the "Optimistic" S_{Eff} recommendations from the EU GeoCapcity FP6 project (*Vangkilde-Pedersen, et al., 2009*) report were used. They are based on experience from natural gas storage facilities in France, Germany and Denmark and supported by numerical simulation of CO_2 injection in Bunter 2 Sandstone reservoirs in the UK sector of the southern North Sea and on numerical simulation of CO_2 injection in the Havnso 2 Structure onshore Denmark (*Vangkilde-Pedersen et al., 2009*). In this work, the S_{Eff} has been evaluated using the two approaches. For the conservative method, the 4% has been chosen based on the evaluation of the US department (*US DOE, 2008*). For the optimistic the S_{Eff} is 10%, according to "the cartoon approach" that is described in Vangkilde-Pedersen et al. (*2009*), since the reservoir is confined from two sides (East and South), but also has zero capacity in one well at the west (Malossa 13).

3.2 Wells

This area, from a structural point of view, includes two ramp anticlines: Malossa to the west and San Bartolomeo to the east. In the present day, these are depleted hydrocarbon fields which were discovered by Eni (Fig.5).

Figure 5. Wells location from Google Earth.

Table 2. Drilling depth of the wells

WELLS	DEPTH (m)
Casirate 001	1296
Casirate 002	1238
Cassano D'Adda	3487
Malossa 001	5545
Malossa 002	6471
Malossa 003	6173
Malossa 004	6197
Malossa 005	2506
Malossa 007	5700
Malossa 008	5927
Malossa 009	5558
Malossa 010	5830
Malossa 011	5450
Malossa 012	5621
Malossa 013	5651
Malossa 014	5421
Malossa A	5497
Malossa B	1371

The Malossa area has been identified only on the basis of the 18 wells data since no seismic data are available: Malossa 1−5, 7−14, Malossa A and B (planned as an injections wells), Casirate 001, Casirate 002 and Cassano D'Adda (Fig. 5). Wells were drilled to use the porous formations for the water disposal produced by the Malossa's hydrocarbon field. The maximum depth reached by the perforation is around 6500 m while the minimum is around 1240 m (Table 2). The wells depth is reported from the rotary table, which is around 100 m in the Malossa B well.

In all the wells geophysical electric logs have been made using resistivity logging and spontaneous potential tools (SP). Only in Malossa B well the sonic log has been made (DT), permitted to estimate the porosity using the Raymer time-average relation (Raymer et al., 1980) (Fig.4) *(Colucci et al., 2016).*

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4. Results

4.1 Reservoir and caprocks

Thanks to ViDEPI (*Visibility of Petroleum Exploration Data in Italy*, (*https://www.videpi.com/videpi/videpi.asp*) promoted by the Ministry of the Economic Development it is possible to have public access to technical documents like seismic logs, geological and structural maps.

The local stratigraphy was reconstructed to identify the caprock-reservoir system. For CO_2 geological storage the potential caprock-reservoir system is represented by the Santerno Clay, deposited during the Pliocene, and a Messinian Sergnano Gravel conglomerate Formation (Figure 4).

The caprock location and thickness, as well as the reservoir's data, are presented in the tables below (Tables 3–4).

Table 3. Caprock depths and thicknesses (Modified after Guandalini et al., 2010).

Wells	Top depth (m)	Bottom depth (m)	Thickness (m)
Casirate 001	810	1073,5	268,5
Casirate 002	910	1110	200
Cassano D'Adda	840	1380	540
Malossa 001	825	1280	455
Malossa 002	842	1107,5	265,5
Malossa 003	802	1192,5	390,5
Malossa 004	775	1483	708
Malossa 005	685	1175	490
Malossa 007	861	1386	525
Malossa 008	725	970	245
Malossa 009	894	1437	543
Malossa 010	782	1132	350
Malossa 011	870	1337	467
Malossa 012	877	1365	488
Malossa 013	842	1320	478
Malossa 014	892	1318	426
Malossa 015	904	1418	514
Malossa A	1050	1112	62
Malossa B	725	970	245

Table 4. Reservoir depths and thickness (Modified after Guandalini et al., 2010).

Wells	Top depth (m)	Bottom depth (m)	Thickness(m)
Casirate 001	1073,5	1266	192,5
Casirate 002	1110	1240	130
Cassano D'Adda	1380	1565	185
Malossa 001	1280	1320	40
Malossa 002	1107,5	1319	211,5
Malossa 003	1192,5	1279	86,5
Malossa 004	1483	1572	89
Malossa 005	1175	1175	0
Malossa 007	1386	1470	84
Malossa 008	970	1070	100
Malossa 009	1437	1471	34
Malossa 010	1132	1166	34
Malossa 011	1337	1339	2
Malossa 012	1365	1375	10
Malossa 013	1320	1320	0
Malossa 014	1318	1331	13
Malossa 015	1418	1425	7
Malossa A	1112	1316,5	204,5
Malossa B	970	1225	155

4.2 Geological Models

The result of the digitalization of the two surfaces: the top of the reservoir and its bottom are shown in Figure 6. The structure is confined in the East and South parts, where the thickness of the reservoir is zero. Based on the decline of the thickness, the reservoir could be interpreted as a stratigraphic trap at its eastern and southern borders. Unfortunately, the model has a lack of data in the northern part. The northern border has been defined based on the 1500 m depth contour and the outcome is presented in Figure 7.

