Cost Optimized CO_2 Pipeline Transportation Grid: A case Study from Italian Industries

P Bumb [1*], U Desideri [2], F Quattrocchi [3], L Arcioni [4]

***Abstract*—**This paper presents the feasibility study of CO_2 sequestration from the sources to the sinks in the prospective of Italian Industries. CO_2 produced at these sources captured, compressed to supercritical pressures, transported via pipelines and stored in underground geologic formations such as depleted oil and natural gas reservoirs, un-minable coal seams and deep saline aquifers. In this work, we present the optimized pipeline infrastructure for the CO_2 with appropriate constraints to find lower cost system by the use of nonlinear optimization software LINGO 11.0. This study was conducted on CO_2 transportation complex network of Italian Industries, to find minimum cost network for transporting the CO_2 from sources to the sinks.

***Keywords*—**CCS, CO_2, ECBM, EU, NAP, LINGO, UNMIG

I. INTRODUCTION

IN the past centuries, fossil fuels have increased green house gases concentration in the atmosphere, with effects on low layer heating and global climate condition changes. Under Kyoto Protocol's directives, many methods for emissions reduction, with limited impact on the economies of the countries that have accepted this document, have been studying: particularly the reduction of CO_2 emission. Carbon Capture and Storage (CCS) technologies, still in test and study phase, consist in a series of procedures to capture CO_2 from industrial flue gases and to store it into appropriate sites to avoid its atmosphere dispersion. The technical aspects of carbon sequestration depend on industrial plant characteristics, while phases of storage and transportation depend on Italian geography and geology. The CO_2 capture through pre-combustion, post-combustion or oxy-fuel combustion depends on type and cycles used by industry, but at the state of art all are usable. To store captured CO_2, considered Italian geological proprieties, the best appropriate sites are geological formation containing hydrocarbon reservoir in use or depleted. For site selection all oil and gas wells situated in Italian territory and managed by UNMIG (National Mines office for Hydrocarbons and Geothermy) have been studied. Among the selected sites, those showing safety and lasting characteristics to insure an adjust permanence, have been chosen. Positions of selected storage sites are compared to Geographical Information System (GIS) of CO_2 emission plants refer to DEC/RAS/065/2006 and DEC/RAS/074/2006. So it's possible to find plant with size and position appropriate for CCS network. Knowledge of CO_2 captured from plants into selected zones, allow giving transportation and storage network dimensions. Pipelines are the transport technologies more appropriate economically. This paper presents a feasibility study of CO_2 capture and storage network via CO_2 pipeline system, with appropriate constraints to find lower cost system by the use of nonlinear optimization software called LINGO 11.0. We work on CO_2 complex network of Italian Industries, to find minimum cost network for transporting the CO_2 from sources to the sinks.

A. CO_2 Transportation

After capture, carbon dioxide must be transported to the storage site. CO_2 is an inert gas and can be easily handled and transported in high pressure pipelines. Alternatively it can be transported in industrial tanks by ship, rail and truck. The risks of pipelines leakage are very small, as it is demonstrated by the long time utilization of oil and gas pipelines, but to minimize any risks, CO_2 pipelines could be routed away from large centres of population to avoid danger caused from CO_2 toxicity. Pipelines can be considered the most suitable method for transporting CO_2, since the cost for this technology depends mainly on the distance, the quantity transported and whether the pipelines are onshore or offshore.

B. CO_2 Storage

There are several possibilities for long term CO_2 storage in safe conditions. Effective storage of greenhouse gases emissions has to last for several hundreds or thousands years, and for this reason, storage sites must have high safety characteristics, low environmental impact and comply with geological and technical standards. [1] [3] [4] [5] [6]. There are three possible ways to store captured CO_2: Geological and Ocean storage in liquid or gaseous form or Geological after a mineral carbonation process [2] [4] [5] [6]. CO_2 storage in geological formations is the most assessed technology because it is also used in oil and gas exploration and production industry, and the potential areas indicated by the recent studies are:

- Deep saline formations;
- Hydrocarbon reservoirs still in use;
- Depleted hydrocarbon reservoirs;
- Coal bed in use or partially out of production.

CO_2 storage in hydrocarbon reservoirs or in deep saline formations is generally carried out at depths lower than 800

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m, where ambient pressure and temperatures assure that CO_2 is in its critical or super-critical state. Under these conditions carbon dioxide density will be 50-80% of the liquid water density, which is in the range of crude oils density, resulting in buoyant forces that tend to drive CO_2 upwards. For this reasons these sites must have an adequate cap-rock to ensure that CO_2 stored remains trapped underground.

