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ZERO EMISSION PORTO TOLLE

ZEPT Project results

ENEL E&R - Research

February 2014

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List of abbreviations

CCS, Carbon Capture and Storage

CCU, Carbon Capture Unit

CRA, Compressor, Refrigerant, Air Cool

CTS, CO_2 Transmission system

DCC, Direct Contact Cooler DCC

DCS, Direct Control System

EUA, Emission Unit Allowances

FEED, Front End Engineering and Design

GGH, Gas Gas Heater

HAZID, HAZard Identification

HAZOP, HAZard and OPerability analysis

HDD, Horizontal Driven Drilling

HVAC, Heating, Ventilation and Air Conditioning

LCOE, Levelised Cost of Electricity

O&M, Operation & Maintenance

SCR, Selective catalytic reduction

Ssl, standard sea level

$ScCO_2$, supercritical carbon dioxide systems (scCO2)

USC, Ultra Super Critical

WFGD, Wet Flue Gas Desulphurization

WP, Work Package

ZEP, Zero Emission Platform

ZEPT, Zero Emission Porto Tolle

EXECUTIVE SUMMARY

The Zero Emission Porto Tolle (ZEPT) Project covered the design, procurement and construction of a demonstration CCS plant as well as the detailed site characterisation, to verify the feasibility of the injection and storage of CO_2 in a safe and verifiable manner.

The project was funded by the European Energy Programme for Recovery (EEPR) during the period 2009-2013.

The plan was to install the CCS demo plant on an Ultra Super Critical 660 MWe unit of the Porto Tolle power plant, which will be co-firing coal and biomass. The post-combustion capture unit was designed to treat a flue gas flow rate of 0.8 MNm^3/h, equivalent to a net electrical output of 250 MWe. The demonstration plant would separate about 1 Mt/y of CO_2 (capture efficiency >90%) to be transported by off-shore pipeline to a deep saline aquifer located about 100 km SE of the power unit.

The ZEPT Project (Porto Tolle) has been suspended due to the decision of the Italian State Council to annul the environmental permit for the Porto Tolle power plant. Given this, and notwithstanding all the efforts put in place, the project promoter reported to the Commission that it was not possible to mitigate the permitting and financial risks and decided to start termination of the contract. The Request for termination was accepted by the Commission (effective date 11 August 2013).

The main results of the ZEPT project are listed below:

- Completion of FEED for the Capture unit and ranking of technology suppliers;
- Completion of the feasibility study for the pipeline routing and risk assessment;
- Assessment of the real storage capacity of the selected structure (North Adriatic Sea);
- Validation of the methodology used for site selection;
- Development of a methodology for the definition of a monitoring plan;
- Development of pilot activities for CO_2 capture to support the selection of the best technology solutions in terms of energy penalty, environmental impact and solvent handling;
- Completion of the detailed cost estimation (Capex and Opex) of the Capture, Compression, Transport and Injection Systems.

The ZEPT project has been developed through different stages, including research activities and engineering and modelling studies for each section of the CCS chain:

First stage – lab activities

The first stage of the Project (not included in the Scope of the EEPR funding) was construction of a test rig, operating at the Enel Ricerca Brindisi labs.

Second stage – Pilot activities

The second stage was the design and realisation of a CO_2 capture pilot plant treating the flue gas at Enel Brindisi coal fired power plant that was ongoing when the EEPR funded Project started. This was completed in April 2010. The permitting procedure for the construction of the pilot was concluded in February 2009.

Tests were undertaken with Mono Ethanol Amine (MEA) at different weight percentages, as well as solvents likely to be used for the Carbon Capture Unit (CCU) at Porto Tolle power plant, to assess environmental, operating and process issues related to CO_2 capture technology.

The objectives of these experimental activities were:

- To gain experience in the design, scale up, construction and operation of the CCU;
- To assess the environmental impact of the process (solvent and additives handling, waste management, composition of CO_2 stream and emissions).

Figure 1 CO_2 Capture Pilot Plant – Brindisi

The pilot activities also included the construction of a CO_2 liquefaction and cryogenic storage plant, to liquefy the CO_2 captured at the capture pilot plant at Brindisi power plant. The liquefied CO_2 would be used for injection tests in a depleted gas field at Cortemaggiore, within the framework of the Eni – Enel agreement of October 2008. The transportation of the CO_2 to the injection site and the injection activity for the integrated pilot was outside of the scope of this demo project although the knowledge gathered would have been rapidly incorporated into the demo project. The commissioning of the plant was concluded in March 2013.

Under the Eni – Enel agreement, the realisation of a CO_2 pilot pipeline had also been planned. A FEED study was developed by SAIPEM (outside of the Scope of the demo project and of the EEPR funding). The FEED studies were concluded in December 2010; the permitting procedure commenced in December 2010 and concluded in May 2011. A cost estimate ±20% has been provided at the beginning of 2011. The cost estimation exceeded the allocated budget for this facility, so the activity was suspended.

Third stage – Demonstration plant design

The third stage would have been the engineering and construction of the demo plant, including the CCU, the CTS (Compression and Transport system) and the Storage sections. The demonstration project for the Porto Tolle retrofit entered the engineering phase, but the activity was suspended due to the permitting issues of the Porto Tolle Power Plant Conversion.

Regarding the CCU, following the preliminary assessment of potential CO_2 Capture technology suppliers, Enel identified a set of companies as the most referenced in the field of CO_2 Capture projects worldwide. All the selected technologies were based on amine absorption of the CO_2. In order to establish a ranking between the potential suppliers, a procedure and a Screening Matrix was developed, based on the company's experience in CO_2 capture, level of development and environmental impact of the process.

Four licensors were selected to develop the FEED for the CCU. The FEED study evaluation for Porto Tolle CCU was completed in 2011 and led to identification of the technologies chosen for the final technology. This activity was put in stand-by, due to permitting issues and delays for the conversion of the Porto Tolle power plant.

Regarding CTS, a European tender was issued on 23rd December 2010 for the CTS FEED study for Porto Tolle project. The successful bidder was selected in August 2011, but the contract (activated only for the Basic Design) was awarded to a Temporary Association of Companies (TAC) in November 2012 and the study was completed in July 2013.

In the CTS Basic Design, all the necessary investigation was carried out for the concept selection of the main project components and cost estimation (CAPEX and OPEX) was provided.

Regarding storage, modelling activities, providing a characterisation of the selected storage site, have been completed. Two sites were investigated and the most promising one for capacity, injectivity, structural and geological features was selected; further specific characterisation of static and dynamic behaviour during CO_2 injection focused on the selected site.

The feasibility study and cost evaluation for an appraisal well to verify and update reservoir information of the structure located in Adriatic Sea was performed. The feasibility study and cost evaluation of the surface system was finalised in May 2012.

