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Thematic Report

Transport session – October 2013

A report from the European CCS Demonstration Project Network

Public version

Proceedings from the Stavanger knowledge sharing event 23 and 24 October 2013

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Introduction

This report summarises main topics raised in the second Thematic Workshop on CO_2 Transport held during the Network Knowledge Sharing Event in Stavanger (Norway) on 23-24 October 2013, hosted by the Sleipner Project (Statoil). The workshop formed one of three parallel tracks of the knowledge sharing event. The other tracks addressed Storage of CO_2 and the Regulatory Development for CCS, respectively.

1. Participants

In the Transport Group, four Network projects were represented: Don Valley (UK), ROAD (NL), Compostilla (ES), and Sleipner (NO).

2. Status report from each project

Each project presented a general overview of the entire project status. Except for the Sleipner Project, the demonstration projects are all basically placed in a state of 'limbo' awaiting further financial agreements and also specific regulation. They have all planned to build pipelines that are sized in excess of the minimum capacity for the demonstration phase, with the intention to extend the use of these pipelines within a possible larger CCS chain to emerge in the future.

ROAD

- The new Maasvlakte Power Plant 3 power station (MPP3) is now in its final stage of hot commissioning, planned to become operational in late 2013. The rated net output power of the base plant (without capture) is 1070 MW_e with 46% thermal efficiency.
- An additional post-combustion capture unit, based on Fluor technology, is planned. This will clean a slip stream of the flue gas, equivalent to 250 MW_e with 90% capture rate. The flue gas temperature will be as low as 50°C.
- Fluor is selected for the engineering, procurement and construction contract (EPC), and will be the main supplier of the capture unit. Construction of tie-ins on the flue gas stack is under way, as well as the 3.4 bar steam extraction line from the cross-over section of the steam

turbine train. The extracted steam will be used at 3 bar for solvent recovery (i.e. slightly superheated steam to be saturated by adding some make-up water).

- The ROAD Project will capture 1.1 Mtpa CO_2, based on 75% utilisation of the power plant (this corresponds to 1.48 or 1.49 Mtpa CO_2 at full load).
- Due to the emission trading price which is currently very low, an unresolved funding gap has occurred. This has placed the project in a “slow mode” since the second quarter of 2012. The funding gap is still to be filled (probably via public money). ROAD is hoping to settle a funding agreement in the coming months.
- The ROAD pipeline comprises two legs: one 5 km onshore pipeline and one 20 km offshore pipeline. Both legs employ an insulated pipe with 16 inch diameter designed for 140 bar (max) and 80°C (max). The pipeline is capable of handling the 1.1 Mtpa of CO_2 in gaseous phase initially captured by the ROAD Project. At a later stage, however, the flow will turn into dense phase as the pressure builds up and the CO_2 stream exceeds the critical point pressure. The capacity of the pipeline will then be as large as 5Mtpa CO_2. This high capacity will allow CO_2 from other sources to be connected at a later stage (if appropriate).
- ROAD is considering future options for further development (as greenhouse gas that is not needed in the winter). The intention is further to connect the transport system to industrial plants and greenhouses, including Shell Pernis, a biodiesel plant, and possibly GreenHydrogen (not definitely abandoned).
- Capture, transport and storage permits are not irrevocable yet due to the onshore part of the (5 km) pipeline. Questions still remain to be answered as to at what depth below the ship road the pipeline is to be laid. This also applies to questions concerning the risks of the CO_2 pipeline breaking an adjacent gas pipeline placed nearby in the same trench.
- No due date for final investment decision (FID) is given, but it seems clear that FID will not be made within 2013.
- Operations of the demonstration plant are now scheduled for 2017-2020, but the timeline for the demonstration phase is still up for negotiation.
- Demonstration will be based on a depleted subsea gas reservoir (P18-4) with a very low reservoir pressure (now below 20 bar). The reservoir is located 3500 meter below the seabed. The intention is to inject 4 Mt of CO_2, although the total capacity of the reservoir is 8 Mt CO_2.
- An adjacent (almost depleted) gas reservoir, P18-2, may be used for additional storage at a later stage if the demonstration project proves to become successful (i.e. 35 Mt additional capacity).