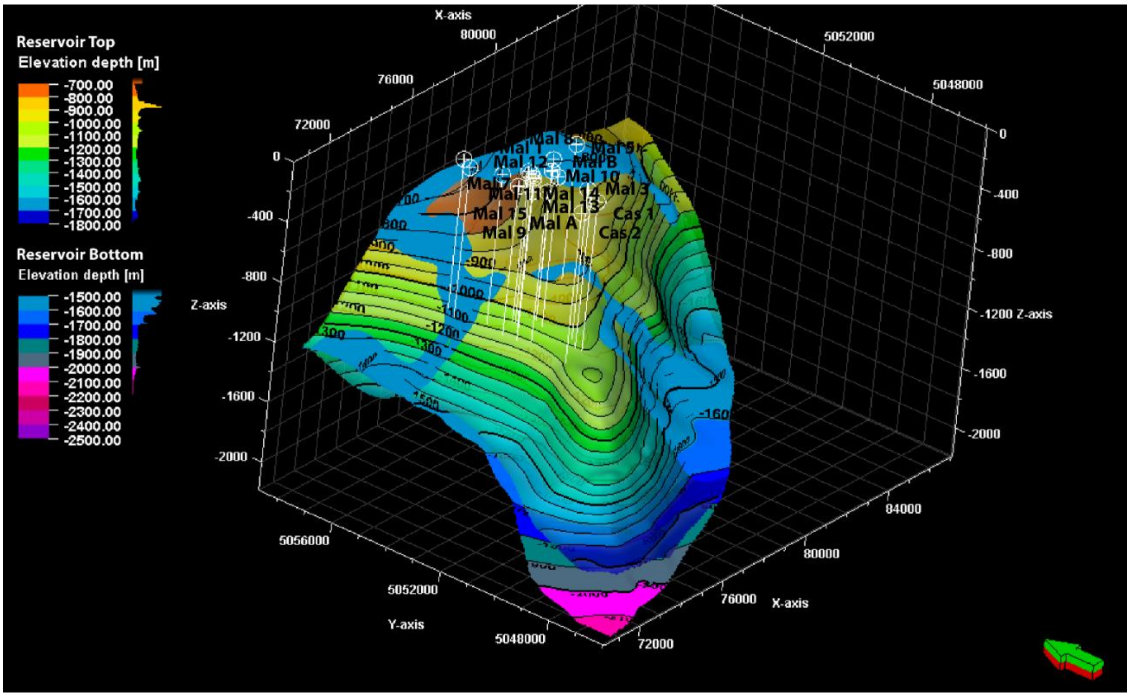

Figure 6. 3D model of the top and bottom of the Sergnano gravel reservoir. The high transparency of the top reservoir allowed to examine where the bottom reservoir merges with the top.

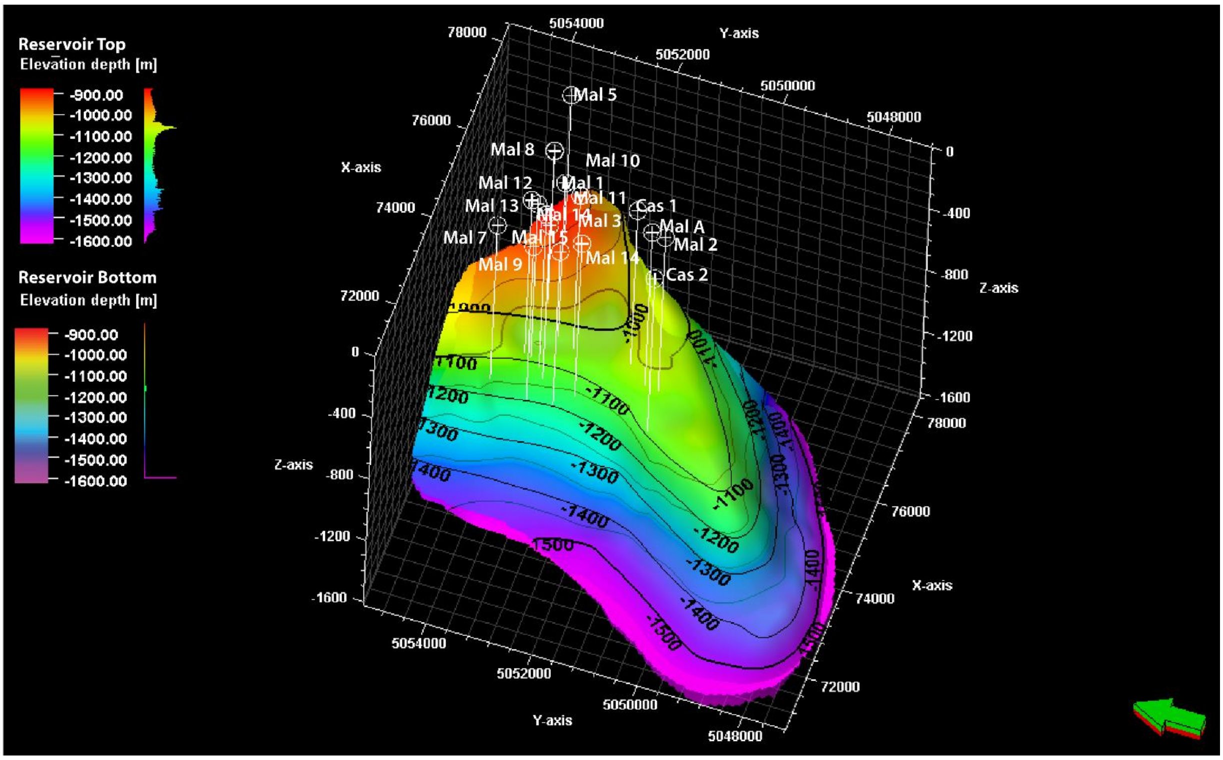

Figure 7. The final version of the 3D geological model of the Sergnano Gravel reservoir Formation top and bottom.

Figure 8 is the 2D contour map of the top of the reservoir with the wells and cross-section line A−B shown. The geological model has been filled with porosity data and the result is presented in Figure 9.