A pre-injection monitoring survey was carried out to quantify the baseline conditions (both on and off-shore), through assessment of the natural pre-existing CO_2 concentrations and fluxes and the local biological carbon cycling processes. The design of an effective seismic monitoring plan was also undertaken.

The documents for the Exploration permit and the Environmental Impact Assessment of the appraisal well were completed, but their submission was postponed, due to the delay in the implementation of the administrative decrees.

With regards to dissemination activities, Enel's effort was focused on gaining public acceptance, which is one of the key factors for the successful development of CCS projects. The public acceptance strategy has been integrated in Enel's communication mix providing visibility for key moments of CCS projects development.

Enel has identified a variety of international and national stakeholders including local communities, government and scientific institutions, research councils, public and private associations, the media, opinion leaders, communication specialists and has promoted a number of public engagement activities developing outreach material tailored to audience and key messages.

Disseminations activities have been focused not only on the technology itself, but on its contribution to the de-carbonisation of the economy, to citizen's life and, thus, to a balanced energy mix, and its role in creating new jobs and innovative opportunities from CO_2 storage and reuse.

Over the last four years, Enel has learned by experience that the social characterisation of stakeholders together with public engagement is necessary from the initial stages of project development to enable their participation in key project decisions.

The sharing of different experiences and the dissemination of the scientific findings to interested parties to address public concerns or communicate value of the technology could be key elements of CCS public acceptance plan.

Moreover, full access to environmental information should be ensured during the operation of CCS projects when seeking active involvement of different stakeholders including but not limited to researchers, local administrators, and citizens' organizations in monitoring committees.

Key lessons learnt

The main outcomes of the ZEPT project are listed below:

- Porto Tolle Demo project Levelised Cost Of Electricity (LCOE) showed a relative increase with respect to the base power plant without CCS of between 40 to 50%, being far from commercial viability or feasibility for an industrial investment;
- A multidisciplinary approach in the development and design of a CCS project, though the organisation of cross-disciplinary working teams is necessary to promote data/information exchange and to evaluate all the potential issues;
- A global risk analysis, involving the power plant and the CCS chain is relevant, in order to assess the impact of deviations in the operating conditions of a section on the others;
- Engineering, Construction and Operation of an industrial scale Pilot provide robust knowledge of the processes and operation for CO_2 capture. This background is crucial to enable commercial and technical negotiations with the supplier based on a solid technical basis;
- Considering the clear inter-dependence of the three CCS components, the development of modelling tools able to simulate a power plant integrated with the whole CCS chain is suggested, in order to predict different operating scenarios and their effects on the different sections;
- Storage in unknown aquifers or reservoirs implies longer time-lines for evaluation, more uncertainties, more initial investment, and higher geological risk during screening stage in relation to EOR or use of a depleted gas field. Specific exploration is , therefore, needed.

- A direct and clear communication strategy with the local population and the stakeholders is important to allow the CCS to be viable;
- Technicians directly involved in CCS projects need to be present at dissemination events, aiming to resolve concerns that arise among the population from lack of knowledge about CCS.

1 INTRODUCTION

This publication covers the main results related to the Zero Emission Porto Tolle (ZEPT) project, funded by EEPR during the period 2009-2013.

The CCS demo plant was planned to be installed on the Porto Tolle power plant, which will be co-firing coal and biomass. The CO_2 capture technology was designed to operate with post-combustion and would treat flue gas from the equivalent to a net electrical output of 250 MWe. The demonstration plant would separate about 1 Mt/y of CO_2 (capture efficiency >90%) to be transported by an on and off-shore pipeline to be stored in a deep saline aquifer located offshore about 100 km South-East of the power unit. The R&D activities undertaken provided experience in designing, construction and operation of CCU and supported the assessment of the environmental impact of the process.

The ZEPT Project (Porto Tolle) has been suspended due to the decision of the Italian State Council to annul the environmental permit for the Porto Tolle power plant. The project faces severe delays and its continuation was conditional on demonstrating, by June 2013, the capacity to mitigate significantly the permitting and financial risks.

Against this background, notwithstanding all the efforts made, the project promoter reported to the Commission that it was not possible to mitigate the permitting and financial risks and decided to start termination of the contract. Request of termination was accepted by the Commission (effective date 11 August 2013).

2 CAPTURE

2.1 Carbon Capture Unit (CCU) Pilot Plant

The CO_2 capture plant is installed at Enel Brindisi Sud (Federico II) coal fired power plant, which is a coal power plant comprising four units with a capacity of 660 MWe each (total capacity 2640 MWe). Every unit is equipped with DeNOx, particulate collector and DeSOx.

Figure 2 shows the layout of the capture-regeneration section. Different processes can be tested due to the layout of the pilot plant. The design allows the plant to operate with a large range of flue gas and solvent flow rates. Moreover the pre-treatment section can be used to modulate the quality of the flue gas treated. This aspect was particularly interesting in evaluating the effect of the impurities on the processes tested in order to evaluate the behaviour of the solvent under different stress conditions.

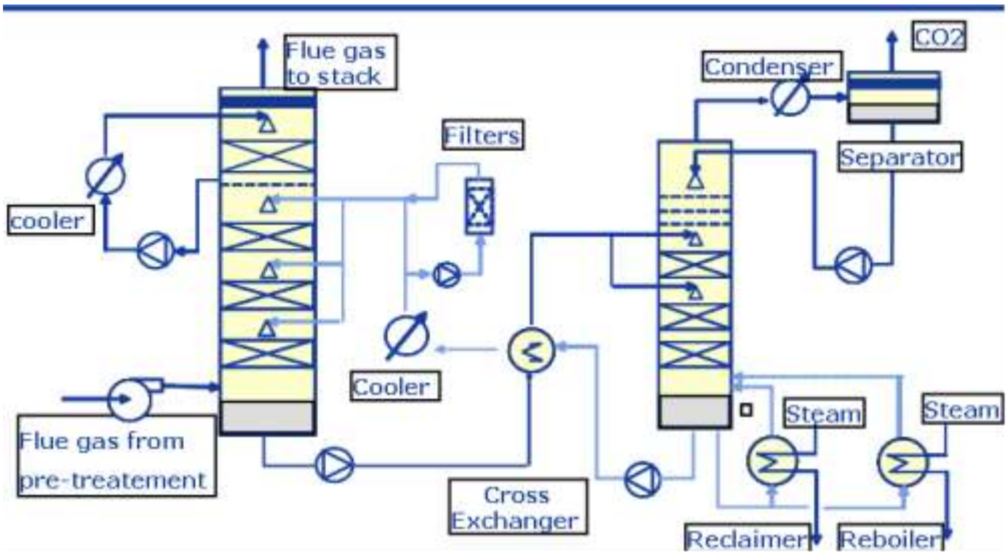

Figure 2 CO_2 Absorption and solvent regeneration sections

The conceptual idea behind Enel's pilot plant is to have flexible facilities that allow testing different capture technologies. This facility offers the possibility to operate in a large range of flue gas flow rate and solvent flow rates.