- Initially, the pipeline will be pigged in order to dry out the pipe. The first pig will probably be pushed with air. An option exists to use several pigs. According to ROAD, this will require a pig trap at the platform. Pigging will then be made after each 5 Mt of CO_2 conveyed through the pipeline, or at least every 5th year.
- Taqa, a large Abu Dhabi-based company, owns the 18-4 platform from which the CO_2 will be injected. Taqa is a partner of the ROAD Project.

Compostilla

- The EEPR engineering work has been developed for future coal CCS Power Plant, based on a 300 MWe circulating fluidized oxy-combustion technology boiler; CO_2 captured will be stored in a deep saline aquifer and transported by a pipeline, 150 km away from the power station.
- So far, a lot has been done to justify the CO_2 transport system as required by the permitting process. This includes assessment of CO_2 release dispersion, crack arrest determination, material behaviour, thermophysical characteristics of pure and impure CO_2, flow assurance, environmental impact, identification of hazards, quantitative risk assessment (QRA), and last but not least the front-end engineering and designs study (FEED).
- The final investment decision (FID) is still pending. Seemingly, the permitting process is placed on hold due to lacking response from the Spanish authorities. The rationale is that since no regulation for CO_2 pipeline transport has been enacted in Spain, Spanish authorities claim to be incapable of permitting such pipeline systems.
- The environmental impact declaration was stopped, and the authorisation process of the project was stopped at the same date. The clarification of this process would, if permits were granted, give authority to the Compostilla Project to request landowners to allow pipeline construction at a fairly small cost. Now, the project is awaiting laws to be put in place to settle the legal framework for CO_2 transport in Spain.
- The project includes a 147 km onshore pipeline to handle the captured CO_2 flow in a steel pipeline buried 1.5 meter below the ground.
- The project is now comfortable with 50 ppm water content, which is far below the level of free water formation, even at the low temperatures which may occur when crossing a high mountain path, peaking at more than 1100 m altitude. The inlet pressure of the pipeline is 150 bar with an outlet pressure of 100 bar. Eventually, the pipeline ends at the injection site at an altitude about 350 m higher than the level of the power plant where the CO_2 is

captured, compressed and fed into the pipeline. Hence, the system is characterised by a large difference in height (maximum 600 m) which requires a significant hydraulic head.

Don Valley

- Don Valley and the emerging British White Rose Project are now being planned to make use of (essentially) the same pipeline, designed by National Grid. The pipeline has two distinct legs: one approximately 85 km long onshore leg, and an offshore leg of similar length. Both legs have the same diameter, but the specification and operational characteristics will differ from onshore to offshore, mainly with regard to pressure, pipe wall thickness, steel quality and external protection and insulation. A pumping station will be placed at the shore, thus connecting the two legs.
- The onshore pipeline is designed for 135 barg Maximum Allowable Operating Pressure, 150 barg Maximum Incidental Pressure, whereas the offshore pipeline is designed for 185 barg. The onshore pipeline has a diameter of 600 mm (24 inch) and 19mm minimum wall thickness (in L450 grade pipe).
- The pipeline is sized beyond demonstration load, as it will convey (initially) only 2-2.65 Mtpa. At full load the capacity would be 17 Mtpa. This large capacity is justified by future needs and the significant economy of scale associated with multiple capture projects sharing common pipeline infrastructure. There is a large prospect for injection locations, including EOR prospects closer to the Danish sector.
- Eventually, multiple additional CO_2 sources close-by are being considered to connect onto the pipeline capacity and, thus, enabling CO_2 to be offered for EOR opportunities.
- In the UK, the Planning Legislation has changed, and the regulations are not (always) foreseeable.
- Now, it is mandatory to have consultation with stakeholders, and to demonstrate that the consultation took place, and further to explain how the outcome of the consultation and the feedback received has been taken into account (or will be used).
- Discussion about public perception. No severe public opposition has been raised in the UK or the Netherlands, mainly due to offshore storage. Even in Spain, despite the onshore storage, no real opposition has seemingly emerged. Locals were easily convinced about the prosperity of having such a storage size.