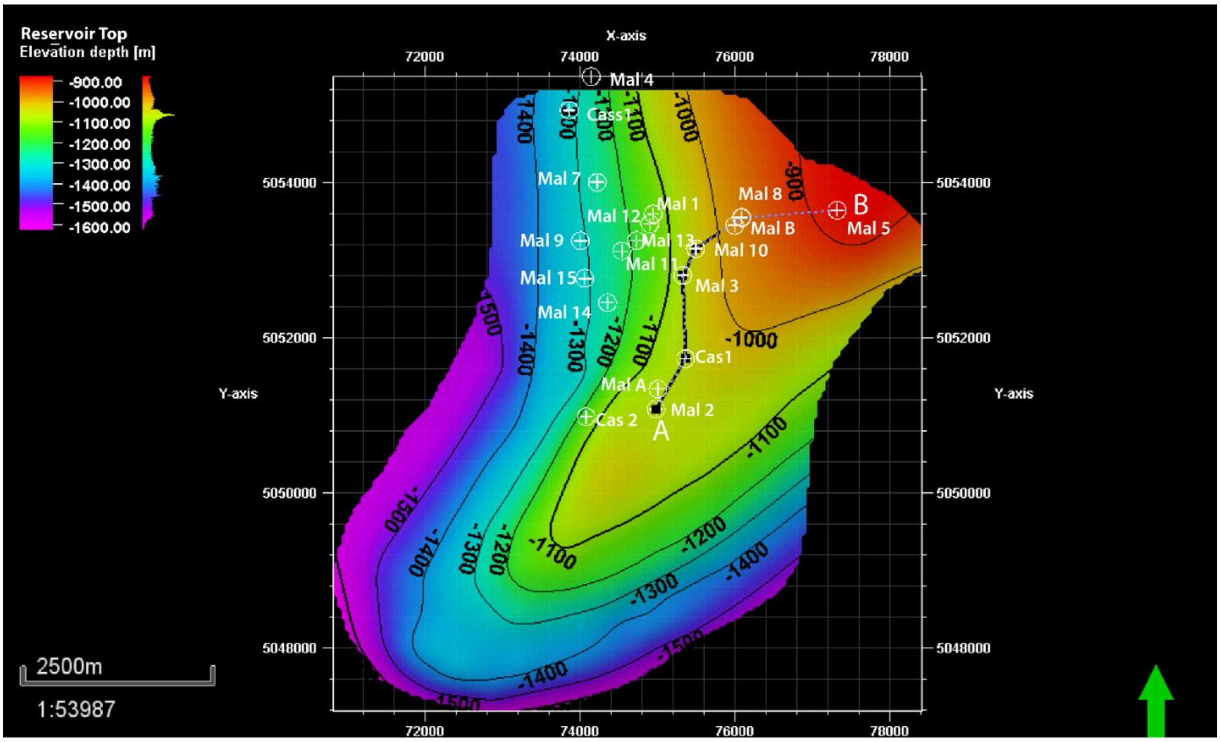

Figure 8. 2D contour map of the Sergnano gravel reservoir top with wells and cross section line A−B.

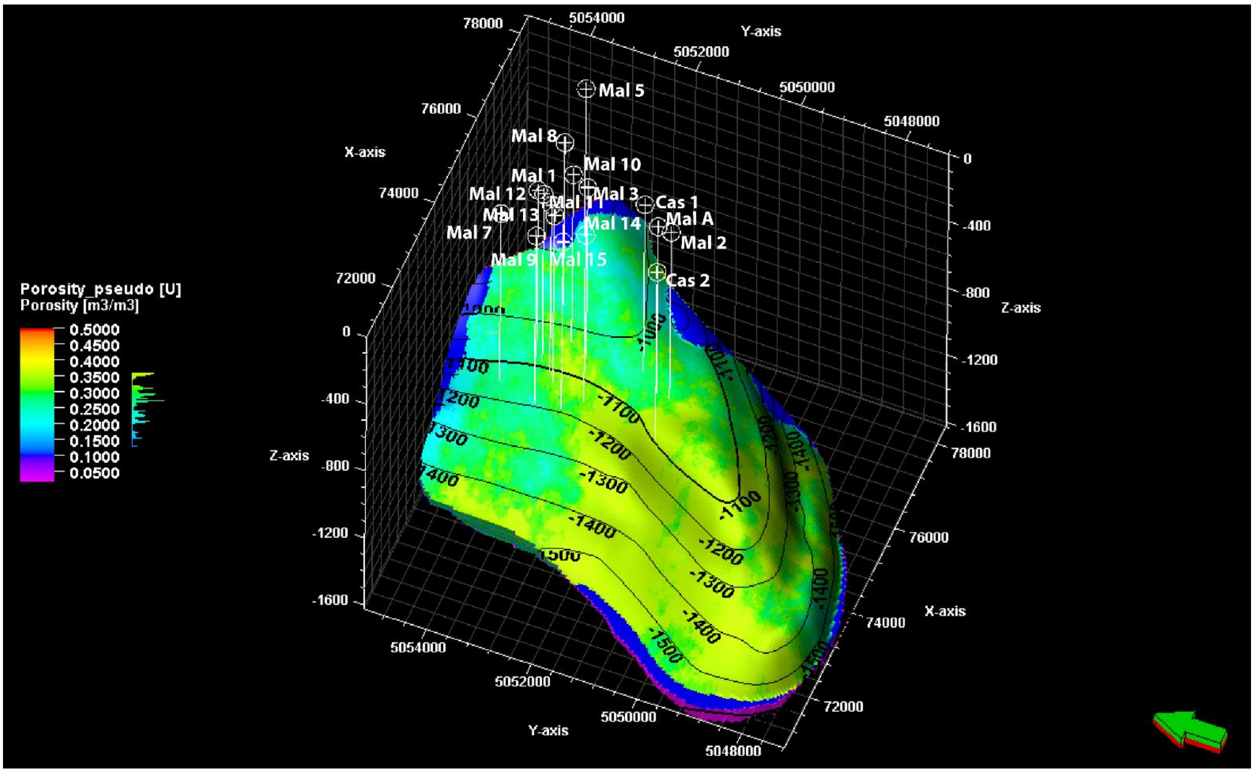

Figure 9. 3D model of the Sergnano gravel reservoir Formation top filled with the porosity data.

The thickness of the Sergnano gravel reservoir Formation varies from 0 m to 210 m (Fig. 10). It is evident that the model is confined as a stratigraphic trap at the East and North borders.

The geological cross section reveals that the Malossa area, in the shallow part, is not deformed (Fig. 11). The reservoir is confined in lens of gravels (Sergnano Formation) and the caprock (the Santerno clay) is enough thick and continuous laterally to avoid any possible leakage.