When injected underground carbon dioxide compresses and fills pore space by partial displacing the fluids that are already present (―situ fluids) and the retained fraction depends on a combination of physical and geochemical trapping mechanisms. Geochemical trapping is also used for long time CO_2 storage and consists in a chemical reaction with the in situ fluids and host rock. In a first phase, carbon dioxide dissolves in the water and then, after a long time, the CO_2 laden water becomes denser and sinks down into the formation. The hydrocarbon reservoirs, for the aforesaid reasons, are also suitable to CO_2 storage, because they contained oil and gas for hundreds years in perfectly safe conditions.

Another type of trapping occurs when CO_2 is preferentially adsorbed onto coal or organic-rich shales replacing gases such as methane, this technique is used for ECBM (Enhanced coal bed methane) that involves carbon dioxide injection into coal bed reservoir depleted to produce methane gas. Recent studies show that the capacity of geological storage sites is very high. Moreover oil and gas reservoirs contain from 40 to 190 $GtCO_2$ at a depth of 900 and 3500 m. Deep saline formation storage can receive thousands of Gega tonnes of CO_2, but for this possibility studies are at an initial phase. In fact there are no big problems because CO_2 is soluble into saline water.

The concerns of leakage from CO_2 storage sites, particularly from geological formations, are of two types: global risks, that involve atmospheric CO_2 concentration growth causing climate change and local risks that involves danger for life, ecosystems and groundwater.

To avoid these risks, it is necessary to continuously monitor the storage site to detect possible CO_2 leakage. Ocean storage is a potential CO_2 storage option, and consists in injecting carbon dioxide directly in the oceans depths deeper than 1000 m, where conditions of pressure and water salinity ensure CO_2 stability and storage for a long time, and there is no practical limit to the amount of anthropogenic CO_2 that could be stored. Ocean storage has not been deployed or demonstrated at a pilot scale, and is still in the research phase. The last method consists in converting carbon dioxide to solid inorganic carbonates using chemical reactions, through alkaline oxides. Mineral carbonation is a process that occurs naturally (―weathering) but very slowly, and it must be accelerated to be a viable storage method for CO_2. The calcination process produces silica and carbonates, that are stable over long time scales and can be disposed in areas such as alkali mines or re-used for construction purposes. After this process, CO_2 cannot be released to the atmosphere with the consequence of a little environmental impact, no need to monitor the disposal sites and no associated risks.

The most applicable way to CO_2 storage is represented by geological storage, because there are many possibilities and capacities to store CO_2 in safe and lasting conditions. If we also consider the flow of CO_2 in liquid phase, it is possible to use the same technologies that have been developed by the oil and gas industry, to collect and pump CO_2 flow into underground geological formation.

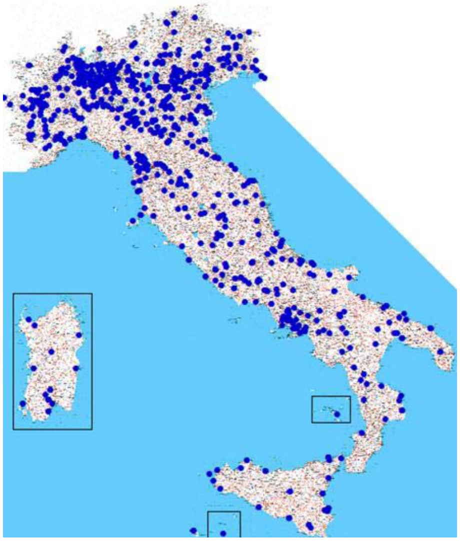

Fig. 1 Distribution of power plants in Italy according to the NAP.