- Pigging will be made initially during the first years, then pigging will be repeated every 5th year. National Grid plans to make use of Magnetic Flux Leakage pigs. The pigs may be equipped with different seals, depending on the pipe diameter.
- The CO_2 is planned to be injected from topsides into the storage site proposed
- Subsea completion could still be regarded as an option, but technology for subsea completion would require further evaluation. There are many unknowns regarding the venting from subsea completed injection wells. Except for Statoil, few companies (if any) have experience with designing and operating such systems.
- The pressure and the temperature will be monitored via 3 onshore block valves.
- A discussion was initiated regarding flow metering and how to verify how much of the CO_2 has been injected and eventually been stored (this topic was continued in a later session, cf. Chapter 8)
- A question about underwater leakages was raised regarding the availability of proper modelling techniques. What is known about it? A parallel is drawn with deepwater storage of CO_2.

3. Specific report on CO_2 compression

Compressor designs for the projects turned out to be rather similar and these designs share roughly the same layout with a number of initial centrifugal compression stages, followed by a section handling wet CO_2, made from stainless steel, injecting the CO_2 flow into a dehydration unit. From this unit the dry CO_2 enters the high-pressure section, made from carbon steel. Except for Sleipner, the projects specify the exit water content (i.e. the humidity) of the CO_2 flow to be equal to or lower than 50 ppmv.

ROAD

- With a maximum outlet pressure of 129 bar, the ROAD compression train comprises 8 stages, whereof the first 4 stages are termed wet stages. The CO_2 flow is cooled down to 30°C in-between each stage. The dehydration unit follows the 4th stage.
- The compression train has 2 recycling loops: one wet recirculation line (recycling CO_2 from stage 4, before the dehydration unit, to stage 1 thus mixed with the compressor inlet flow), and one dry recirculation line (recycling high-pressure CO_2 from stage 8, after the cooler, to stage 5).

- Due to proprietary information, ROAD is not entitled to reveal the exact power demand required to run the compression train. The reason is mainly that some of the steam required to operate the reboiler for recovering the solvent used in the capture unit will pass through a thermo-compression unit. This is a new feature covered by a non-disclosure agreement. Without knowing all the details, one may draw wrong conclusions about the capture process. ROAD is free to state, however, that the power demand will be higher than 15 MW and lower than 20 MW when handling 159 tph of CO_2.This corresponds to 94 – 126 kWh per tonne CO_2, accounting roughly for 60% of the power required by the entire CCS chain.
- For the CO_2 purification, only a dehydration system is included (and a polisher in the FGD unit in order to reduce the amount of sulphur compatible with post-combustion capture schemes).
- A water content below 50 ppm will cause no problem since the design temperature is -10°C. At this temperature free water cannot occur.
- The oxygen content will be less than 500 ppmv (and likewise: N_2<350 ppmv, acetaldehyde <10 ppmv and Ar<7 ppmv). No chemicals are to be added to the CO_2 flow.
- Like the main condenser of the power plant, the intercoolers will exchange heat with a closed cooling water cycle. This cycle will release heat to the adjacent seawater. The design temperature of the surrounding sea is 12°C (i.e. the lowest reference temperature determining the design of the power cycle).
- The peculiarity of the ROAD Project is that it will employ two distinct operational modes: a) initially, the CO_2 will be kept in gaseous phase with the temperature kept at its maximum (80°C), b) as the reservoir pressure gradually builds up during the initial operations, the flow will, after some time, turn from gas to dense phase flow (liquid). Studies of this approach have been made to prevent the Joule-Thomson effect. The high initial temperature (80°C) has been selected to compensate for the low reservoir pressure, and to avoid overheating the immediate surroundings.
- As a result of these studies, two-phase flow must be adhered to and considered as a specific design feature.