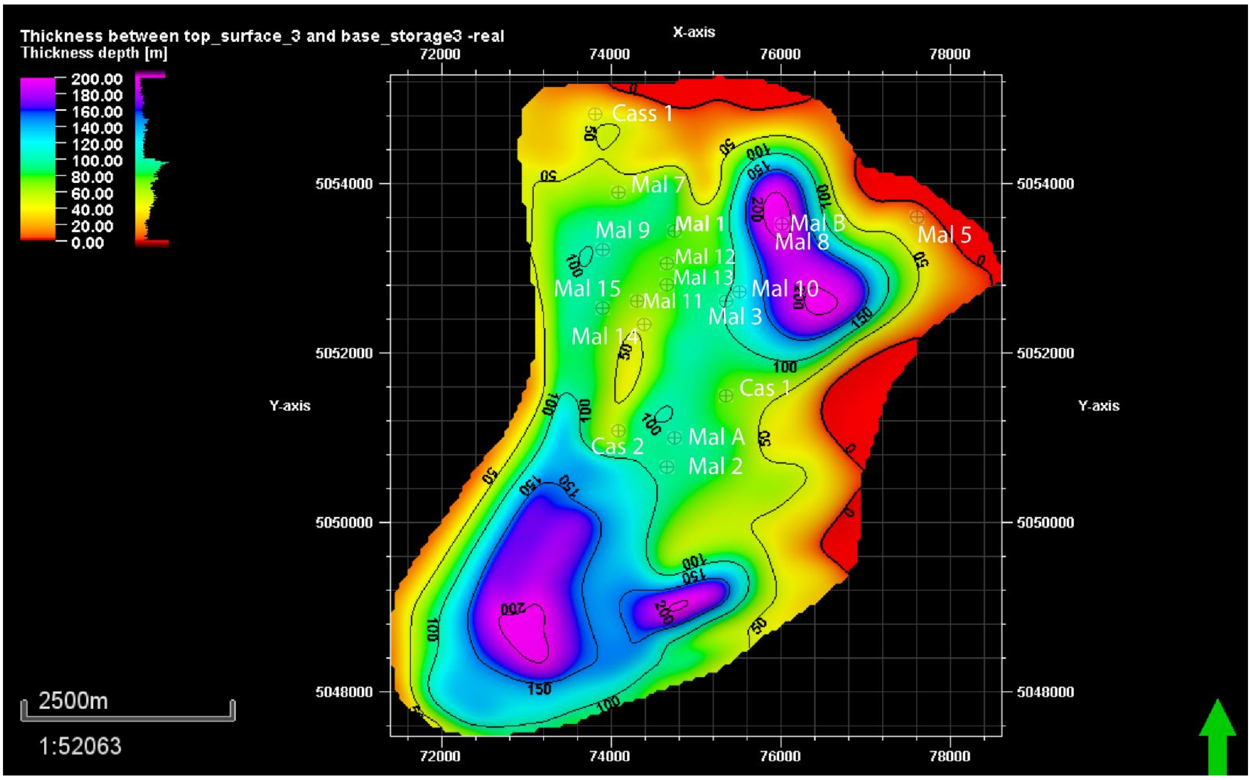

Figure 10. Thickness map of the Sergano Gravel Formation reservoir rocks declined at the East and North.

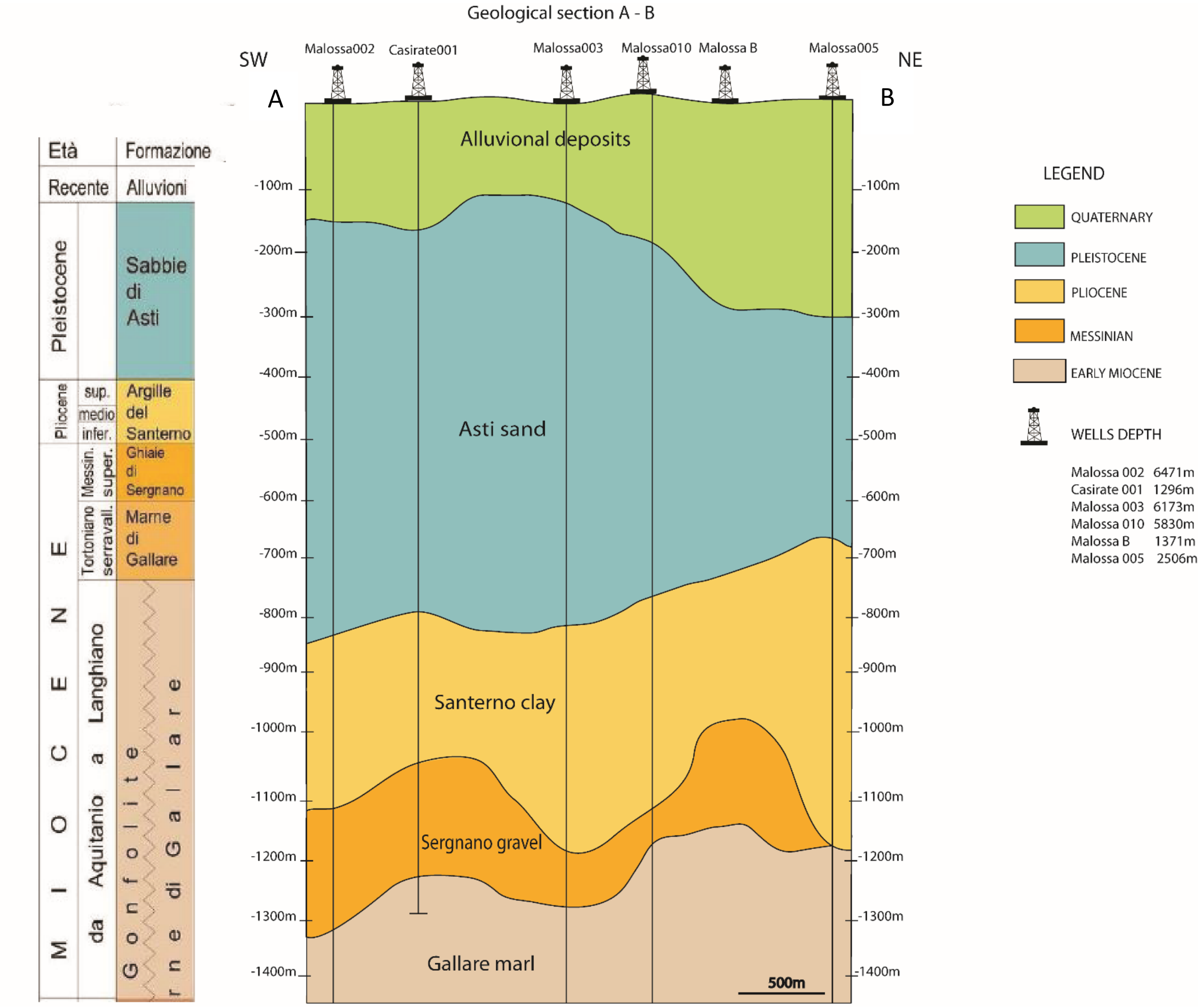

Figure 11. Geological cross section along the A–B line shown at the Figure 6. Stratigraphic chart from Guandalini et al. (2010).