The Enel CO_2 Capture Plant is currently one of the largest infrastructures available in Europe for CO_2 capture. The assessment of processes that has been carried out on it is particularly significant for the sizing of the plant and for its presence on an operational site.

Benchmarking campaign for MEA 30%

Testing using as solvent MEA 30% wt was carried out at the Brindisi Pilot Plant from September 2010 to March 2011, with more than 1000 operational hours. It was considered as a benchmarking exercise to define the baseline performance of the pilot. All testing undertaken later was evaluated according to the performance recorded during the benchmarking exercise. In particular, the methodology to assess the processes has been set for the MEA 30%, which was used as a reference benchmark, and then applied as a standard experimental methodology to assess the processes.

CO_2 capture process comparisons

The tests carried out at the Brindisi Pilot Plant had as its main objective the investigation of the performance of amine technologies for CO_2 separation and are available or semi-available for a full scale/industrial application.

Through this testing period, Enel gained the necessary skills, not only to evaluate the technologies mature for an industrial application, but has also gained experience and skills for the management and maintenance of the amine plants.

Overall from the 2010 to July 2013 Enel has performed tests for 8000 hours of operation during which four technologies were thoroughly tested, following a standard assessment process in order to have comparable results.

Foreseen activities for further development of the technology

As one of the most important infrastructures existing in Europe, its scale enables the Enel Pilot Plant to optimise the integration of CO_2 capture in a power plant, aiming to significantly reduce the overall efficiency penalty of the combined power plant and capture unit.

The results produced have provided technical information relating to the operation of large scale power plants and further will provide information on ways to improve capture operational flexibility and test new process solutions.

Regarding the CCU operability and flexibility, the Enel pilot enabled testing on a pilot plant similar to the industrial scale. The tests were carried out in order to demonstrate:

- Emission control options. The flexibility of the flue gas pre-treatment section allowed investigation of different conditions of the flue gas fed in the CCU. The effect on the amine process was also monitored;

- Operability and flexibility options to determine operability limits; to assess the possibilities to operate the power plant, including the capture plant, in a flexible way to allow "capacity on demand" within a time frame of hours.

- Process analytical techniques and control options (including dynamic response).

Environmental performance: Dispersion modelling

Modelling activity aimed at assessing the environmental impact of amines degradation products was carried out for the Porto Tolle case study. Recently, the emission of amine solvent or their degradation products potentially generated in post-combustion CO_2 capture plants, posed concerns about the high toxicity of this kind of compounds. Amine solvent degradation products include nitrosamines and nitramines which can affect human health or raise environmental issues. According to current scientific knowledge, their emission is unlikely, but, given concerns over their high toxicity, a robust environmental assessment plays a strategic role for the development of the technology at a commercial scale.

Simulations have shown that the impact of solvent and degradation products on the area is almost negligible. In fact, in the worst case investigated, air concentrations are about one or two orders of magnitude lower than the recommended exposure values.

These simulation results must be considered preliminary, as they are based on the current state of the art which is characterised by knowledge gaps and uncertainties. Further investigation is needed in order to fill the gaps about the behaviour of these elements and to develop a robust evaluation of the impact on human health and the environment.

2.2 CO_2 LIQUEFACTION AND CRYOGENIC STORAGE PLANT

The pilot activities also included the plan of constructing a CO_2 liquefaction and cryogenic storage plant, in order to liquefy the CO_2 captured at the CO_2 capture pilot at the Brindisi power plant. The liquefied CO_2 could be used for injection tests in a depleted gas field at Cortemaggiore, under the Eni – Enel agreement of October 2008. The CO_2 transportation to the injection site and the injection activity for the integrated pilot is outside of the scope of this demo project although the knowledge acquired will be used in the demo project.

A European public tender for the supply and installation of this facility was issued in December 2009, but the tender was cancelled because the only technical offer considered suitable exceeded the budget allocated for this activity. A new tender was launched on 25th July 2011; the contract for the supply and construction of the plant was awarded to a Temporary Association of Companies (TAC) in October 2011. The permitting procedure was successfully completed in September 2010.

The plant was designed to treat 2.5 t/h of flue gas from the CO_2 capture pilot plant and is divided into three main sections:

- A cleaning and compression section in order to eliminate possible impurities and to compress the CO_2 stream up to the adequate pressure for the liquefaction;
- A liquefying station, in which the CO_2 is liquefied in a shell and tube condenser, using a refrigerant fluid as a cold source;
- A storage station made of one cryogenic vessel of 50 m^3 capacity.

2.3 CARBON CAPTURE UNIT

General approach

The CCU demo plant has been designed to treat a flue gas flow rate of 0.81 MNm^3/h and to a power capacity of 250 MWe net. The CO_2 capture efficiency is 90% of the treated flue gas.

Given the objective of demonstrating CO_2 post-combustion capture at industrial scale by 2015 and provide a commercial retrofit solution by 2020, Enel selected the Porto Tolle CCU technology from among the first generation processes, including all the chemical absorption processes with amine solution which have been demonstrated in the oil and gas industry at industrial scale.