II. THE PROJECT

The aim of this paper is to present a feasibility study for CO_2 capture and storage system with the pipeline optimization technique for the Italian Industries. The first step consists in the analysis of CO_2 emissions sources. Starting from the Italian National Allocation Plan [NAP] 2005-2007 [7] [8], which complies with the EU Emission Trading System and includes all the relevant CO_2 sources. The NAP points of emissions are reported on a GIS system that shows GHG sources distribution situation on the Italian territory. Figure 1 shows the GIS representation of the distribution of the main CO_2 emissions points in Italy. By assigning geographic coordinates to every emission point, it is possible to visualize the distribution of CO_2 sources on the Italian territory with the necessary information relative to factory type and yearly allowances. In this way it is possible to estimate the geographic distribution and emissions amounts in various Italian regions. Among the various storage systems, geological storage is surely the most feasible for geographical and economic reasons: in fact, the Italian geological structure is characterized by several hydrocarbon reservoirs either in use or depleted. To assure good storage performance and safety conditions, oil and gas reservoirs must have many important characteristics such as:

- Protection Cap-rock;
- Geological stability;
- Depth of 1000-2000 m.;
- Oil and natural gas must be partially exploited.

The UNMIG (Italian National Mines Office) database contains all oil and gas exploration and production activities in Italy and was considered as the basis for economic and technical considerations for the selection of the sites for geological CO_2 storage. The following constraints, based on the geological and economical analysis, were considered for the selection of the storage site:

- Onshore sites, to minimize transportation costs;
- With depth higher than 1500m;
- With production or storage authorizations;
- Located in Italy.

The last characteristic is important to reduce transportation costs. Location storage sites were selected near areas that have the largest amount of CO_2 emissions. With these constraints, the storage sites were introduced in the GIS platform to have both emission points and storage sites on the same tool (Figure. 2).

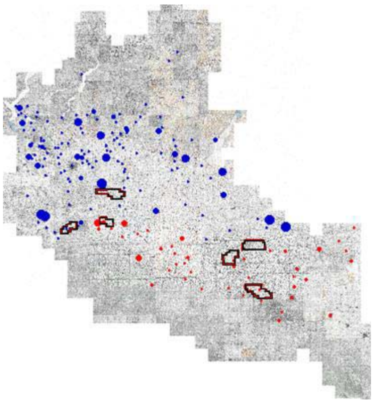

Fig. 2 Geographical position of emission points and storage sites

A. CO_2 Transportation Method

In this project we describe a mathematical model for a pipeline infrastructure for CO_2 sequestration and utilize mathematical programming techniques [9] to find minimum cost strategies for building and operating this pipeline network. We have use non-linear programming approach to find the capital cost of the network depends nonlinearly on the diameter and the length of each pipe and its flow rate. We use a nonlinear programming solver to find the lowest cost solution, subject to constraints on the flow rates over time from the sources and to the sinks. For a CO_2 sequestration network, the sources provide the —demand for sequestration, and the sinks provide the finite —supply of capacity. The network problems that arise in CO_2 sequestration are indeed quite sparse and the objective (cost) function is non convex and nonlinear.

1) Optimize pipeline network

To design and optimize the pipeline infrastructure for CO_2 sequestration, the nonlinear optimization software LINGO is used to find the minimum cost for building and operating the pipeline network. The capital cost depends nonlinearly on the diameter and the length of each pipe and its flow rate. The network problem in CO_2 sequestration for the Italian industries has objective function i.e. cost function nonlinear and non-convex. Therefore, it is good to use LINGO for finding minimum capital cost pipeline infrastructure for CO_2 sequestration.

2) Design Problem

The objective function that has to be optimized (cost of the CO_2 pipeline network) selects one design out of the design space (lowest cost for CO_2 pipeline network). In the optimal solution many of the design variables are zero. These represent components that are not building. Variables that are non-zero in the optimal solution are building and the values give us appropriate sizing of the pipelines.

3) Nonlinear Optimization model for CO_2 sequestration

Pipeline capital cost for CO_2 sequestration network minimizes cost function subject to four sets of constraints.

- Conservation of mass at the sources,
- Flow balance at the intermediate nodes,
- Requirement that the total flow into each sink during one period of time cannot exceed a minimum amount allowed by the sink,
- Requirement that the total flow into each sink throughout the lifetime of the system cannot exceed the total capacity of the sink.

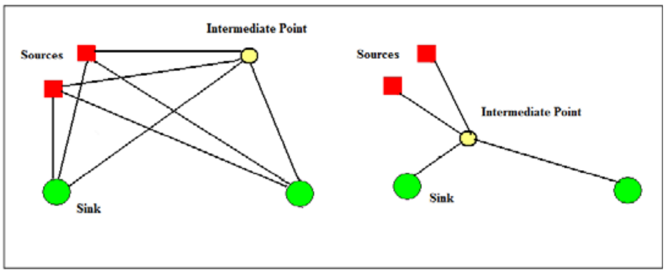

Fig. 3 Showing general layout of the algorithm

Figure 3 shows the general layout of the CO_2 transport grid by the application of the software. The red squares represents the sources, the green circles represent the sinks, and the yellow circle represents the additional node where flow from the sources come together for consolidation.