4.3 CO_2 storage capacity estimation

The estimated storage capacity of the Sergnano Gravel reservoir Formation is presented in Table 5.

Table 5. Data for the CO_2 storage capacity calculation.

Ahφ (pore volume from Petrel)	$710*10^6\ m^3$
Ah (bulk volume from Petrel)	$2831*10^6\ m^3$
Min porosity	12.5%
Average porosity	26%
Max porosity	38%
Net to Gross Ratio (NG)	50%
Average Pressure	11.2 Mpa
Temperature at 1200 m depth	40°C
CO_2 density	$691.44\ kg/m^3$
S_{Eff} Cons./ Opt.	4%–10%

CO_2 storage capacity, Mt			
Optimistic		**Conservative**	
Min	11.87	**Min**	4.75
Max	37.58	**Max**	15.03
Average	24.79	**Average**	9.91

The calculation of the thickness, the area and the average porosity of the structure was taken from the calculation of the pore volume from Petrel. The average porosity is 26% (calculated using the Petrel model) alters between a minimum value of 12.5% to a maximum of 38%.

The total CO_2 storage capacity of the Malossa structure based on the conservative approach, considering the average porosity, is 9.91 Mt whereas the total CO_2 storage capacity based on the optimistic approach is 24.8 Mt.

5. CCS Scenario

5.1 Methods and data

For modelling of CCUS scenarios it is possible to include data on cement plants and other large emission sources located in the vicinity. It is also important to evaluate the possible transport routes such as available natural gas pipelines infrastructure, roads and railways. Storage sites for scenarios could be chosen among the most prospective structures in saline aquifers and depleted oil and gas fields. Parameters which are sensible for cost estimation should be considered to decrease transport and storage costs (*Shogenova et al., 2018*).

According to the methodology developed by the Cleanker project (*Shogenova & Shogenov, 2020*), the amount of the produced CO_2 applied in the scenario should be the most recent one and for the cement plants it is expected that CO_2 should be captured using Ca-looping technology. Other technical parameters include the pipelines design and the injection infrastructure.

All the data for the produced CO_2 emissions, clinker and cement and for the used fuel by the cement plants were collected by the CLEANKER project and were allowed to be used in this study.

The pipelines will be designed using X70 steel and 1500 lb flange rating (rated to 25.5 Mpa upper working pressure) with a maximum allowable working pressure of 15 MPa. The pipeline diameter was be selected depending on the distance and the flow rate of CO_2 calculated for the specific scenario *(EPRI,2015, Shogenova & Shogenov, 2020*).

Injection infrastructure will include wells, storage site facilities and monitoring equipment. Operation can include old wells reuse (if any available), new wells drilling, geophysical well logging and well-head pressure and temperature monitoring, CO_2 injection and monitoring of the storage site. It will include baseline monitoring, operational monitoring and post-closure monitoring. The number of wells needed was determined by the CO_2 flow rate, and storage reservoir properties including thickness, total injection depth and permeability (*EPRI, 2015*).

For CCS scenarios the estimated in this work average optimistic storage capacity of the Sergnano Gravel reservoir in Malossa structure was applied. The distance of pipelines was estimated using QGIS.

5.1.1 Industrial CO_2 emissions

The data for industrial CO_2 emissions were taken from the EU Emission Trading System. It contains three operating phases (*EU ETS, 2018*): phase 1 from 2005 to 2007, phase 2 from 2008 to 2012 and phase 3 runs from 2013 to 2020. The next step is the finalization of phase 4 (2021−2030).

Table 6. CO_2 *emissions from industrial installations as a percentage of the previous year.*

Country	2014	2015	2016	2017
Italy	92.78	102.24	99.22	100.16

During 2015−2017 registered in EU ETS emissions did not decrease in Italy (Table 6).

The map below shows the location of two Buzzi Unicem and one Heidelberg owned cement plants in the Northern Italy, selected for the Italian CCS scenario (Fig. 12).