Compostilla

- The raw compressor, integrated with the compression and purification unit, CPU, lifts the pressure from atmospheric level to 30 bar. The compressor comprises 6 stages and requires

2 x 10 MW at full load consumption. The subsequent product compressor will require 2 x 7.5 MW.

- Both compressors will be radial compressors to be supplied by a German manufacturer.
- No sulphur will be present, but some water will occur, mainly saturated water vapour at (or close to) the dew point condition just after the flue gas cooler condenser (prior to the CPU).
- The CO_2 inlet temperature of the pipeline will be 50°C.

Don Valley

- The compression train required at the power plant will be influenced by the final capture plant technology configuration. A booster pump will, however, be required to shift from onshore to offshore transport conditions, as the pressure of the latter is slightly higher.
- The booster pump requires in the region of 2 x 900 kW, each handling 1.325 Mtpa CO_2 in two parallel multistage centrifugal pumps.
- Another pump (1 x 418.5 kW) will be provided as stand-by, intended to replace the two booster pumps (above) only at flow rates lower than 0.56 Mtpa CO_2.
- No supplier has been chosen yet.

4. Flow assurance modelling including transients (ROAD Project)

ROAD

An extensive Flow Assurance presentation was given by ROAD, highlighting the peculiarities of the ROAD Project:

- ROAD is the only project targeting a depleted gas field, with down-hole pressure below 20 bar at the outset of the period injecting CO_2. This leads to a very low wellhead pressure, and the need to allow for a large pressure drop between the pipeline pressure and the wellhead pressure. Evidently, this will be associated with a significant temperature drop, due to Joule-Thomson cooling.
- The impact of the Joule-Thomson cooling can be compensated for by increasing the temperature of the CO_2 flow prior to injection (maximum 80°C).
- As a separate cooler will not be used at the wellhead, ROAD is the only project to have a pipeline that intends to bring CO_2 to the wellhead at temperatures well above the ambient (sea) temperature level to the injection site, in order to mitigate the Joule-Thomson cooling.

A number of specificities of the pipeline design and operational philosophy were detailed, including:

- The need for directional drilling below shipping routes.
- The acknowledgment that two-phase flow occurs in the wellbore, leading to low wellhead temperature under certain circumstances.
- The acknowledgment that two-phase flow may occur during restart, with possibilities of fast liquid slugs travelling through the pipeline.
- The flow conditions and various impacts on the design of the pipeline were presented.
    - Under steady state, operations showing the impact of pressure and inlet temperatures on the local temperature and pressure of the CO_2 flow within the pipeline. The transport system can be controlled by adjusting the temperature of the CO_2 flow and the pressure control valve (PCV).
    - Similar studies were presented showing the cool down, and cool-down times under shutdown. Essential is the draining of the pipeline into the reservoir and, thus, minimising the amount of CO_2 to remain in the pipeline. Hence, two-phases can be avoided with low reservoir pressures.
    - Under start-up, the initial liquid hold-up, and the liquid hold-up at re-starting a pipeline filled with dense CO_2, were presented. The findings show that once the

pressure allows, the pressure control valve should be opened, and free flow should occur until single gaseous phase is established. Although slugs may occur, they will be manageable.

- Hence, an appropriate control philosophy has been established for the whole operating regime including shut-down and start-ups.
- Studies of the behaviour of slugs are interesting. They suggest that slugs and two-phase flow in 16 inch CO_2 pipelines will occur. Pressure spikes might then be possible when the pressure control valve (PCV) is open and slugs from the pipeline may hit the PCV.
- From flow assurance modelling, the following conclusions were drawn:
    - Slug flow at start-up is expected.
    - Pressure transients can be controlled, and low temperature can be avoided by minimising the pressure drop and velocities. Some vibration is, however, expected.
    - Due to the slugs, the flow will become instable when CO_2 is injected into the well.