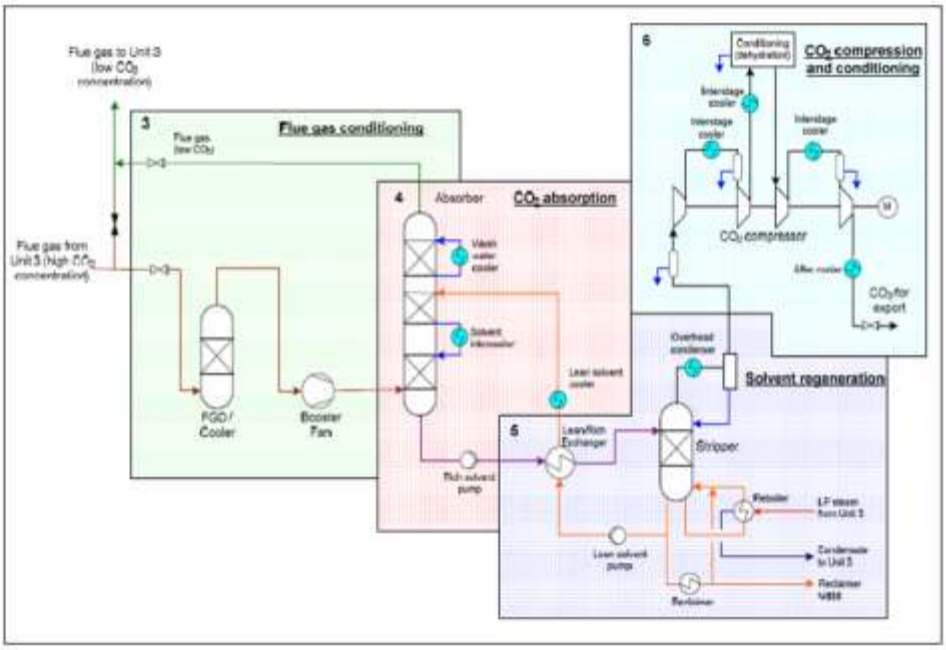

Figure 3 Process scheme for CCU

The flue gas is routed to a pre-treatment section, in which cooling and SOx removal is carried out, to minimise the degradation of the solvent used and to reach the adequate temperature for the absorption process. SOx are absorbed from the flue gas; the temperature of the flue gas will be reduced according to the process used in the selected technology. The flue gas is then sent to the absorber column, designed to remove the carbon dioxide contained in the flue gas. The absorber is made of two/three packed beds with structured packing. The exact size of the absorber depends on the final technology selected.

The flue gas enters the bottom of the absorber and flows upward, reacting with the solvent solution, in a counter-current mode. On the top of the absorber, one or more water washing packed bed sections will be provided, to cool the treated gas leaving the absorber, to recover entrained solvent and to remove solvent degradation components.

The treated flue gas is routed to the stack for discharge to the atmosphere, while the carbon dioxide-rich solvent leaves the absorber and is pumped by the rich solvent pump, to the regeneration section (stripper), in which the CO_2 chemical absorption process is reversed.

The carbon dioxide-rich solvent that leaves the bottom of the absorber is sent to one or two lean/rich heat exchangers, where the temperature of the rich solvent rises. This occurs by exchanging heat with the lean solvent that is re-circulated back to the absorber. The lean solvent is further cooled as required for the absorption process.

The stripper is made of two packed beds, with random or structured packing, with a washing section on the top of the stripper. The diameter and height depend on the technology selected.

The CO_2 rich solvent from the lean/rich heat exchanger enters the stripper below the wash section and flows down through the packed beds, counter-currently to stripping steam, which removes CO_2 from the rich solvent. The solvent is distributed across each bed with channel type liquid distributors.

The semi-lean solvent is collected on the bottom and is sent to the reboiler, where it is heated by condensing low pressure steam and where the stripping steam, mainly consisting in water and CO_2, with traces of solvent, is generated. The vapour flows up the stripper through the packed beds and exchanges heat with the falling rich solvent liquid, promoting the CO_2 desorption and solvent regeneration.

The reboiler return pipework delivers the heated two phase mixture to the stripper below the packed bed; the remaining liquid is separated by gravity from the steam and CO_2 vapours. The lean solvent liquid is then extracted from the bottom of the stripper and passed through the lean/rich exchanger to recover heat to the incoming rich solvent flow.

In order to remove impurities from the circulating solvent, a small percentage of the lean solvent flow is routed to a cleaning system to remove particles (introduced from the flue gas), pollutants, trace elements and degradation products.

Amine is liberated by boiling the solution utilising condensing high pressure (HP) steam and is returned to the main solvent loop. At the end of the reclaiming cycle, demineralised water is fed into the reclaimer to improve amine recovery and reduce the quantity of amines remaining in the unit.

In the washing section of the stripper, water is used to wash entrained solvent out of the vapour stream and remove some of the vapour phase solvent from the overhead. The resulting vapour from the top of the stripper, containing CO_2 saturated with water, is then cooled. The contained water is partially condensed in a condenser, using cooling water, or, if suitable, vacuum condensate, that could optimise energy integration. The two phase mixture from the condenser is sent to the overhead accumulator, where the CO_2 is separated from the condensed water.

The CO_2 rich vapour is sent to the CO_2 product compressor. In case of high pressure in the stripper or when the CO_2 is out of specification, it can be vented to the absorber stack ducting return.

Selection approach

The selection of the technology for the CCU consisted of three main stages:

a) Pre – selection among the amine based technologies;

b) FEED development and evaluation;

c) License and engineering tender and contract award.

The technology qualification criteria and the procedure followed is reported but the final result of the qualification process has not been disclosed as the process stopped before the negotiation of License and Engineering contract, meaning that the selection of the CCU technology was not finalised.

Technologist's qualification criteria and procedure

In order to establish a ranking between the potential suppliers, a procedure and a Scoring Matrix was developed in collaboration with EPRI. EPRI is an independent, non-profit, public-interest organisation engaged in collaborative research, development, and demonstration on behalf of the power industry with over 1,000 participants worldwide. It is recognised for technical excellence and scientific integrity and credibility. EPRI is highly experienced at handling research projects on behalf of the US Department of Energy and power industry knowledge sharing on an international scale. Moreover, it is heavily engaged in global climate change research, including five large-scale CCS demonstration projects that involve numerous companies.

A Scoring Matrix weighting relevant selection criteria was defined jointly. The most relevant criteria, among the others, were:

- Company size and level of experience (engineering capabilities, and references related to the separation of CO_2 from coal or heavy fuel oil combustion gas, using amine type technology);
- Competitiveness of the technology (impact on cost of electricity, impact on Porto Tolle Power Plant).

2.4 CARBON CAPTURE UNIT- POWER PLANT INTEGRATION

2.4.1 Main interfaces between the CCU and the Porto Tolle power unit

The CCU plant has to be considered ideally as an island on which all utilities and main streams will be connected to the Porto Tolle power plant systems. Sea/river cooling water (as well as pumps) will be provided, in order to cool down the closed cooling circuit water. Flue gas ducts will be branched off from (and returned to) existing FGD unit outlet (upstream the GGH clean gas side).

The CCU unit was planned to be managed by a dedicated control system; it could, however, be interfaced with the Porto Tolle power plant main control room.

The CCU is designed to operate at design load when the unit is in service with an electrical load higher than 70%. When the load is lower, the CCU load will be reduced accordingly.

The CO_2 compression system will be specified on the basis of the pressure required by the injection well and the total pressure drop along the pipe.

The waste water treatment can receive a flow rate of approximately 30 m^3/h from the CCU. The Waste water treatment includes:

- pH-value correction;
- Oily water treatment;
- Heavy metal precipitation.

Any waste water potentially contaminated with amines or ammonia will not be sent to the waste water treatment, but recovered internally at the CCU or will be exported for proper treatment/disposal.

The critical interfaces are represented below:

- Availability of low pressure steam supply to CCU;
- The FGD is in proper operation;
- Availability of flue gas supply (with all parameters of the flue gas feed suitable for the operation of the CCU).

In order to reduce the power loss on the steam turbine associated with the operation of the CCU, possible heat integration between the CCU and the Unit Steam Cycle has been studied. Low grade heat is available in the CCU in all the sections where cooling is required by the process following, i.e.:

- Flue Gas Cooling in the Pre-Treatment section
- Solvent cooling in the CO_2 absorption section
- CO_2 condenser in the Stripper Section
- Gas intercooler in the CO_2 Compression section

Of the above options for heat recovery, only recovery from the Stripper Section proved economically viable, and will be implemented. In the other sections of the plant, the available heat is at a temperature which is low to be usefully recovered. The capital cost of the provision needed for the heat integration will not be recovered by the reduced power penalty on the Unit Steam Turbine.

The heat recovery from the stripper section is planned to be implemented using vacuum condensate extracted by the plant's steam condenser. The vacuum condensate will be pumped to the stripping section where it will be heated in the CO_2 condenser downstream of the CO_2 Stripper. The pre-heated vacuum condensate will be returned directly to the steam cycle deareator or after the first condensate pre-heater, reducing the steam extraction needed. As a result of this heat integration, the power penalty of CCU operation will be reduced.

3 CO_2 TRANSMISSION SYSTEM (CTS)

Basic Design

The CO_2 compression and transport chain is shown in Figure 4. The offshore infrastructure will be located in the Adriatic Sea (about 94 km from Porto Tolle).

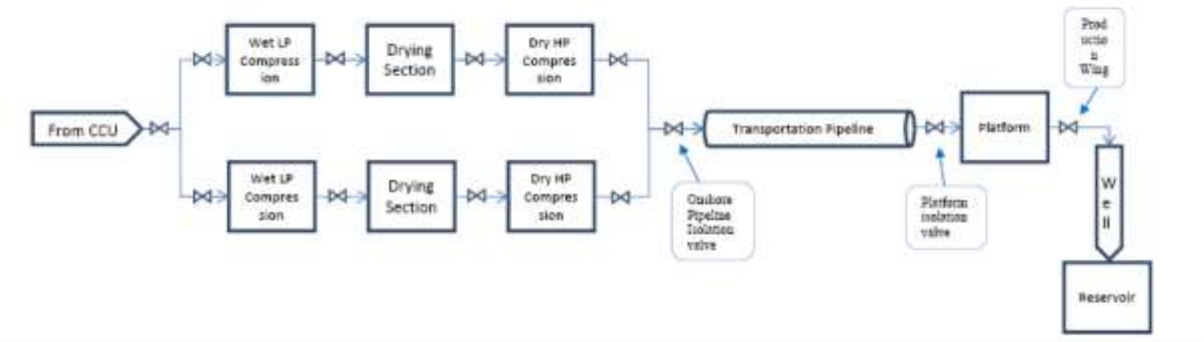

Figure 4 CO_2 Compression and transport chain

The Basic Engineering was performed and addressed the following main issues:

- Mobilisation;
- Preparation of Project Control Documents;
- Material Selection studies;
- Corrosion studies;
- Preliminary flow definition parameter studies;

- Desk study for conceptual pipeline routings, with three distinct alternative routes;
- Identification and study of project constraints arising from environmental sensitivity;
- Pipeline installation methods in shallow areas (inshore waters close to Porto Tolle);
- Seabed stability inshore;
- Concept studies for CO_2 compressors and the CO_2 compressor station;
- Concept for CO_2 dehydration;
- Concept definition of surface wellheads and offshore platform CO_2 injection plant;
- Concept studies for Xmas tree selection;
- Concept philosophy for onshore terminal and offshore platform, plant control and instrumentation philosophy;
- Offshore platform power supply and communication system concept selection;
- Concept for onshore terminal and offshore platform;
- Preliminary philosophy for operation;
- Concept philosophy for inspection and maintenance of onshore and offshore installations;
- Preliminary HAZOP/ HAZID studies;
- Definition of battery limits between the different areas of supply;
- Definition of all main CTS project configurations such as electrical supply selection criteria, communication and automation system criteria;
- Preliminary cost evaluation for CTS Project implementation.

The main operation targets defined for the CTS Project are listed hereafter:

- The whole CTS chain should be able to operate during the 10 years foreseen for the CCS project, with about 4500 operating hours per year at full capacity and 1400 hours at 50% capacity;
- The offshore platform should be an unmanned facility remotely controlled by the Porto Tolle control room;
- The operation primary objectives are ensuring a high HSE (Health, Safety & Environment) standard, complying with local legislation, international Codes and Standards and company policies;
- The operation should ensure a proper injection of the CO_2, completely safeguarding reservoir integrity;
- The CTS chain should be operated in a cost effective manner while safeguarding the entire technical integrity of all the assets;
- The operation of the CTS chain should allow pipeline depressurisation only in exceptional events, such as threatening safety of people, assets and environment and for decommissioning purposes.
- The CTS will follow downstream the CO_2 Capture Unit to be installed at Porto Tolle power plant and will include:
    - Onshore compression unit;
    - Onshore pipeline terminal;
    - Onshore pipeline.

4 STORAGE

The site selection was carried out on the basis of modelling activities, providing a characterisation of the selected storage site. Two sites were investigated and the most promising one for capacity, injectivity, structural and geological features has been selected; further specific characterisation of static and dynamic behaviour during CO_2 injection has been focused on the selected site.

The feasibility study and cost evaluation for an appraisal well to verify and update reservoir information of the structure located in Adriatic Sea was carried out. The feasibility study and cost evaluation of the surface system was finalised in May 2012.

4.1 Pre-feasibility study on site selection

The potential storage site in Adriatic Sea was selected through a detailed characterisation, developed for two sites. To facilitate public acceptance, the interest was focused on the offshore areas. Localisation criteria used were:

- Distance from the emission source (max 200 km for economic feasibility);
- Depth of reservoir (between 800 – 2500 m);
- Caprock – existence of a non-permeable and sealing geological formation;
- Reservoir physical properties (porosity and permeability);
- Seismicity – area must be stable to ensure the structural conditions necessary for storage;
- Heat flow: the heat flow should not be high, so as not to modify CO_2 stability conditions

Geological and geophysical data analysis

The first characterisation of the storage sites was completed by integrating borehole data with the analysis of seismic profiles acquired by different oil companies (AGIP in particular). These analyses were developed during the oil explorations conducted in Italy since the late ’50s up to 31/12/2007. The borehole data contained the following information:

- Lithology by cuttings analysis;
- Name, age and depth of the geological formations;
- Lithology column of the drilled succession;
- Presence of mineralisation;
- Sediment deposition environment;
- Fossil association;
- Log data (Resistivity log; Sonic log; Gamma ray log, Neutron log; Self Potential log).