4) Nonlinear optimization problem

LINGO optimization software can handle nonlinearities and the cost function in our model is nonlinear, thus this solver can work in the model for pipeline infrastructure for CO_2 transportation. The model has the following form [10]:

$$\min Cost\ (s,L)$$

$$s.t. \sum_{j\in D} s_{ij} + \sum_{k\in R} s_{ik} = Q_i, i \in O$$

$$\sum_{i\in O} s_{ij} + \sum_{k\in R} s_{kj} \le s\max_j, j \in D$$

$$\sum_{i\in O} s_{ik} - \sum_{j\in D} s_{kj} = 0, k \in R$$

$$\sum_{t\in T}\left(\sum_{i\in O} s_{ij} + \sum_{k\in R} s_{kj}\right) \le scap_j, j \in D$$

The cost function [10] that we use depends nonlinearly on the flow over the pipe and its length:

$$Cost\ (s,L) = \frac{C_o \sum_{i\in O}\sum_{j\in D}\left(\frac{s_{ijt}}{s_o}\right)^{0.48}\left(\frac{L_{ij}}{L_o}\right)^{1.24}}{\sum_{i\in O} Q_i}$$

where C_0, s_o, Lo are constants. This cost function represents the cost for one day.

III. INDUSTRIAL DATA FOR SOURCES AND SINKS FOR CO_2 STORAGE

The following tables stated in the Appendix shows the industrial data for CO_2 transport profile over which the optimized network is applied.

Table 1, showing industrial data for the Lazio area of Italy. Two sources Centrale Termoelettrica Torrevaldaliga Nord and Centrale Termoelettrica Torrevaldaliga Sud with emission 7340 and 712 kton/yr respectively and the storage site with 120 and 80 MLtonns respectively.

Table 2, showing industrial data for the Sardenia area of Italy. Two sources Stabilimento di Sarroch and Saras Raffinerie Sarde S.P.A. with emission 542 and 5990 kton/yr respectively and the storage site with 80 and 200 MLtonns respectively.

Table 3, showing industrial data for the Porto Tolle area of Italy. Source Porto tolle with emission 7810 kton/yr respectively and the storage site with 50, 100, 80 and 40 MLtonns respectively.

Table 4, showing industrial data for the Sulcis area of Italy. Source UB Sulcis - ITE Portoscuso with emission 1000 kton/yr and the storage site with 60 MLtonns.

*Table 5***,** showing industrial data for the Calabria area of Italy with emission 8000 kton/yr and the storage site with 20, 80, 60 and 100 MLtonns respectively.

IV. CO_2 TRANSPORTATION (RESULT OBTAINED)

After the application of non-linear optimization software LINGO following results on CO_2 transportation optimization is obtained:

A. *Result obtained for Lazio Area of Italy*

When the CO_2 optimization technique is applied it has been found that for optimizing the transportation cost one additional node is required where flow from the sources come together for consolidation. The location of this intermediate node is variable in our model.

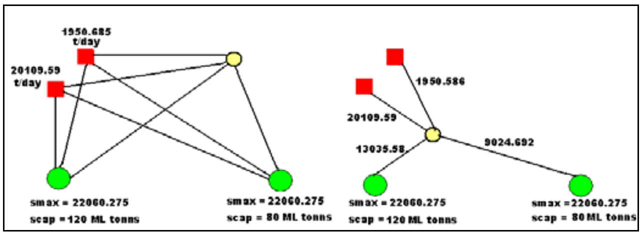

Fig. 4 Solution of the CO_2 transport grid for the Lazio Area

Figure 4, Shows solution of the CO_2 transport grid for Lazio Area of the Italy. The red squares represents the sources, the green circles represent the sinks, and the yellow circle represents the additional node where flow from the sources come together for consolidation. The number above the red square represents the output from each source per day and the number below the green sinks represents the daily flow into a sink (smax) and the total capacity of each sink (scap). On the left, all possible links are drawn to setup the problem. On the right, the optimal solution is shown with the flow listed. For this system we have assumed that the flow is constant over the total lifetime of 24 years of the system. The optimum flows are 13035.58 t/day and 9024.692 t/day respectively to the respective storage sites.