5. Experimental activity on CO_2 transport at Statoil

The experimental work on CO_2 transport at Statoil is motivated by the necessity of reducing uncertainty in operations and to improve aspects relating to health, safety and environmental issues (HSE). This particularly pertains to pressure waves that may occur in pipelines and assessments of how fast pressure waves propagate. The purpose of this knowledge is to prevent pipeline rupture and crack propagation, as well as understanding how shut-ins may be affected (i.e. valves, piping and instrumentation).

It is also necessary to better understand the flow behaviour of CO_2 at varying pressure and temperature conditions. In the event of a sudden pressure release, the temperature of the CO_2 will drop immediately. The temperature drop may, however, be affected by the heat transfer from the nearest surroundings (seawater, air, ground, depending on how the pipeline is exposed). A proper understanding of these variables will have a bearing on the design of pipelines and the way pipelines are operated. At very low temperatures the steel may get brittle, and in order for pipelines to be deemed sufficiently safe, the temperature must not exceed specific levels.

Against this backdrop, Statoil is conducting extensive experimental studies of flow circuits emulating CO_2 pipeline operations. Plausible incidents are studied, such as pressure release of pure and impure CO_2 against various backpressures (e.g. into the ambient air or into low-pressure vessels, either with or without flow restrictions). Emphasis is placed on the temperature development against time at various distances along the pipeline. These studies include the impact of inclining the pipe, taking into consideration the characteristics of the pipeline, its insulation and surrounding conditions (heat transfer).

6. Modelling CO_2 flows – usage and constraints

In a presentation by SINTEF, two research challenges were especially addressed: a) fracture race, caused by fast transients in CO_2 mixtures that may cause longitudinal ruptures in CO_2 pipelines, and b) depressurisation of enclosed systems carrying CO_2. Both cases may have a severe effect on the operational behaviour as well as on the nearest surroundings, which call for extensive research and experimentation. Whereas a longitudinal crack will propagate at a velocity that depends generally on the characteristics of the pipe (i.e. material selection and physical dimensions) and the internal pressure and temperature, the pressure wave will propagate at the speed of sound, determined by the state of the CO_2 flow, such as a) the composition of the CO_2 mixture, b) the internal pressure, c) the temperature of the CO_2 stream and d) the flowing conditions, whether the CO_2 occurs in either gaseous or dense phase, or combined (two-phase flow).

The term *transient multiphase flow* of a CO_2 stream was presented. A transient multiphase flow can occur a) during start-up, especially with the first filling of the plant, b) during shut-down, especially if the plant is being emptied either on purpose or in an emergency situation (accidental release), or c) as a result of varying amounts of CO_2 being produced. Moreover, as is the case with the ROAD Project, CO_2 may contain two phases at the wellhead, depending on the pressure requirements for the reservoir.

Two extreme directions of transients were explained: a) *slow transients* impacting mass and energy travelling with the velocity of the fluid, and b) *fast transients* affecting pressure, and pressure travelling at the speed of sound relative to the fluid velocity. Typically, numerical schemes may accurately predict either a slow or a fast transient (some models even predict both transients fairly well).

Commercial 1D flow codes, like OLGA and LedaFlow, are developed to predict slow transients, and to match pressure loss at steady-state conditions. Some modern numerical schemes are far better at tracking fast transients.

Various thermophysical measurements and models were used to explain the concept of depressurisation with pressure-wave propagation and phase equilibrium at and between the frozen and equilibrium conditions. Furthermore, the speed of sound was presented as a function of the void fraction (from 0 – 1, full and empty pipe). Effects of residual components, like N_2, were also presented emphasising the importance of reducing the amount of inert gases in CO_2 transport systems.

Equation of state models (EOS) were compared, especially how Span-Wagner and Peng-Robinson compare along the pipeline in the event of depressurisation.