Storage capacity evaluation

To evaluate the storage potential of a potential site, the EU GeoCapacity project method was used. The same procedure is also used in the USA and Canada for estimating the CO_2 storage potential of saline formations. This method provides an estimate based on bulk volume of the aquifers referred to as the “effective storage capacity” (i.e. the reservoir capacity evaluated considering technical cut off limits and technically viable estimate). Based on a preliminary evaluation, a potential storage capacity can be obtained.

4.2 Modelling activities

Starting from the results obtained in the regional study, a structure for CO_2 storage was selected and the modelling activities implemented. The characterisation studies focused on two main structures in the Northern Adriatic Sea, about 100 km from Porto Tolle power station and 5 km apart. The most promising is the second one. It lies offshore about 25 km from the coast.

A number of geomechanical issues were addressed in a project for geological CO_2 sequestration in a saline aquifer or depleted reservoir to be evaluated by UNIPD (University of Padua). They include:

- The analysis of the stress-strain conditions of the aquifer-reservoir/caprock system in order to prevent the possible leakage of CO_2 through mechanically-induced fissures;
- The possible activation of pre-existing faults;
- The related motion of the sea bed and coast areas.

Dynamic studies

Dynamic studies showed that the structure is adequate, for capacity and that the overpressures and the migration of CO_2 that will be reached during injection and in a subsequent wide period (90 years) are acceptable.

A study of the “optimal location” for the injection well was carried out following the chosen criteria: structure identified as favourable, adequate injection clean sand thickness sequence, and safety zone around each pre-existing well already drilled in the area for oil&gas exploration (low-risk leakage). All simulations showed very similar characteristics in terms of fracturation pressure, threshold pressure and CO_2 plume extension. The selected well is the one farthest from existing wells.

In addition, simulations were performed for an injection rate corresponding to the total estimated amount of CO_2 for the new Porto Tolle power plant. Results of the study showed that the structure would be suitable for this rate of CO_2 injection as the induced overpressure is below the threshold pressure.

Similarly, geomechanical simulations predictions were extended up to 20 years after the injection. For each scenario an initial normal and compressive stress regime was addressed. A sensitivity analysis was also undertaken for the most uncertain parameters defining the yield surface, i.e. the cohesion and friction angle.

At a more general level, the results emphasised the safety of the sequestration in relation to possible shear and tensile failure of the storage structure and its caprock.

4.3 Monitoring plan

Design of an effective seismic monitoring plan was provided by OGS. They concluded that the reservoir formations characteristics and depth are such that the CO_2 presence should be detectable through the seismic method. Moreover, the conditions were even more suitable for the overburden formations. Hence, an early detection of possible leakages through fracture systems and/or degraded well casing should be possible. OGS also undertook a feasibility study of the monitorability of the CO_2 geological storage second structure.

From this modelling, OGS concluded that the reservoir formations characteristics and depth are such that the presence of CO_2 should be detectable by the seismic method. Hence, a monitoring plan based on a series of repeated 3D seismic conventional marine surveys would be enough to image the CO_2 plume, follow its evolution over time and detect possible leakages. Those surveys should be above the area of injection, focused on possible pathways to the fluid migration. The main acquisition parameters for the proposed baseline and time repeated surveys were identified to ensure high repeatability. A tender for a possible effective monitoring plan was prepared.

It is important to underline, that even if the present work sought to design an optimal seismic monitoring plan, the comparison and integration of the results with all the other physical, geochemical and biological data that will be acquired in the area, has improved the reliability and usefulness of the monitoring.

4.4 Injection well

A study to assess the feasibility of an appraisal well was carried out by ENI, the major Italian oil & gas company. The study was conducted to verify and update reservoir information of the structure located in Adriatic Sea. The scope of the Injection well was the drilling of an appraisal well, which will be temporarily abandoned after the data acquisition is completed. Depending on test results the well will be re-entered at a later stage to be completed once a permanent structure/platform is in place. From a drilling point of view no particular problems are foreseen. The feasibility study provided a positive response. The relevant time and cost estimates have been developed.

Material selection

A material selection study dealing with the corrosion assessment and the preliminary material selection for the well completion of the CO_2 injection well within the project was carried out.

The injected fluid composed mainly of CO_2 impurities, e.g. oxygen, sulphur dioxide and nitrogen dioxide which are the more corrosive chemical compounds. In supercritical carbon dioxide systems ($scCO_2$), corrosion severity is particularly dependent on the water content. In particular, in under-saturated supercritical carbon dioxide systems, where the water content is lower than the solubility limit at operating conditions, the corrosion rate is negligible. At injection conditions, the design water content is one order of magnitude lower than the solubility limit and, considering that the solubility of water in $scCO_2$ increases with pressure and temperature, liquid water phase is not expected along the well profile.

The oxygen, sulphur dioxide and nitrogen dioxide content in the injected fluid are several orders of magnitude lower than the values at which laboratory tests on carbon steel show severe corrosion attacks even in under-saturated $scCO_2$. Finally, the expected fluid corrosivity is negligible considering the under-saturated characteristics of the injected flow (no liquid water phase) and the low content of impurities. As the liner is similar to the tubing, carbon steel can be selected. Carbon steel or low alloy steel can be selected if no frequent and long shut-in interventions are foreseen. On the other hand, super 13Cr martensitic stainless steel is also a safe selection in temporary operations as it is fully resistant to CO_2 corrosion at high pressure.

Preliminary data acquisition program

The main targets of Data Acquisition in the appraisal well were:

- Complete petro-physical characterization of reservoir (porosity, permeability, storage capacity, free fluid and saturation value);
- Geochemical characterisation of reservoir cap rock, to prevent CO_2 migration upwards;
- Chemical characterisation of reservoir matrix and formation fluid, to understand chemical reaction during CO_2 injection;
- Upgrade of geological model from static to dynamic point of view, to control the extent of CO_2 migration within the storage formation;
- To verify the pressure and temperature down hole that must be high enough to enable the storage of CO_2 in a compressed fluid phase, maximizing the quantity stored.

To obtain the necessary data, a preliminary data acquisition program in terms of sampling, logging, geomechanical characterisation was developed.

5 DISSEMINATION ACTIVITIES

5.1 Public acceptance plan

With regards to dissemination activities, Enel's effort focused on gaining public acceptance, which is a key factor in the successful development of CCS projects. The public acceptance strategy was integrated in Enel's communication mix providing visibility for key moments of CCS projects development.

Enel identified a variety of international and national stakeholders including local communities, government and scientific institutions, research councils, public and private associations, the media, opinion leaders and communication specialists. Numerous public engagement activities were promoted to develop outreach material tailored to audience and key messages.

Dissemination activities focused not only on the technology itself, but also on its contribution to the de-carbonisation of the economy and thus to a balanced energy mix. Its role in creating new jobs and innovative opportunities from CO_2 storage and reuse was also promoted.