B. *Result obtained for Sardenia Island of Italy*

When the CO_2 optimization technique is applied it has been found that for optimizing the transportation cost one additional node is required where flow from the sources come together for consolidation. The location of this intermediate node is variable in our model.

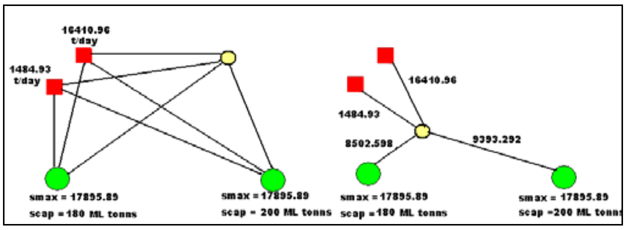

Fig. 5 Shows solution for the Sardenia Island of Italy

Figure 5, Shows solution of the CO_2 transport grid for the Sardenia Island of the Italy. The red squares represents the sources, the green circles represent the sinks, and the yellow circle represents the additional node where flow from the sources come together for consolidation. The number above the red square represents the output from each source per day and the number below the green sinks represents the daily flow into a sink (smax) and the total capacity of each sink (scap). On the left, all possible links are drawn to setup the problem. On the right, the optimal solution is shown with the flow listed. For this system we have assumed that the flow is constant over the total lifetime of 58 years of the system. The optimum flows are 8502.6 t/day and 9393.3 t/day respectively to the respective storage sites.

C. Result obtained for Porto Tolle Industry of Italy

When the CO_2 optimization technique is applied for the Porto Tolle area of Italy. For this area there exibhit one emission point called Porto Tolle with four storage zone as shown in the Figure 6. Figure 6, Shows solution of the CO_2 transport grid for the Porto Tolle Area of the Italy. The red squares represents the sources, the green circles represent the sinks. The number above the red square represents the output from each source per day and the number below the green sinks represents the daily flow into a sink (smax) and the total capacity of each sink (scap). For this system we have assumed that the flow is constant over the total lifetime of 34 years of the system. The optimum flow is 4204 t/day, 8058 t/day, 6446.4 t/day and 2863.8 t/day respectively to the respective storage sites.

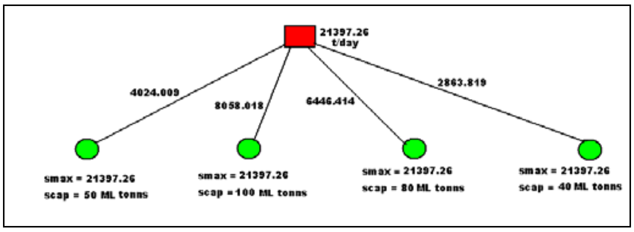

Fig. 6 Shows solution for the Porto Tolle Area of Italy

Minimum value of the objective function i.e. cost for one day is 0.026047 $/tCO$_2$.
Net present value when this system operates for 32 years 0.3018 $/tCO$_2$.

D. Result obtained for UB Sulcis ITE Portoscuso Industry of Italy

When the CO_2 optimization technique is applied for the UB Sulcis ITE Portoscuso of Italy. For this area there exibhit one emission point called with one storage sink. Figure 7, Shows solution of the CO_2 transport grid for the UB Sulcis ITE Portoscuso Industry of the Italy. The red squares represents the sources, the green circles represent the sinks. The number above the red square represents the output from each source per day and the number below the green sinks represents the daily flow into a sink (smax) and the total capacity of each sink (scap). For this system we have assumed that the flow is constant over the total lifetime of 60 years of the system.

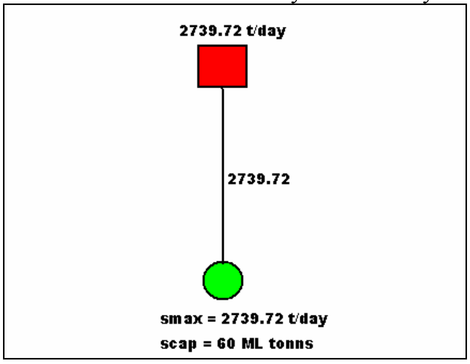

Fig. 7 Solution for the UB Sulcis ITE Portoscuso Industry of the Italy

Minimum value of the objective function i.e. cost for one day is 0.025 $/tCO$_2$.

E. Result obtained for Calabria Industry of Italy

When the CO_2 optimization technique is imployed for the Calabria Industry of Italy.

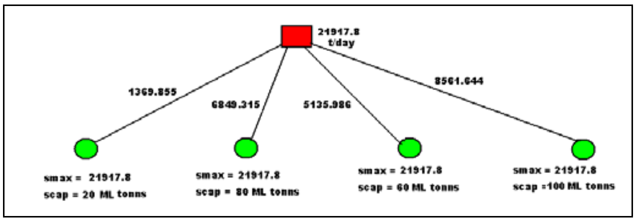

Fig. 8 Shows solution for the Calabria Industry of Italy

Figure 8, Shows solution of the CO_2 transport grid for the Calabria Industry of the Italy. The red squares represents the sources, the green circles represent the sinks. The number above the red square represents the output from each source per day and the number below the green sinks represents the daily flow into a sink (smax) and the total capacity of each sink (scap). For this system we have assumed that the flow is constant over the total lifetime of 32 years of the system. The optimum flows are 1369.85 t/day, 6849.3 t/day, 5136 t/day and 8561.6 t/day respectively to the respective stoarge sites.
Minimum value of the objective function i.e. cost for one day is 0.077 $/tCO$_2$.

V. CONCLUSIONS

The transportation project results show that it is possible to develop a CCS system in Italy, characterized by sites that it is possible to use to store CO_2. Utilization and development of capture and storage technologies are important for the reduction of CO_2 emissions. By applying transportation cost model of the CO_2, we will get optimum transportation operating cost with the optimum amount of CO_2 transportation in the pipeline.

VI. APPENDIX

TABLE I LAZIO AREA

Sources	Emission (kton/yr)	Longitude	Latitude	Sink 1 Distance (km)	Sink 2 Distance (km)	Capacity Sink 1 (MLtonns)	Capacity Sink 2 (MLtonns)
Centrale Termoelettrica Torrevaldaliga Nord	7340	11.75	42.12	11.4	18	120	80
Centrale Termoelettrica Torrevaldaliga Sud	712	11.81	42.11	15.5	22.3	120	80

TABLE II SARDENIA

Sources	Emission (kton/yr)	Longitude	Latitude	Sink 1 Distance (km)	Sink 2 Distance (km)	Capacity Sink 1 (MLtonns)	Capacity Sink 2 (MLtonns)
Stabilimento di Sarroch	542	9.015	39.097	29.8	81.5	180	200
Saras Raffinerie Sarde S.P.A.	5990	9.018	39.077	32.2	83.8	180	200

TABLE III PORTO TOLLE

Sources	**Emission (kton/yr)**	**Longitude**	**Latitude**	**Sink 1 Distance (km)**	**Sink 2 Distance (km)**	**Sink 3 Distance (km)**	**Sink 4 Distance (km)**
Porto tolle	7810	12.49	44.95	56	34	28.8	34
				Capacity Sink 1 (MLtonns)	**Capacity Sink 2 (MLtonns)**	**Capacity Sink 3 (MLtonns)**	**Capacity Sink 4 (MLtonns)**
				50	100	80	40

TABLE IV SULCIS

Sources	**Emission (kton/yr)**	**Longitude**	**Latitude**	**Sink 1 Distance (km)**	**Capacity Sink 1 (MLtonns)**
UB Sulcis - ITE Portoscuso	1000	8.413	39.202	31.2	60

TABLE V CALABRIA

Sources	**Emission (kton/yr)**	**Sink 1 Distance (km)**	**Sink 2 Distance (km)**	**Sink 3 Distance (km)**	**Sink 4 Distance (km)**
Clean coal new	8000	155	108.5	47.8	120
		Capacity Sink 1 (MLtonns)	**Capacity Sink 2 (MLtonns)**	**Capacity Sink 3 (MLtonns)**	**Capacity Sink 4 (MLtonns)**
		20	80	60	100

VII. ACKNOWLEDGEMENT

We wish to thank University of Perugia, INGV for the support of all the activities performed for sharing the Italian industrial Data for sources and sinks for CO_2 storage system. We will like to give special thanks to Prof. Ashis Bhattarcherjee, IIT Kharagpur without whose constant support and guidance the above research work is impossible.

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