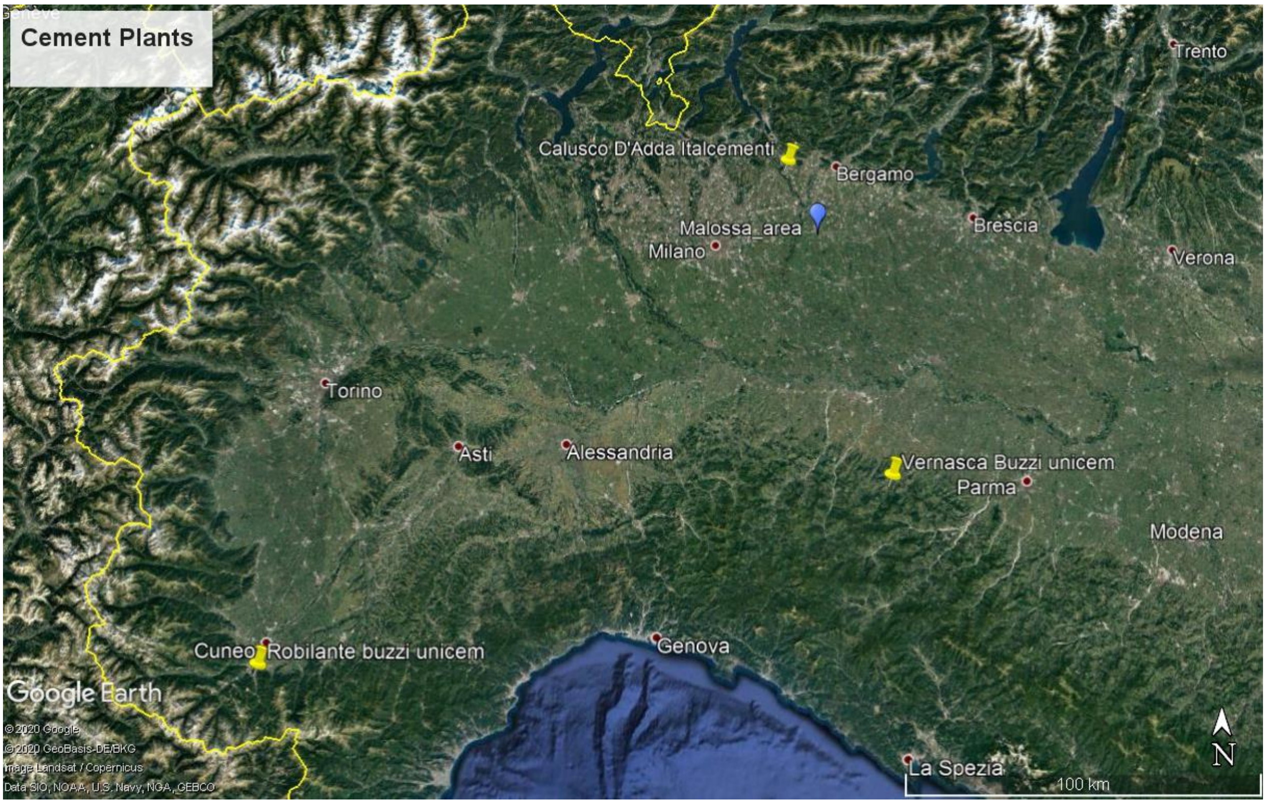

Figure 12. Location of three cements plants selected for CCS scenario in the Northern Italy.

The tables below show the total amount of CO_2 emissions for the year 2018 from three selected cement plants (Table 7). The different type of fuel used is presented in Table 8.

Table 7. CO_2 *Emissions produced by two Buzzi and one Heidelberg cement plants in the Northern Italy.*

Location			Name of the plant	Company Owner/owners	CO_2 total emission (Kt/yr) 2018
Italy	Robilante	Piemonte	Buzzi Unicem Robilante	Buzzi Unicem	694.93
Italy	Vernasca	Emilia Romagna	Buzzi Unicem Vernasca	Buzzi Unicem	445.363
Italy	Calusco D'adda	Bergamo	Italcementi	Heidelberg italcelcementi Spa	903.583

Table 8. Different type of fuel used.

Name of the plant	Consumption Type of fuel	Fuels (Units)	
		2018	**Units**
Buzzi Unicem Robilante	**Petrol coke**	60.165	Kt
	Refuse-derived fuel Refuse-derived fuel (RDF) (fuel produced from various types of waste)	48.724	Kt
	Coal	2.302	Kt
Buzzi Unicem Vernasca	**Natural gas**	839.43	1000 Nm^3
	CAV (high viscosity oil)	42.944	Kt
	Animal meal	4.174	Kt
Italcementi Calusco D'Adda	**Petcoke, gas and RDF**	3706	Tj

5.1.2 Buzzi Unicem – Vernasca and Robilante cement plants

The CLEANKER (CLEAN clinKER production by calcium looping process) project got EC support from October 2017 to September 2021 under the Horizon 2020 call "Enabling decarbonization of the fossil fuel-based power sector and energy intensive industry through CCS" to advance the integrated Calcium looping process for CO_2 capture in cement plants (www.cleanker.eu).

The core activity of the project is the design, construction and operation of a CaL demonstration system including the entrained-flow carbonator (the CO_2 absorber) and the entrained-flow oxyfuel calciner (the sorbent regenerator).

This demonstration system will be connected to the Buzzi Unicem kiln of the Vernasca cement plant (Italy) and will capture the CO_2 from a slip stream of the flue gases from the kiln, using the same raw meal that is used for clinker production as CO_2 sorbent (*Fantini et al., 2019*).

In particular, the CLEANKER will develop the integrated CaL process configuration, by building a demonstration plant that will be connected to the 1.3 Mt/year cement plant in Vernasca.

Buzzi Unicem was found in 1907 by Buzzi brothers with a production site in Trino. In its home country, Buzzi Unicem manufactures and distributes cement, ready-mix concrete, natural aggregates and related products.

In the cement division, the company operates 9 plants, 4 grinding facilities, 2 terminals located throughout the country. With a production capacity of approx. 10.8 million tons/year, Buzzi Unicem is the second largest industry player in the country.

Vernasca cement plant is located in a small village called Mocomero in the province of Piacenza. The cement plant is near the Vernasca town which is 110 km far from Milano and 140 km from Bologna. Whereas, the Robilante cement plant is located in the Robilante village, in the north-west.

The table below showed the production of cement and clinker for the year 2018 for both cement plants (Table 9).

Table 9. Clinker and Cement production in Robilante and Vernasca cement plants.

Production / Cement plants / Year	Clinker (Kt)	Cement (Kt)
	2018	**2018**
Robilante Buzzi Unicem	859.69	571.046
Vernasca Buzzi Unicem	575.47	786.113

5.1.3 Heidelberg Italcementi SPA – Calusco D'Adda cement plant

HeidelbergCement is one of the world's largest building materials companies. With the takeover of the Italian cement producer Italcementi, HeidelbergCement became the number one in aggregates production and ready-mixed concrete and number two in cement. Both companies complement each other perfectly: on the one hand due to major similarities in product areas and organization structures, and on the other hand due to their different geographical footprints without major overlaps. The core activities of HeidelbergCement include the production and distribution of cement and aggregates, the two essential raw materials for concrete. Our downstream activities include mainly the production of ready-mixed concrete, but also of asphalt and other building products in some countries (https://www.heidelbergcement.com/en/company).

The cement plant of Calusco D'Adda is one of the most advanced plants of the production system of Italcementi, efficient and at the same time environmentally friendly. Founded in 1907, it became part of the production network of Italcementi in the first postwar period. In past the plant was at the center of some important first interventions of renovation and modernization with particular attention to the production cycle, control systems, the reduction of energy consumption and the quality of products.

In 2004 the cement plant was completely renovated, becoming one of the most performing and sustainable plants in Europe. Thanks to revamping, the advanced production performance corresponds to high environmental performance, with very low emission levels and low consumption of raw materials, fuels and water resources.

In 2006 an underground strip was activated along 10 kilometers that connects the quarry Colle Pedrino (Palazzago - BG) with the deposit of the raw materials limestone and marl of Monte Giglio (Calusco d'Adda). The start of this tunnel has allowed avoiding the circulation on the road of beyond 10.000 road trains per year (https://www.italcementi.it/it/cementeria-di-calusco-d-adda). The clinker and cement production in Calusco D'adda cement plant is presented in Table 10.

Table 10. Clinker and Cement production of the Calusco D'Adda cement plant.

Production Cement plant / Year	Clinker (Kt)	Cement (Kt)
	2018	**2018**
Italcementi Calusco D'adda	1097	955

5.2 CCS scenario for the cement plants

In this section different optional scenarios have been created, considering that the average storage capacity of Sergano Gravel reservoir in the Malossa structure is 24.8 Mt (optimistic method).

The first scenario considers CO_2 storage from the three cement plants, which together produce 2.044 Mt of CO_2 per year, so the Malossa structure will allow the storage of the emission for at least 12 years. In this way 8.43 Mt of CO_2 can be stored from the Robilante Buzzi Unicem cement plant, 5.4 Mt from Vernasca Buzzi Unicem and 10.96 Mt from Calusco D'Adda Italcementi (Table 11).

The second scenario considers just two cement plants. In particular CO_2storage capacity for, Vernasca Buzzi Unicem and Calusco D'Adda Italcementi will be enough for more than 18 years (Table 11).

The third scenario evaluates the storage of the CO_2 emission for the single cement plant. Definitely, the storage capacity will be enough for a longer period for every plant. Respectively, it is 35.7 years for Robilante, 55.7 years for Vernasca and just 27.40 years for Calusco D'Adda. Considering that maximum possible duration of CCS project is about 30 year, the storage capacity will be enough for the full project duration for any single plant (Table 11).

Two wells are necessary for each scenario: one for injecting the CO_2 and the other for monitoring. If the scenario includes two cement plants together, such as Robilante Buzzi Unicem and Calusco d'Adda

Italcementi, the total numbers of wells (injection and monitoring) are two. The numbers of wells increased for three plants scenario because 4 wells will be needed (2 injection and 2 monitoring).

Table 11. CO_2 emissions (blue) and project duration (green) for three North-Italian CCS scenarios.

Technical parameters	Cement Plants			Total CO_2 emissions, Mt
	Buzzi Unicem Robilante	Buzzi Unicem Vernasca	Italcementi Calusco D'adda	
CO_2 emissions per year, Mt	0.695	0.445	0.904	2.04
Duration of storage for 3-plants scenario, years	12.1			24.8
Total CO_2 emissions for 3-plants scenario, Mt	8.43	5.40	10.96	24.8
Duration of storage for two plants scenario, years	-	18.4		24.8
Total CO_2 emissions for 2-plants scenario, Mt	-	8.2	16.6	24.8
Duration of storage for one plant scenario, years	35.7	55.7	27.4	24.8
Total CO_2 emissions for one-plant scenario, Mt	24.8	24.8	24.8	24.8

5.2.1 CO_2 transport

Onshore CO_2 can be transported by either pipelines, trucks or railways. In this work, CO_2 pipelines will be constructed along available roads and natural gas pipelines. Available natural gas pipeline infrastructure is presented in the North of Italy (*GIE- http://www.gie.eu/index.php/maps-data/gse-storage-map*). The proposed CO_2 pipelines routes are proposed to be constructed along available roads and natural gas pipelines (Fig.13, Table 12). The total distance from the Robilante cement plant is 330 km, from Vernasca is 125 km. The common part of the CO_2 pipelines from these plants is about 100 km. The distance by pipelines from Italcementi Calusco D'adda is only 34 km (Table 12).

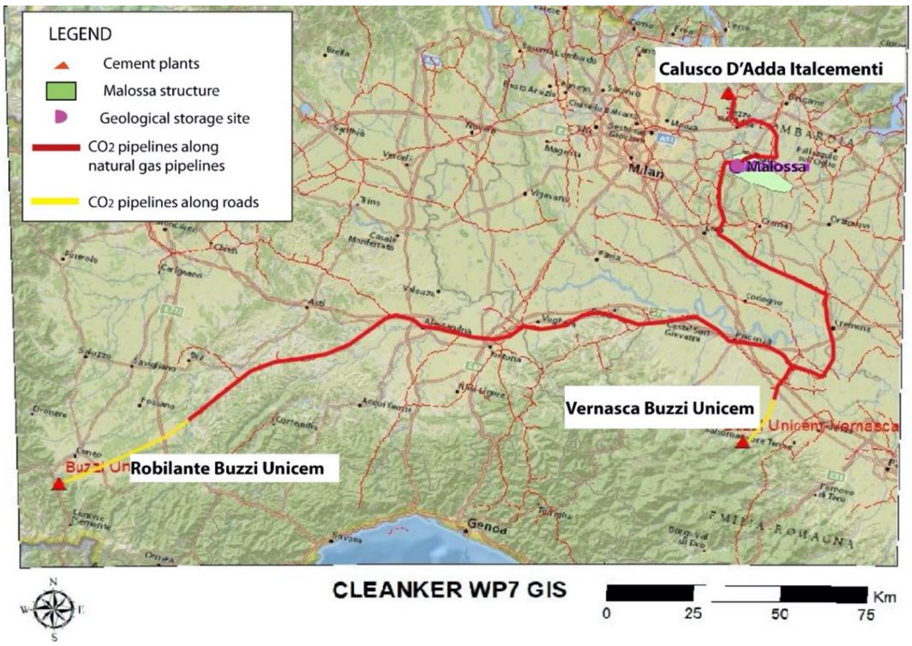

Figure 13. Proposed CO_2 pipelines constructed along available roads and natural gas pipelines.

Table 12. CO_2 pipelines distance for three North-Italian CCS scenarios.

Technical parameters	**Cement Plants**			**Total pipeline distance per scenario, km**
	Buzzi Unicem Robilante	**Buzzi Unicem Vernasca**	**Italcementi Calusco D'adda**	
CO_2 pipeline distance (from one-plant/common), km (3-plants scenario)	230/100	25/100	34	389
CO_2 pipeline distance, km (2-plants scenario)		125	34	159
CO_2 pipeline distance, km (one-plant scenario)	330	125	34	

The pipelines will be designed using X70 steel and 1500 lb flange rating (rated to 25.5 Mpa upper working pressure) with a maximum allowable working pressure of 15 MPa. The pipeline diameter was selected depending on the distance and flow-rate of CO_2 calculated for the specific scenario will be applied *(EPRI, 2015*). The pipelines of 180-, 220- and 280-mm diameter were selected for all three scenarios, considering that maximum CO_2 flow for the 3-plants scenario is 2 Mt per year, for the 2-plants scenario is 1.35 Mt per years and for the 1-plant scenarios is less than 1 Mt per years, and that maximum distance for one plant scenario is 330 km (Tables 12, and 13).

Table 13. CO_2 *pipelines diameter for three North-Italian CCS scenarios.*

Technical parameters	**Cement Plants**			**Total pipeline diameter and distance per scenario**
	Buzzi Unicem Robilante	**Buzzi Unicem Vernasca**	**Italcementi Calusco D'adda**	
Pipeline diameter for 3 plants scenario (from one plant/common), mm	220/220	180/220	180	220 mm – 330 km; 180 mm –59 km
Pipeline diameter for 2 plants scenario, mm		220	180	220 mm – 125 km; 180 mm – 34 km
Pipeline diameter for one plant scenario, mm	280	220	180	
Total pipeline diameter and distance per one plant scenario	280 mm – 330 km	220 mm – 125 km	180 mm – 34 km	

6. Discussion

The aim of this work was to propose and explore geological storage options and local transport infrastructure for captured CO_2 emissions in order to realize a full value chain CCS (Carbon Capture and Storage) scenario.

The background reveals the necessity of the cement industry to reduce the CO_2 emission in the atmosphere to satisfy the global climate agreement and European Climate Policy, aiming to carbon-neutral Europe by 2050. Cleanker project funded by Horizon 2020 is developing Calcium looping oxyfuel CO_2 capture technology, which will be demonstrated in the Vernasca cement plant (Italy).

In this framework, the synergy between multiple CO_2 emitters, which can share local transport infrastructure and storage sites will help to develop cluster projects. This approach reduces costs and risks for the applications of CCS technology.

According to the planned activities described for the WP7, in the Cleanker methodology report (*Shogenova & Shogenov, 2020*), the geological modelling represents the first step.

The studied area includes a depleted gas field. The presence of significant numbers of wells together with literature data, allowed me to construct the 3D geological model.

The lack of seismic investigations, especially in the South part of the Malossa structure added uncertainty to the model of the structure, its real size and borders.

For CCS applications the CO_2 injected into the reservoir should be in a supercritical, gas or liquid phase. It means that its volume could be drastically reduced, compared to that one at the surface. This factor permitted to store large quantities of CO_2 at the depth of more than 800 m. These conditions are satisfied for the Sergano Gravel reservoir in Malossa structure with the top at about one km depth, while the depleted gas field has a minimum of five km depth.

It is known that the depleted gas and oil fields represent the best setting for the CCS technologies, but if on one hand, they are optimal for geological reasons, on the other hand, the economic aspects are disadvantageous since the costs are higher for such large depth. Also increased depth means increasing temperature at least up to 165°C, which is a negative factor for CO_2 density.

Speaking about costs, the wells presented in the field were drilled during the last century (60-70s years) and they were abandoned after the exploration. Reusing of the old wells will be mostly impossible and drilling of new ones will be needed. Costs could be saved only if the old (available) wells are not yet abandoned (in case they are used for hydrogeological or other aims).

Focusing the attention on the economic aspects, also the transport costs are relatively conspicuous. The presence of natural gas pipelines is useful since the CO_2 pipelines could be built in parallel, avoiding additional geological investigations.

Usually, pipelines represent the most advantageous way of transporting CO_2, especially, when storage site and emitters are nearby. Also, transporting CO_2 by pipelines will not produce additional CO_2, that is not the case with other transport options. In these scenarios, the most feasible and economic could be the two plants scenarios. The reason related to their location. Vernasca and Calusco D'adda are located closer and they can shear one injection well and one monitoring well. Contrary, the most expensive scenario is for any single plants, especially, if it is are located far away from the storage site.

The scenario for the three cement plants together is not the best for the storage capacity obtained in the calculations and used for the modelling. However, after additional investigation (seismic explorations) of the structure, the capacity could be improved. If the result is not satisfactory, it will be useful to consider a deeper reservoir. It is possible to use the depleted gas field, and even if the costs are elevated, it will be possible to include CO_2 use for Enhanced Hydrocarbon Recovery and Geothermal Recovery (*Shogenova et al., 2018*).

7. Conclusions

The investigated area is located in the Northern Italy in the Lombardia Region. By using the ViDEPI database, lots of data about the wells drilled in the area for gas exploration allowed to define the caprock-reservoir system.

The caprock has been identified in the Santerno Clay Formation, while the reservoir in the Sergnano gravel Formation. The reservoir depth in the Malossa structure ranges between 970 m to 1500 m. The porosity values of the gravels vary from 12.5 to 38%, with an average of 26%. It means that it is a potentially high-quality reservoir with high permeability up to 1500 mD. The factor, that decreases the quality of the reservoir is the presence of clayey interlayers with lower porosity and low permeability in some parts of the Malossa structure.

Well data and literature data analysis permitted the reconstruction of the 3D geological model of the storage site. In particular, using Petrel software (Schlumberger), the top and bottom surfaces of the reservoir have been determined and petrophysical properties have been populated in the model. The structure is a stratigraphic trap, potentially closed from two sides (N−NE), where the reservoir is declined.

After that, the CO_2 storage capacity of the structure has been estimated. Two approaches have been used: optimistic and conservative. The average optimistic capacity is 24.8 Mt, while the conservative one is 9.91 Mt.

Furthermore, different scenarios for the three cement plants have been considered. In these calculations, the optimistic capacity is used, based on good reservoir properties (high porosity and permeability). As the southern borders of the structure are uncertain the seismic exploration and other exploration methods are needed to evaluate the real borders of the structure and as baseline research for the monitoring of CO_2 storage.

In the three-plants CCS scenario, the Sergnano gravel reservoir in the Malossa storage site is shared between the three cement plants (Robilante, Vernasca and Calusco D'Adda). This storage site will be exploited for 12 years by all the emitters together. For the two-plants scenario, the storage site could be used for 18 years, while for one-plant scenarios the storage capacity will be enough for the full project duration. However, the one-plant scenario will be the most expensive. Contrary, the synergy between the three cement plants will support the sharing of the CO_2 transport, injection and monitoring facilities and it will cut the costs drastically. The most attractive could be the two-plants scenario (Vernasca and Calusco), as it will be enough for 18 years and injection and monitoring infrastructure could be shared. In addition to that, the vicinity of the CO_2 source to the storage site is favourable points for reducing the costs.

In this framework, some important results have been obtained from this project. This area seems to have promising characteristics for the application of CCS technology. A further survey in the area is needed to allow construction of a geological model of the Sergnano gravel reservoir in the Malossa storage site with more details and fewer uncertainties.

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