Regarding software for dynamic CO_2 simulation, the following was stated:

- STONER: Single-phase dynamic simulator (mainly used in the USA)
- OLGA: Upstream numerical model characterised by its accuracy in predicting mass flow, although the code is less accurate in predicting pressure transients. A new imbedded feature, CO2-VIP, improves the handling of CO_2 flow systems in OLGA using fluid properties defined by pressure and enthalpy. This approach has proved to be more accurate in single-phase flow (or near single-phase flow) than if fluid properties are based on pressure and temperature.
- PipeTech: No slip model used for coupled fluid-fracture (brittle and ductile) simulation. This code is able to predict dry-ice formation.
- HYSYS Hydraulics: This model is not feasible for single component CO_2 simulation.

Finally, comparison of OLGA against MUSTA was discussed, notably how pressure is predicted along the pipeline subject to sudden pressure drop in the CO_2 pipeline.

The conclusions drawn are as follows:

- New models are required for the optimisation of CO_2 transport systems and to improve safety.
- Two phases and multi-phases may occur in CO_2 transport systems during normal operations and during start-up, shut-down, and sudden depressurisation.
- Accurate properties of impure CO_2 mixtures are needed.
- The estimation of the speed of sound in two-phase flow models depends on assumptions made with regard to equilibrium. New models are required for non-equilibrium thermodynamics if fast transients are simulated.
- Commercial tools for transient simulation of CO_2 flows are scarce. The most complete code is OLGA, which is developed to handle slow transients. It lacks the ability of estimating hydrate and dry-ice formation. The code handles steady state pressure drops. It lacks,

however, the accurate thermophysical models required for CO_2 mixture typical of present power plants (coal and natural gas), and CO_2 to be gathered from industrial processes.

7. Regulatory approaches to safety approval of a CO2 pipeline design.

National Grid, in a joint session with the Regulatory Development group, summarized their regulatory approaches to safety approval of CO_2 pipeline design in the UK, with the aim of initiating a discussion around the similarities/ differences between Member States.

nationalgrid

Regulatory regime for onshore pipelines

Parameter	Response
What is the primary safety legislation	*Health and Safety at Work Etc. Act (HASWA) 1974* *Pipeline Safety Regulations (PSR) 1996*
Legislative approach	*'Risk based'* and *'Goal setting'*, it has to be demonstrated that risks are ALARP (As Low As Reasonably Practicable)
Who regulates safety?	UK Health and Safety Executive (HSE)
What is the pipeline design code?	British Standard Institution (BSI) standard BS EN 14161 (which is based on ISO 13623) and the code of practice for onshore pipelines – PD 8010
What are the design principles?	Area is defined as Class 1, 2 or 3 based on population density and infrastructure, design factor is specified according to area class (0.72. 0.3, not allowed)
Approach to separation/proximity distances	Based on the hazard factor for the fluid or individual risk level
Is a planning consent required?	Yes
What is the main planning legislation	*Planning Act 2008* (as amended by the *Localism Act 2011*)
Who grants planning consent?	UK Planning Inspectorate
Is safety linked to the planning consent	Yes

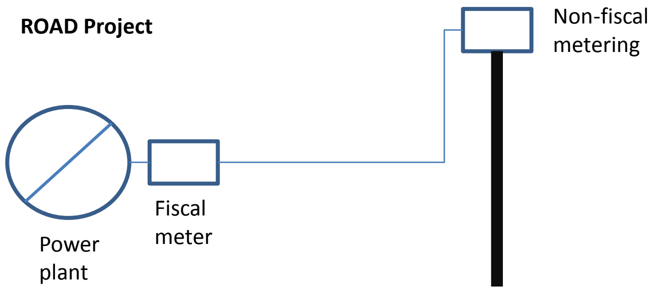
- The primary legislation is HASWA, this is the umbrella risk based legislation which requires demonstration of ALARP. Specific regulations are enacted under this legislation, including PSR. The specific legislation is 'goal setting' and places the duty upon the risk creators to demonstrate the risk is ALARP.
- The HSE require compliance with European standards (BS EN 14161) and UK codes (PD 8010) as a minimum in demonstrating ALARP.
- The UK code specified the requirements for routing and design. The separation distance is used to define a route corridor, over which the population and infrastructure is assessed. The area is Class 1 if the population density is ≤ 2.5 persons per hectare, Class 2 if it is

greater than 2.5 persons per hectare, and Class 3 if the population and building density is high. High pressure, hazardous pipelines may operate at a design factor up to 0.72 in Class 1 areas, 0.3 in Class 2 areas, and are prohibited in Class 3 areas.