Over the last four years Enel has learnt by experience that stakeholders and social characterisation along with public engagement are necessary from the initial stages of project development in order to enable their participation in key project decisions.

Sharing different experiences and the dissemination of the scientific findings to interested parties to address public concerns or communicate value of the technology could be key elements of CCS public acceptance plan.

Moreover, full access to the environmental information should be ensured during the operation of CCS projects seeking active involvement of different stakeholders. This information should be available to audiences including but not limited to researchers, local administrators, and citizens' organisations in monitoring committees.

5.2 Involvement actions

Enel's strategy for CCS public acceptance development was implemented through:

- Stakeholder Engagement: Enel consolidated its partnership with the Fondazione Sviluppo Sostenibile (a local non-profit organisation) for the CCS Observatory. This is involved in monitoring and communication of the developments in CCS technology and regulatory framework worldwide. The main achievements during the period of collaboration with CCS Observatory included preparatory work for the transposition of the EU directive into an Italian CCS law, the maintenance of a well-documented website on CCS (www.osservatorioccs.org), collaboration on a series of events and research initiatives;
- Publicity: CCS was one of the key topics of Enel's corporate advertising campaign supported with specific visuals. The campaign was on air worldwide in 2009 and in 2011;
- Employee engagement: Enel reinforced its internal CCS communication through regular articles on the company intranet and a special edition of Enel's in-house tool which was dedicated to CCS and Enel's projects.
- Social research: in order to map population's perceptions around climate change and the role of CO_2 and alternatives to mitigate CO_2 emissions, Enel has conducted qualitative research in around the Brindisi and Port Tolle Power plants and quantitative research, post EU Eurobarometer. The outcome of the research allowed the company to constantly update the stakeholder matrix and better understand stakeholder rationale thus improving the public engagement strategy;
- Participation and organisation of dissemination activities: The following list includes the events in which Enel participated during development of the Project:

Participation to European and International scientific conferences and seminars

Enel has actively participated to the meetings of the European CCS Demonstration Project Network. Enel attended all the network sharing events hosted by the CCS Demonstration Projects' sites. The fourth Sharing Event was held in Enel's Brindisi Power Plant where the company operates its pilot capture unit. Some specific topic were discussed (management issues, stakeholders' management, etc.) along with the main topic which is the sharing of the lessons learnt from CCS communication.

In addition, Enel delivered a keynote speech on public acceptance at the European CCS Demonstration Project Network Dissemination Event in Rotterdam in 2011, and at the Global CCS Institute Regional meeting in 2013 sharing with the participants the public acceptance strategy and lessons learnt during these years.

Organisation, in collaboration with National and International institutions, of thematic workshops and seminaries addressed to different audiences

- CO_2 GeoNET Open Forum

Enel supported the European Network of Excellence on the Geological Storage as Main Sponsor for its sixth (May 2011), seventh (April 2012) and eighth (April 2013) Open Forum in Venice. Numerous participants were involved including industries, regulatory bodies, demonstration projects of CO_2 geological storage, Associations, European Commission, NGO's, etc.

- WEC Italia

Enel sponsored two conferences organised by World Energy Council Italy. These conferences focused on the Evolution of the Regulatory Framework on CCS (2011) and on the role of CCS in the European strategies for de-carbonisation (2013).

Special Events

- Visibility of Brindisi CO_2 capture pilot plant

Enel inaugurated Brindisi CO_2 capture pilot plant in March 2011. The Commissioner for Energy G. Oettinger, the Italian Minister of Environment and representatives of other national, international and regional institutions attended the event.

Since then, the Enel Brindisi CO_2 capture pilot plant hosted different institutional, scientific and explanatory visits. It also consisted the venue for several national and international workshops dedicated to CCS. In December 2011, Enel hosted at Brindisi, in collaboration with Italian Ministry of Environment, the 2nd Sino-Italian scientific meeting on CCS, attended by representatives of Chinese Ministry of Science and Technology, Chinese research Institute, Italian Ministry of Environment, Italian Ministry of Economic Development, Carbon Sequestration Leadership Forum and the research community.

- Fareambiente

Enel has collaborated with Fareambiente (an Italian environmental association) in the organisation of a series of regional and national workshops on the new environmental strategies. The objectives of Fareambiente were to demonstrate and explain to the public the existing technologies to reduce the impact of the industry and energy generation to the environment. The workshops targeted broad audiences, from the research community to local administrations and communities, which made it effective for public engagement.

All the events were supported with printed and video materials and web content produced within the framework of the EEPR program.

Information Centre

During the activity period Enel continued to work at the creation and dissemination of information material on CCS and CO_2, which include:

- Preparation of publishable material about CCS technology and the Brindisi capture pilot plant (brochures, info graphics, roll-ups)
- Material for mobile exhibitions and video-documentaries (photos, information panels, animated graphics, CCS simulation).
- Web content (info graphics, virtual tours to the Brindisi CO_2 pilot capture plant and to the future Porto Tolle power station).

5.3 Tools and material

A project website (www.portotolleproject.com) was created in 2010 and maintained through a constant update with relevant news, and through sharing important documents.

All the information and communication material including virtual tours to Brindisi pilot plant and to the future Porto Tolle power station were systematically uploaded on the website. This activity was aiming to reach the entire stakeholders group through a web 2.0 environment and communicate the achievement of Enel's projects, During the whole period there was a constant growth in website "hits" with average annual statistics of about 10,000 visits. In addition, CCS and Enel's CCS topics were communicated through Group's web platform and social networks.

6 CONCLUSIONS AND LESSON LEARNT

General

The most important lessons learnt were in the organisation of cross-disciplinary working teams, promoting information/data exchange about the different CCS sections. A multidisciplinary approach is, indeed, mandatory for the success of a CCS project.

Considering the clear inter-dependence among the three different sections of the CCS chain, the development of modelling tools able to simulate the power plant integrated with the whole CCS chain is suggested, to predict different operating scenarios and their effects on the different sections.

In addition, attention is required in the evaluation of the reuse of existing equipment/buildings for CCS scopes: Review of material selection and check of the compatibility of the existing infrastructures with CO_2 properties have to be performed. The reuse of existing infrastructures represents an important aspect in the development of a CCS project and can underpin the viability of a CCS project.

The following tables summarise the main lessons learnt:

Table 1 Pilot activities lessons learnt

Process design	Issues for CCS application	Lessons learnt
CO_2 Capture - MEA	• Assessment of MEA absorption technology	• Reliability • Power consumption • Capture performance • Optimisation of existing reference methods for sampling and analysis of MEA
	• Operation	• Definition of operating procedures
	• Costs	• Solvent consumption • Corrosion inhibitors • Waste treatment management and solvent disposal • Operating costs optimization
	• Environmental assessment	• CO_2 stream composition • Emissions (MEA, NH_3, other organic compound) • Development of methods for sampling and analysis of volatile aldehydes (like Formaldehyde and acetaldehyde) and volatile organic acids • Environmental impact
CO_2 Capture - Advanced Solvent	• Assessment of absorption technology	• Reliability • Environmental impact • Capture performance • Reduction of power consumption with respect to MEA (-10÷20%) • reaction rate • Development of methods for sampling and analysis of the solvents and their Degradation products
	• Operation	• Definition of operating procedures • Solvent consumption • Corrosion inhibitors
	• Costs	• Waste treatment management and solvent disposal • Reduction of capital and operating costs with respect to MEA
CO_2 pipeline	• Design	• CO_2 composition – impurities effect • materials: internal corrosion, fracture propagation • water content: hydrate formation, corrosion issues • flow assurance
	• HSE	• CO_2 dispersion modelling

Table 2 Main lessons learnt related to CCU FEED

Process design	Issues for CCS application	Lessons learnt
Flue gas pretreatment	• SOx < 10 – 20 mg/Nm[3] • HF, HCl < 5 mg/Nm[3] • Dust < 10 mg/Nm[3] • Reduced Flue gas temperature(< 45°C) *Specific design values depends on cost optimization based also on the selected CCU technology*	• Flue gas cooling and additional desulphurization is required. • Additional dust removal is plant dependent
Capture plant flexibility	Capture Unit are generally highly flexible in term of turndown capacity limit and speed of load variation. Limiting sections are the flue gas booster fan on one side, and the CO_2 compressor on the other.	CCU: turndown to 30% of nominal capacity and load variation >2%/minute is easily achieved Compressor: turndown below 80-85% is achieved with recirculation. Modularisation is an option to increase flexibility
Flue gas emission control	Target: low or negligible emission to the environment. The potential introduction of new pollutants in the exhaust gas is one of the main concern	Flue gas washing section on top of absorber (sequential sections): 1st water wash: Always present, reduces ammine emission to some mg/Nm3 and heavy degradation products, but is ineffective on ammonia emission 2st and 3rd water wash (optional): Further reduction of ammine emission, ineffective on ammonia Final acid wash (optional): Effective on ammonia, residual ammine
Energy saving schemes	Energy recovery schemes	Options: External Heat Recovery schemes Internal Heat Recovery schemes Mechanical Vapor recompression
Wastes	Target: achieving the neutrality of the water balance, mainly to avoid wastewater production	How: • by controlling the treated flue gas temperature, with washing water cooling. • by tracing tank levels in the solvent loop • by laboratory analysis on ammine concentration
Erection philosophy	For a CCU, the modularization approach is preferable	Advantages: • Acceleration and cost reduction for erection process • Improvement of work quality • Reduction of workers number within the site • Improvement of the safety within the working environment
Material selection	Corrosion due to ammine solution, wet CO_2 or industrial or marine environment	Inquired options: • Stainless steel (304; 316), CS with SS cladding, Duplex, Carbon Steel • New materials: Concrete + Thermoplastic Lining: Attractive solution for Absorber fabrication, material validation to be monitored.
HSE	Solvents and CO_2 HSE issues	• Risk assessment: HAZID and HAZOP analysis • Operator training • BAT application to reduce emission and waste production

Table 3 CTS lessons learnt

Process design	Issues for CCS application	Lessons learnt
CO_2 Transport	• Design	• Compressor selection • Materials: corrosion issues, hydrate formation • Pipeline routing selection and installation methods • Xmas tree selection • CO_2 dehydration • Offshore platform concept selection • Concept definition of surface wellheads and offshore platform CO_2 injection plant • Control philosophy
	• Operation	• Preliminary operating philosophy definition • Metering
	• Costs	• Preliminary CAPEX and OPEX estimation (acc. -20/+30%)
	• HSE	• HAZOP

Table 4 Lessons learnt for storage section

Process design	Issues for CCS application	Lessons learnt
CO_2 Storage	• Site characterization	A deep knowledge of the area is essential to build a: • geological and structural model (structure closure, faults..) • petrophysical model (porosity and permeability..) • dynamic flow model (CO2 plume fate, pressure increase..) • geomechanical model (stress-strain conditions, uplift of sea bottom…) • injection strategy (well location, injection rate..)
	• Monitoring	Baseline (in order to distinguish natural gas fluxes from potential storage-related leakage) is essential • Off-shore pre-injection survey: physical and chemical characterization of the column and dissolved gases, characterization of sediment interface and water/sediment, benthic communities, oceanographic measurements, chemical-physical parameter continuous monitoring. • On-shore pre-injection survey (soil gas and diffusive degassing, shallow aquifer and dissolved gas) • Pre-injection micro-seismicity During operation: • seismic monitoring plan (acquisition parameters definition) • operational injection parameter (P, T..) control philosophy
	• Injection well	• Well design (injection vs monitoring weel) • Materials: corrosion issues, tubing string and casing (carbon and low alloy steels are resistant to CO_2 corrosion) liner (super 13Cr martensitic stainless steel) • Preliminary data acquisition program • Environmental impact assessment study
	• Costs	• At a feasibility stage, preliminary CAPEX and OPEX estimation can be drawn with accuracy ±30%

Table 5 Lessons learnt for dissemination activities

Process design	Issues for CCS application	Lessons learnt
Dissemination and Public Acceptance	• Public acceptance plan	• Social characterization is necessary to identify key stakeholders and elaborate and constantly update the outreach strategy and communication plan • To get the maximum effect out of the communication effort and to constantly gain credibility, public acceptance plan must reflect the development phases of the project; • The communication cannot be only focused on the CCS itself; in order to prepare the population for understanding and acceptance of the new technology, it is necessary to give the whole framework, included CO2 and climate change • Considering current economic and political situation, institutions and NGOs have been losing their credibility, so the viral and direct communication becomes crucial
	• Message strategy and communication style	• The message strategy must be well balanced between the reduction of the environmental impact and tangible and visible advantages for the population (new jobs and local development, energy security, cost of energy, CO_2 reutilization) • The communication materials used for public engagement needs to be clear and comprehensive to all the targets; too technical language and communication style might be seen as something alien to the population • The communication materials needs to address the CCS topic with the terms already familiar to the population • Turing the communication with the communities, the messages must be addressed by people involved directly in the project development and not by the communication experts; however the "massagers" must be trained for public speaking and interaction with the communities
	• Project management	• Public acceptance experts needs to be integrated to the project management team • The main challenge of the public acceptance experts is the coordination of different communication dimensions (institutional affairs, press, communication, etc.) and elaboration of the technical information • Early public engagement is the key factor of the success of the whole project