- The code defines the separation distance according to a substance factor assigned according to the hazard category of the fluid, or the individual risk posed by the pipeline

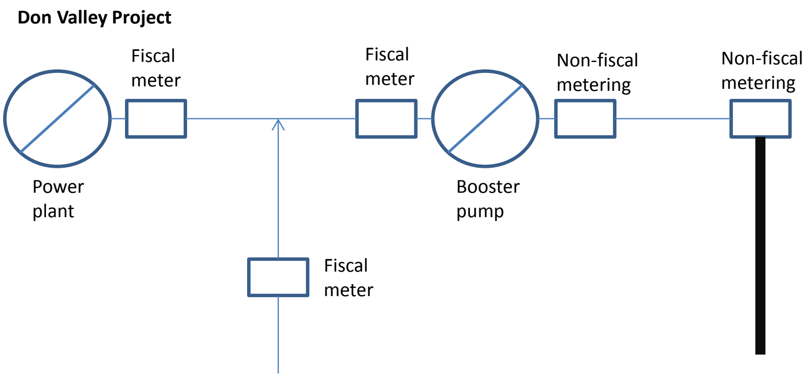
8. Flow metering

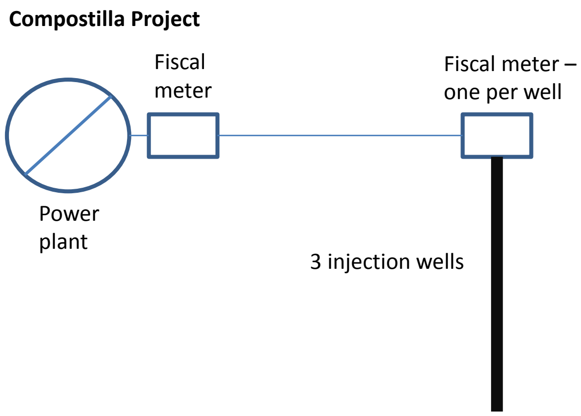
ROAD Project sketched some ideas about the metering concept to be developed:



The ROAD Project considers dividing the system into one fiscal metering station at the export valve at the power plant, and one metering station on the topside of the P18-4 platform in front of the injection well. The latter flow meter will probably be non-fiscal, used mainly for flow recording. The accuracy of the fiscal meter will typically be +/- 1%, and it will most likely be a coriolis meter measuring the mass flow of the CO_2 stream transported through the pipe. The non-fiscal meter at the wellhead may be of simpler and more robust design, for instance a venturi meter. This kind of metering technique may even sustain slugs in systems with two-phase flow.

A similar approach was made for the Don Valley Project and for Compostilla, as outlined below:





Other metering techniques were discussed, like orifice meters and turbine meters. The main problems associated with these metering techniques are a) pressure loss, and b) calibration. Turbine meters especially must be frequently calibrated, and there is so far no way of ensuring proper calibration with this kind and size of metering devices required for the amount of CO_2 to be piped by the demonstration projects.

Another issue is the overall accuracy taking the whole system into account. When applying a Monte Carlo method, the level of accuracy of the resulting mass flow may drop from +/- 1% (the accuracy of the flow meter itself) to probably 4-6% as a whole. Hence, proper analysis will be required until the projects finally can decide on how the metering should be ensured.

The European CCS Demonstration Project Network was established in 2009 by the European Commission to accelerate the deployment of safe, large-scale and commercially viable CCS projects. To achieve this goal, this community of leading demonstration projects is committed to sharing knowledge and experiences.
The successful deployment of this key technology will allow Europe to reach its environmental objectives, stimulate job creation, and generate a sustainable economic and industrial base.

Network support provided by: