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Abstract

During 19 and 23 October 2015 the IMPACTS CCS course „The impact of the quality of CO2 on transport and storage behaviour", organised by the Institute for Studies and Power Engineering (ISPE) from Romania, took place at the International Conference Center and Central Library of the University Politehnica of Bucharest. 43 participants representing students and academia, research institutes, gas and oil industry, power sector and national regulatory authority have formed the audience for the lectures kept by IMPACTS researchers from Ruhr-University Bochum (RUB), Germany; SINTEF Energy Research, Norway; Netherlands Organisation for Applied Scientific Research (TNO); Progressive Energy Ltd. (PEL), United Kingdom and Fundación Ciudad de la Energía (CIUDEN), Spain.

The main goal of the course was to facilitate knowledge sharing to representatives of Romanian industry, research institutes and academia based on the main results obtained during the implementation of IMPACTS project. The IMPACTS project has the objective to develop a CO_2 quality knowledge base required for establishing norms and regulations to ensure safe and reliable design, construction and operation of CO_2 pipelines and injection equipment, and safe long-term geological storage of CO_2. The project studies the impacts of relevant impurities in the CO_2 stream on the design, operation and costs of the capture, transport and storage infrastructure and to provide recommendations for optimized CO_2 quality through techno-economic assessments (amongst other considerations).

This summary memo gives an overview regarding the contents of the course, the discussions and the questions raised by the trainees.

Public introduction (*)

The CCS course „*The impact of the quality of CO_2 on transport and storage behaviour*" was held in Romania during 19 and 23 October 2015. The event, held at the International Conference Center and Central Library of the University Politehnica of Bucharest, was adjusted to the level of Master students being open for students, research institutes, regulatory authorities and people from industry.

The main objective of the course was to provide knowledge sharing to students and people from industry based on the main results obtained during the implementation of IMPACTS project. The IMPACTS project has the objective to develop a CO_2 quality knowledge base required for establishing norms and regulations to ensure safe and reliable design, construction and operation of CO_2 pipelines and injection equipment, and safe long-term geological storage of CO_2. The project studies the impacts of relevant impurities in the CO_2 stream on the design, operation and costs of the capture, transport and storage infrastructure and to provide recommendations for optimized CO_2 quality through techno-economic assessments (amongst other considerations).

The training course material was based on: the IMPACTS toolbox, thermodynamic reference models for CO_2 mixtures relevant for CCS and the framework for CCS risk assessment taking HSE aspects into account, the impact of the quality of the CO_2 and CCS chain integrity, and finally the IMPACTS recommendations report.

The training sessions have been organised in an interactive manner thus facilitating a vivid dialogue with viewpoints and knowledge exchange between lecturers and trainees The IMPACTS CCS course was divided in ten (10) technical sessions based on the topics of the proposed lectures:

- Session 1: Models on thermodynamic properties and equilibrium;
- Session 2: Typical CO_2 mixtures and operating conditions, transport and storage gap analysis, classification of CO_2 impurities;
- Session 3: Typical CCS chains;
- Session 4: Corrosion of pipeline steels caused by CO_2 mixtures;
- Session 5: The influence of CO_2 mixture composition;
- Session 6: Techno-economic analyses of impacts of CO_2 quality;
- Session 7: Operational and material effects of impurities in CO_2 streams;
- Session 8: Chemical and physical effects of impurities on CO_2 storage;
- Session 9: Risk assessment of CO_2 transport and storage infrastructure;
- Session 10: IMPACTS recommendations.

43 Romanian participants representing students and academia, research institutes, gas and oil industry, power sector and national regulatory authority have formed the audience for the lectures kept by IMPACTS researchers from Ruhr-University Bochum (RUB), Germany; SINTEF Energy Research, Norway; Netherlands Organisation for Applied Scientific Research (TNO); Progressive Energy Ltd. (PEL), United Kingdom and Fundación Ciudad de la Energía (CIUDEN), Spain.

(*) According to Deliverables list in Annex I, all restricted (RE) deliverables will contain an introduction that will be made public through the project WEBsite

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1 INTRODUCTION

The CCS course „*The impact of the quality of CO_2 on transport and storage behaviour*” was arranged in Romania during 19 and 23 November 2015 by the Institute for Studies and Power Engineering (ISPE) being the main activity of Task 3.3.2 of WP33 “Implementation of results” within IMPACTS project.

The CCS course, held at the International Conference Center and Central Library of the University Politehnica of Bucharest, was adjusted to the level of Master students being open for students, research institutes, regulatory authority and people from industry. The event was organized as a 4-day training of the participants and 1-day wrap-up meeting between lecturers and the organizers for the analysis of the feedback received.

The main objective of the course was to provide knowledge sharing to students and people from industry based on the main results obtained during the implementation of IMPACTS project. The IMPACTS project has the objective to develop a CO_2 quality knowledge base required for establishing norms and regulations to ensure safe and reliable design, construction and operation of CO_2 pipelines and injection equipment, and safe long-term geological storage of CO_2. The project studies the impacts of relevant impurities in the CO_2 stream on the design, operation and costs of the capture, transport and storage infrastructure and to provide recommendations for optimized CO_2 quality through techno-economic assessments (amongst other considerations).

Although initially the course was planned to take place in March 2015, is has been re-scheduled for October 2015 in order to have more project results available for dissemination. The training course material was based on: the IMPACTS toolbox, thermodynamic reference models for CO_2 mixtures relevant for CCS and the framework for CCS risk assessment taking HSE aspects into account, the impact of the quality of the CO_2 and CCS chain integrity, and finally the IMPACTS recommendations report. The training sessions have been organised in an interactive manner thus facilitating a vivid dialogue with viewpoints and knowledge exchange between lecturers and trainees. The seminar agenda is presented in *Appendix 1*.

The proposed CCS course topics and structure are in line with the Romanian CVET (Continuous Vocational Education Training) policies for the period 2014-2020, bringing together researchers, academia, regulators and industry representatives.

Invitation letters have been sent out few months before the event in an attempt to attract as many participants as possible. It was also tried to attract students from the countries neighbouring Romania. Therefore, invitations were sent to Energy Saving and Energy Management Institute of Kiev Polytechnic Institute from Ukraine, Faculty of Mining and Geology of University of Belgrade - Serbia, Institute of Power Engineering of Academy of Science from Moldova, National Technical University of Athens – Greece and Technical Institute of Sofia – Bulgaria. However, probably due to the summer vacation period, no registrations were received from these countries.

The CCS course gathered 54 participants, out of which 43 trainees that highly appreciated the event. The trainees were students and representatives of academia (University Politehnica of Bucharest, Constantin Brancusi University of Targu Jiu, Lucian Blaga University of Sibiu, University of Petrosani and Valahia University of Targoviste), representatives from research institutes (GeoEcoMar, Geological Institute of Romania, ECOMET, IPROCHIM), representatives from the gas and oil industry, such as Romgaz (National Natural Gas Company), OMV Petrom and CONFIND Campina, representatives from the power sector

(Oltenia Energy Complex, Geoconsulting and ISPE) and representatives from the national regulatory authority (ANRM – National Mineral Resources Agency). The list of participants can be found in *Appendix 2*.

Lecturers have been the following IMPACTS researchers with proven experience in the CCS field (in order of their appearance on the agenda): Stefan Herrig, lecturer of Ruhr-University Bochum (RUB) from Germany; Jacob Stang, research scientist at SINTEF Energy Research from Norway; Filip Neele, project manager at the Netherlands Organisation for Applied Scientific Research (TNO); Charles Eickhoff, project manager of Progressive Energy Ltd. (PEL) from United Kingdom; Amy Brunsvold, research scientist at SINTEF Energy Research from Norway; Geir Skaugen, research scientist at SINTEF Energy Research from Norway; Miguel Angel Delgado Calvo, R&D project manager at Fundación Ciudad de la Energía (CIUDEN) from Spain; Juan Andres Marin Vidal, head of pilot plant for CO_2 geological storage at Fundación Ciudad de la Energía (CIUDEN) from Spain; Ingrid Raben, risk analyst at the Netherlands Organisation for Applied Scientific Research (TNO).

A collection of IMPACTS public information and knowledge sharing material consisting in IMPACTS newsletters and published articles has been prepared and distributed to the participants. A roll-up and a poster (*Appendix 3*) have been created and used as promotion materials.

Two questionnaires have been prepared with the purpose to collect post-training feedback from the trainees. The first one, “CCS Opinion Survey” was intended to identify the level of information and awareness of the trainees about CCS technology (climate change, in general) and the course’s topics. The second one, “Assessment Questionnaire”, was intended to find out the trainees’ evaluation of the IMPACTS CCS course overall. The two questionnaires are presented in *Appendix 4*.

Finally, when the technical sessions were over all trainees have received diplomas certifying their attendance to the IMPACTS CCS course. The certificate for attendance can be found in *Appendix 7*.

2 OPENING SESSION

Dr. George Darie, the Prorector of University Politehnica of Bucharest (UPB), opened the IMPACTS CCS course with a welcome address. He expressed his appreciation regarding the topic covered by the CCS course, followed by an academic partnership with ISPE and the willingness to host the event at the International Conference Center and Central Library of the UPB. He emphasised the good cooperation between UPB and ISPE during the years by participating in different research projects and knowledge sharing events in the energy and environment (climate change) fields.

He has made a short presentation of UPB, its mission and objectives. Being founded over 190 years ago, UPB is the largest and the oldest technical university in the country and among the most prestigious universities in Romania. The mission of UPB has been thought over as a blend of education, research and innovation. The UPB's goal is to be, among the greatest universities in Europe, able to design and optimize processes that lead to a knowledge-based society and to reaching the goals of the sustainable economic growth.

Dr. Darie underlined that the university's master curricula have been continuously adapted to address the GHG emissions reduction concern at international level, the study of clean coal technologies being included, with special attention to carbon capture, usage, transport and storage.

The Prorector ended his speech by wishing good luck and successful training sessions to all participants.

In addition to the Prorector's speech, Dr. Cristian Dincă, Associate Professor at UPB, has made a brief presentation of the Politehnica's involvement in CCS research. He started by emphasizing the UPB's interest in increasing the number of researchers in the CCS field by including new topics in the master and PhD curricula, mainly in the Power Engineering Faculty and in the Chemistry Faculty. Therefore, in the doctoral and post-doctoral programs, the PhD theses are focused on the optimization of the CO2 capture process integration in the power plants. The Master programs dedicated to CCS include courses on capture, transport and storage processes, as well as on the integration of the CCS chain in the energy and industrial sector.

Dr. Dincă continued with an overview of the UPB's most recent research projects in the field of CCS. One international and two national projects have been introduced by presenting mainly their objectives and the partners involved in their implementation.

Finally, having in view the visit to the UPB research facilities included in the course agenda, Dr. Dincă has shortly presented the pilot installation for circulated fluidized bed combustion with chemical absorption process from the Laboratory of Renewable Energy Sources of the Power Engineering Faculty.

The following speaker was **Dr. Claudia Tomescu**, Head of Thermomechanical Systems Department of the Institute for Studies and Power Engineering (ISPE) and the project leader of ISPE in IMPACTS project. She's made a short presentation of ISPE, a consulting and engineering company with 65 years experience in power plants designing and environmental protection studies. By its studies and projects, ISPE developed practically the entire national energy chain, from energy generation up to end-consumers, including measures for increasing the energy efficiency and promoting the use of renewable energy sources.

Dr. Tomescu continued with a few words on the Romanian CCS Demonstration Project named GETICA. GETICA CCS is planned to implement a full chain operational CCS system, capturing 1.5 million tonnes of CO_2 emissions per annum from an existing 330 MW unit (no.6) of the Turceni Power Plant in Oltenia, Romania. The CO_2 from the capture plant (using post-combustion capture technology with chilled ammonia) will be transported for 50 km through underground pipelines to be stored in onshore deep saline formations. The project coordinator was the Romanian Government through the Ministry of Economy, Trade and Business Environment and the project shareholders were Turceni Energy Complex (the entity that owns the power plant generating CO_2 emissions and today named Oltenia Energy Complex), Transgaz (national natural gas transport company) and Romgaz (national natural gas storage company).

The Global CCS Institute has provided AU$2.55 million grant in support of a feasibility study for the GETICA CCS demonstration project. The feasibility study has been done by a technical consortium including: ISPE – Romania: project management, power plant and CO_2 transport technological consultant (the latter with support from INTETECH Consultancy – UK); Alstom Carbon Capture – Germany: Carbon Capture Plant technology; GeoEcoMar – Romania: geological consultant; and Schlumberger Carbon Services – France: CO_2 geological storage technology.

A NER300 application was submitted to the EU in February 2011. The project reached the reserves shortlist but not the final stage. In 2014, due to economic crisis, the Government decided that the investment for GETICA is not a priority so the project has been put on hold.

Dr. Tomescu ended by telling the participants that ISPE is trying to keep staying in contact with the latest research on CCS until funding enabling the work to progress towards the CO_2 capture and transport FEED study and storage appraisal phases will be found and GETICA CCS will be placed back on the priority list of the Romanian Government.

The last speaker of the opening session was Dr. Amy Brunsvold, research scientist from SINTEF Energy Research, with an overview of the IMPACTS project, its main objectives and the involved partners. She stressed the importance of the IMPACTS project, a project trying to investigate what are the effects of impurities in CO_2 transport and storage. Although a lot of work has been done on pure CO_2 and how it acts in pipelines and storage, it is known that different capture processes will lead to flue gases that have been purified but still have some fraction of impurities. IMPACTS became a project due to the lack of experimental data and verified property models for mixtures of CO_2 and impurities from various CO_2 capture processes. That requires a better understanding the effect of impurities on materials, equipment, processes, operation and safety procedures and how impurities will affect the storage integrity.

Dr. Brunsvold ended with a short description of the three sub-projects of IMPACTS and their interconnections.

3 TECHNICAL SESSIONS

3.1 Introduction

The IMPACTS CCS course has been divided in ten (10) technical sessions based on the topics of the proposed lectures:

- Session 1: Models on thermodynamic properties and equilibrium – covered with lectures by Stefan Herrig, lecturer of Ruhr-University Bochum (RUB) and Jacob Stang, research scientist at SINTEF Energy Research;
- Session 2: Typical CO_2 mixtures and operating conditions, transport and storage gap analysis, classification of CO_2 impurities – covered by Filip Neele, project manager at the Netherlands Organisation for Applied Scientific Research (TNO);
- Session 3: Typical CCS chains – covered by Charles Eickhoff, project manager at Progressive Energy Ltd. (PEL);
- Session 4: Corrosion of pipeline steels caused by CO_2 mixtures – covered by Amy Brunsvold, research scientist at SINTEF Energy Research on behalf of Centro Sviluppo Materiali (CSM), the Italian partner in IMPACTS project;
- Session 5: The influence of CO_2 mixture composition – covered by Geir Skaugen, research scientist at SINTEF Energy Research;
- Session 6: Techno-economic analyses of impacts of CO_2 quality – covered by Charles Eickhoff, project manager at Progressive Energy Ltd. (PEL);
- Session 7: Operational and material effects of impurities in CO_2 streams – covered by Miguel Angel Delgado Calvo, R&D project manager at Fundación Ciudad de la Energía (CIUDEN);
- Session 8: Chemical and physical effects of impurities on CO_2 storage – covered by Juan Andres Marin Vidal, head of pilot plant for CO_2 geological storage at Fundación Ciudad de la Energía (CIUDEN);
- Session 9: Risk assessment of CO_2 transport and storage infrastructure – covered by Ingrid Raben, risk analyst at the Netherlands Organisation for Applied Scientific Research (TNO);
- Session 10: IMPACTS recommendations – covered by Amy Brunsvold, research scientist at SINTEF Energy Research.

The training course material was prepared based on the project outcomes: the IMPACTS toolbox, thermodynamic reference models for CO_2 mixtures relevant for CCS and the framework for CCS risk assessment taking HSE aspects into account, the impact of the quality of the CO_2 and CCS chain integrity, and finally the IMPACTS recommendations report.

Excerpts from the course presentations can be found in *Appendix 5*.

3.2 Session 1: Models on thermodynamic properties and equilibrium

The first topic debated on the first day of the CCS course was "*Fluid Property Calculations in the 21st Century with Multiparameter Fundamental Equations of State*" presented by Stefan Herrig from RUB. Mr. Herrig started his lecture by a short introduction on what a fundamental equation of state (EOS) is and how to calculate thermodynamic properties from a fundamental EOS. Once one of the fundamental equations of state (thermodynamic potentials) is known, all properties can be calculated by combining derivatives of the fundamental EOS. Mr. Herrig talked about empirical fundamental EOS and how to describe mixtures with empirical EOS. Empirical fundamental EOS are usually formulated in terms of the Helmholtz free energy to be able to describe the whole fluid surface with a single formulation.

Mr. Herrig continued by presenting a series of thermodynamic models that could be used for describing fluid mixtures, such as one-fluid corresponding states model and Helmholtz models with departure function. He compared the GERG-2008 model by Kunz and Wagner, the most accurate thermodynamic model currently available for the description of fluid mixtures (originally developed for natural gas mixtures) and EOS-CG, developed at RUB and improving GERG-2008 for CO2-rich mixtures. The EOS-CG model is referred to as "equation of state for combustion gases and combustion gas like mixtures" (EOS-CG) and allows for calculations of mixtures containing carbon dioxide, water, nitrogen, oxygen, argon, and carbon monoxide.

Finally, Mr. Herrig presented the TREND software (version 2.0) developed at RUB and made available in Spring 2015 as an interface for users for defining mixtures or pure fluids and the algorithms will give the state properties and also predict the fluid phases. The TREND software is also able to help describing solid phases within the phase equilibria.

During the second part of his lecture, Stefan Herrig challenged the trainees with few exercises applying the presented knowledge. The participants downloaded the respective exercises from a link to RUB's server that had been set up prior to the CCS course. The exercises that were solved and discussed in the class are presented in *Appendix 6*.

The first day ended with a visit to the UPB's research facilities. The participants visited the three (3) new laboratories of the **Center for Research and Eco-Metallurgical Expertise – ECOMET**:

- the ***Advanced Materials and Nanomaterials Laboratory*** (specialized in nanomaterials preparation and testing in water treatment processes, characterization of all type NMs including small angles measurements on nano-powders; elaboration of special alloy materials with high entropy - with use in energy and defence industry; tests and investigations for evaluating the technical condition of industrial equipment; assessing the remaining useful life of industrial equipment's; technical analysis post-crash of metallic materials; investigation and the expertise of structural metallic materials by optical microscopy, scanning electronic microscopy and X-ray microanalysis including chemical analysis of ferrous and nonferrous metal materials by optical emission spectrometry and X-ray spectrometry; qualitative and quantitative phase analysis by X-ray diffraction, including measurement of residual internal stresses by X-ray diffraction; mechanical tests; non-destructive structural analysis of metallographic replicas according to ISO 3057 on industrial products able seamless and welded for inspection and expertise;

- the ***Environmental Assessment and Technology Laboratory*** (specialized in analyses of waters, soil, waste and leachate from wastes for the determination of metals using spectrometer methods; analyses of the content of pollutants in water and soil samples; qualitative and quantitative analyses of various organic compounds with environmental risk of various samples of liquid (water) or dissolved solids (soil, waste) using chromatography; detection of cations and anions in aqueous solutions);
- the ***Air Pollution and Climate Change Laboratory*** (specialized in carbon footprint for various products/technologies; air dispersion modelling and environmental risk assessment (PM10) for industrial sites, etc.)

The last visit was done at the ***Renewable Energy Sources Laboratory*** of the Power Engineering Faculty. This laboratory is designated for teaching and research work in the field of thermo-physical-chemical characterization of solids and reproducing at lab scale and semi-industrial pilot scale the thermo-chemical processes of pyrolysis, gasification and combustion applied to divided solid products, as well as solid products in mud type suspension. The lab has last generation equipment for chromatography analysis - mass spectrometry, atomic absorption and UV visible spectrophotometry, FT-IR spectrophotometry, calorimetry and thermogravimetry.

The second day of the CCS course started with the lecture "*Measurement of Impurities and Equilibria in CO_2 Mixtures*" presented by **Jacob Stang** from SINTEF. In introduction Mr. Stang underlined that carbon capture technologies do not produce pure CO_2, but a CO_2-rich mixture with varying amounts of other compounds (impurities). One of the main purposes of the IMPACTS project was to reveal the effects of these impurities on the remaining parts of the CCS chain (transport and storage). He talked about the influence of impurities on vapour-liquid equilibrium (VLE) and on other properties, such as viscosity, freeze out, hydrates, etc. This leads to challenges in numerical modelling; accurate thermodynamic models are needed for calculations and to make sure that, for instance, hydrate formations are avoided in processes.

SINTEF has developed capabilities for accurate VLE measurements on CCS relevant systems. The corresponding cell allows for measurements much more accurate than with most other VLE cells and it was used in IMPACTS to measure phase equilibrium in mixtures with CO_2. Mr. Stang described the rig that has been designed at SINTEF for accurate phase equilibrium measurements. Equipped with several safety features, including an advanced gas warning system, and manufactured using particularly corrosion resistant materials, it has been designed to be able to measure VLE data for essentially all mixtures relevant for IMPACTS. This even includes mixtures with H_2S, NOx and SO_2. The only serious exceptions are cryogenic mixtures, since the rig is designed for a temperature range from 60°C to 150°C. Pressures up to 20 MPa can be covered.

Mr. Stang continued on how SINTEF is using the equipment for doing the temperature measurement calibration and bath uniformity characterization, the preparation of gravimetric calibration mixture, gas blending, chemical analysis, gas chromatography (GC) calibration of binary mixtures, or the pressure measurements accuracy and calibration. He concluded with some results from SINTEF measurements for CO_2-N_2 system and CO_2-O_2 system.

3.3 Session 2: Typical CO_2 mixtures and operating conditions, transport and storage gap analysis, classification of CO_2 impurities

Session 2 was covered by **Dr. Filip Neele** from TNO, with the lecture titled "*Typical CO_2 Mixtures and Operating Conditions, Transport and Storage Gap Analysis, Classification of CO_2 Impurities*". He organized his lecture in three (3) parts: an introductory part on the reasons of researching and implementing CCS technology, a second part on CO_2 mixtures and transport and storage gaps related to impurities in captured CO_2 and a third part on carbon capture utilisation – CCU.

Firstly, Dr. Neele made a short introduction about global warming and its consequences on the environment. He showed some of the latest relevant information of the IPCC's Fifth Assessment Report (AR5) regarding the trends in stocks and flows of greenhouse gases (GHG) and their drivers and cross-sectoral mitigation pathways and measures, including CCS. The IEA Blue Map Scenario shows that CCS can provide ~20% of CO_2 mitigation by 2050; this means that 3,400 full scale CCS plants will be needed (with each plant delivering about 3 $MtCO_2$/yr). Furthermore, Dr. Neele illustrated the status of CCS large-scale projects at global level - 55 projects in various stages with a combined capacity of 106 Mt/yr. He talked about two of these projects: the Europe's first CO_2 storage project, operating since 1996 in the Sleipner field in Norway and the ROAD project, located in the harbour area of Rotterdam, one of the EU flagship projects, which has the first storage permit in Europe (published in 2013) for storing CO_2 in a depleted gas field offshore. This led to a discussion mostly with the participants from power generation industry on the increase of the price of MW after the installation of the CCS technology on the power plant. The discussion then moved to the challenges regarding the different CO_2 geological storage options, the most active and interested in the subject being the participants from the gas and oil industry. Dr. Neele finished the first part of his lecture with some information on Romania's storage capability resulted from the FP7 Geocapacity project (2008).

For the second part of his lecture Dr. Neele began with an overview of CO_2 mixtures that can be expected from a variety of combinations of capture technologies and emission sources. He continued with the impurities commonly found in CO_2-rich mixtures and the combinations identified in IMPACTS that produce the highest levels of impurities and the worst quality of CO_2. Then pipeline dimensions and operating conditions as they were designed for various CCS projects and demos have been showed. Emphasis was put on the analysis of the critical issues and the knowledge gaps regarding how the impurities in CO_2 can affect the CCS chain elements in terms of operational conditions, pipeline materials and storage. After a short classification of impurities by their relevance the conclusion was that impurities do play an important role and they should be taken into account in the design of the overall CCS system.

The final part of Dr. Neele's lecture consisted of a presentation of other utilisations for CO_2, in which many European countries have become interested, rather than simply store it underground forever. Some of these utilisations refer to enhanced hydrocarbon recovery (EOR/EGR) that could be very interesting for the oil and gas industries. He then showed some ideas of CO_2 usage in the Netherlands. As an example, he presented the CCUS network in operation today that collects about 400 ktons CO_2/yr from two sources in the harbour of Rotterdam and delivers it to greenhouses. Studies have showed that the volumes that can be used for other utilisations of CO_2 are too small. The conclusion is that although CCU is interesting, it is not a solution for climate-related emission reduction. However, CCU can support the development of capture and transport infrastructure.

Well aware of the potential impact of CCS on Romania's energy system, the audience was interested to hear about the backgrounds to the need for CCS, as well as critical about how CCS might be introduced in Europe. As Europe's Member States each have their own fuel mix, with some countries relying more on fossil fuels than others, the audience was interested to discuss implications for Romania of applying CCS to their industrial and power sector. While this topic could obviously not be solved, this led to interesting exchanges of ideas.

3.4 Session 3: Typical CCS chains

Session 3 covered the "*Choice of Benchmark CCS Chains for Illustrating CO_2 Quality*", a topic proposed for discussion by **Charles Eickhoff** from PEL. He began by explaining the purpose of having benchmark CCS chains in the IMPACTS project. Reference CCS chains have been established in order to provide comprehensive benchmarks from which to measure what impact CO_2 impurities would have on the CCS chain performances and also what are the changes to the chain economics due to introduction of other possible mitigations within the CCS chain. When establishing the chains it was tried to make then as simple as possible. So they were reduced to three elements: the capture element that generally includes compression, the transport element and the storage element.

Mr. Eickhoff continued by presenting types of capture process of interest in IMPACTS: power post-combustion, power pre-combustion, power oxyfuel, gas processing, and energy intensive industries capture (steel, cement). Moving on to transport elements, Mr. Eickhoff talked about the two types of transport that can be included in a typical CCS chain: pipeline and shipping. Then he went on by presenting storage types and locations. The IMPACTS project concentrated mostly on the offshore storage and identified some of the key storage formations that are in the North Sea: Brent sandstone, Rotliegand sandstone, chalk, etc.

Criteria for choosing the benchmark chains that have been used in IMPACTS were shortly presented. The following were taken into account: capture and transport types, storage types and environmental conditions, stream mixing, conditions (pressure and temperature), different materials, structure integrity, instrumentation, health and safety. The result was a choice of six (6) chains plus a combination chain:

- power post-combustion (amine) / pipeline offshore / gas field;
- power post-combustion (chilled ammonia) / short on-shore pipeline / on-shore aquifer;
- power pre-combustion / long pipeline offshore / oil field;
- power oxyfuel / pipeline offshore / oil field with EOR;
- gas processing / shipping / gas field;
- cement / pipeline offshore / chalk oil field;
- power pre-combustion – power oxyfuel – steel / long pipeline offshore / oil field – gas field – saline aquifer sandstone.

In addition, Mr. Eickhoff, showed costings for the various elements of the various chains that were gathered and analysed during the IMPACTS project.

The last thing Mr. Eickhoff talked on the second day of the course was impurity ranges, why they are important and how they potentially can be changed at the point of capture and during the flow through the chain.

3.5 Session 4: Corrosion of pipeline steels caused by CO_2 mixtures

During session 4 Dr. Amy Brunsvold from SINTEF had a lecture on "*Corrosion Resistance of C Steels Linepipe in Presence of CO_2 Mixtures: Literature Review*". The objective of her lecture was to present the work done by CSM partner from Italy and Tsinghua partner from China during the IMPACTS project regarding the evaluation of corrosion and stress corrosion degradation risks of CO_2 streams with impurities (H_2S, CO, NOx, SOx, and water) during pipeline transport.

Dr. Brunsvold started with literature review. After a short background on CO_2 pipelines and an introduction on corrosion she talked about the formation of corrosion in CO_2 pipelines, the CO_2 corrosion of carbon steels and the different CO_2 corrosion films formed at carbon steel surface. She also explained how temperature, pressure, flow velocity and steel microstructures can affect the CO_2 corrosion of carbon steels.

When presenting the uniform corrosion testing activity from CO_2 mixtures done by Tsinghua, Dr. Brunsvold talked about the four (4) different steel grades (X60, X65, X70, X80) and the testing program (sealed autoclave for 72h exposure time) that have been used and described in a few words the testing facility of Tsingua. The results obtained by Tsingua referred to the effect of water content and pressure on the corrosion rate for all four types of used steel. She also showed the conclusions obtained after comparing the experimental results with the simulated corrosion rates.

Dr. Brunsvold ended session 4 and the second day of the course by presenting the stress corrosion testing activity from CO_2 mixtures done by CSM. Similarly to the uniform corrosion testing activity, she made an overview of the materials (X60, X60W, X65, X70) and the testing program (four point bent beam, 720 h exposure time), as well as the CSM testing facility, that have been used. Finally, the results obtained by CSM were presented. General corrosion has been observed in all testing condition and one of the results showed that H_2 seems to promote stress oriented hydrogen initiated corrosion.

3.6 Session 5: The influence of CO_2 mixture composition

The third course day was opened by **Geir Skaugen** from SINTEF with the lecture "*The Effect of Impurities for Pipeline and Tanked Transport of CO_2*". Mr. Skaugen began his lecture with a few introductory words regarding the effect of impurities on CO_2 thermodynamic properties, on its density and dynamic viscosity. Having in mind the huge differences in densities and different phase behaviour previously discussed Mr. Skaugen moved on to presenting two (2) case studies regarding the effect of impurities on two transport chains: compression of CO_2 for pipeline transport (P-CO_2) and liquefaction of CO_2 for tanked transport (L-CO_2). The boundaries for this survey were: to have a CO_2-feed stream after a capture process, low pressure humid CO_2 saturated in water at atmospheric conditions (1 bar and 25°C) for both cases, to have a low temperature storage for the liquid CO_2 case and CO_2 to be transported in a 500 km pipeline for the piped CO_2 case.

The first case study was the pipeline transport of CO_2. Mr. Skaugen explained the P-CO_2 conditioning chain when feeding humid gas at atmospheric pressure, the cases used for the study (base case – only CO_2 and water from the capture process before the conditioning and compressing during the pipeline transport, oxy case – CO_2 removed from an oxyfuel combustion plant and gas case - CO_2 removed from a gas processing plant), the maximum impurity levels and boundary conditions. He also indicated what the power consumption per ton CO_2 for conditioning for all compression stages and all cases (base, oxy and gas), as well as for the on-shore transport on the 500 km pipeline was. The results of the analysis showed that with 4% impurities from N_2 and O_2, the transport power consumption in a 24-inch pipeline configuration can increase by 50%. Pressure profiles containing error propagation and uncertainty in density and viscosity and temperature profiles for the 24-inch pipeline configuration were depicted.

In the following minutes of his lecture, Mr. Skaugen tried to answer the question: "Will a crack in the pipeline, when initiated, propagate or will it stop?" For this he presented some information on fracture propagation and pipe design and the CO_2 phase behaviour in this situation.

Similarly, the second case study on tanked transport of CO_2 was presented. Mr. Skaugen explained the L-CO_2 conditioning chain after capture for shipping transport, the studies cases, maximum impurity levels and boundary conditions. Then the power consumption for liquefaction and the refrigeration requirements for cooling before expansion were analysed. At the end, he discussed the effects from VLE accuracy on heat transfer and gave suggestions for flash gas handling. Some of the conclusions for this case study were that the effect of impurities can be severe at low pressure storage pressure and accurate prediction of low temperature vapour-liquid – and solid – equilibrium are of vital importance in order to optimize this chain.

3.7 Session 6: Techno-economic analyses of impacts of CO_2 quality

The second lecture that **Charles Eickhoff** from PEL prepared for the IMPACTS CCS course was "*Techno-Economic Analysis of CO_2 Quality Impact on CCS Chains*". He started by explaining what is a techno-economic analysis and how it was approached in the IMPACTS project. The techno-economic analysis provides insight into cost-benefit decisions about projects and involves two basic elements (the technical requirements to achieve a defined outcome and the economic changes that this implies) that can be combined in a financial model capable to model the technical issues and vary the assumptions to look for optimal solutions.

Mr. Eickhoff displayed an outline of the use of cost functions by indicating the multi-variant influences of impurities, by presenting two examples for showing the capture cost function and the pipeline steel cost function, and by explaining the build-up of the overall cost function.

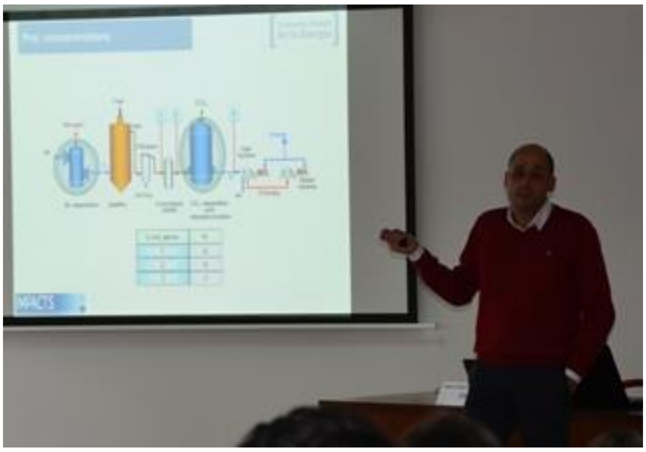
The lecture was continued with the presentation of the techno-economic (TE) model created in IMPACTS, which was built in Excel and was designed to be very flexible to allow different chains to be modelled. Mr. Eickhoff commented on different sheets that are composing the TE model, the parameters and specifications that they contain and how the model uses cost functions and produce optimizations.

After interpreting some of the results obtained from the corrosion tests done by the Italian and the Chinese partners in IMPACTS, he explained what are the key impacts of impurities on cost of capture in an integrated gasification combined cycle - IGCC (Capex and Opex) when tightening the specification and when relaxing the specification from the standard Benchmark plant. He also described similar cost variations for other capture processes (Post-combustion, Oxyfuel and Gas processing). The variation in density of the mixture with the nitrogen content and the effect of N_2 on multi-stage compression efficiency were described.

Moving on to the effect of impurities on the capacity of different storage locations at different depths Mr. Eickhoff continued with a graph showing the overall capacity of aquifer storage by depth and explaining what is the effect of adding additional N_2-O_2 to the mixture. He also discussed the effect of N_2 on CCS chain storage capacity with depth and the effect of N_2 & H_2O reduction on pre-combustion capture costs.

Mr. Eickhoff mentioned the fatal flaws or red lines arising from impurities that need to be overlaid in a TE analysis and that may be in the form of increased risk to structural integrity, heightened risks to human health or increased possibilities of environmental damage. He finished his lecture with a few words on SLOT (Specified Level of Toxicity) and SLOD (Significant Likelihood of Death). He concluded that IMPACTS have not identified any "red lines" because, generally, the identified risk issues, such as stress corrosion, toxicity of impurities or environmental damage, which might be potential candidates for being red lines issues, can be mitigated at some cost at the design stage.

3.8 Session 7: Operational and material effects of impurities in CO_2 streams



The last speaker of the third course day was **Miguel Angel Delgado Calvo** from CIUDEN who started his lecture with the topic "*CO_2 Transport: the CO_2 Stream Composition Depends on the Capture Process*". Firstly, he made an introduction on the types of CO_2 transport and examples of pipeline characteristics have been presented. He discussed the CO_2 phase diagram in terms of pipe transport versus ship transport. He showed the pure CO_2 properties for gas, supercritical and liquid phases. When talking about the captured CO_2 properties, he gave its definition and specified that when it is compared with pure CO_2 one can observe modifications in density, viscosity, phase diagram, optimum pressure and temperature and plant lifecycle. Then he presented the captured CO_2 compositions for different capture processes.

Mr. Delgado Calvo continued with an overview of the CO_2 capture technologies. He described in details the operating principle and the resulted CO_2 composition in volumes for the three capture technologies (post-combustion, pre-combustion and oxy-combustion). For post-combustion technology he explained the sorbent absorption theory (with both amine and ammonia solvents) and presented the elements of the post-combustion scheme. Then he introduced the audience into the basic reaction that takes place when using the pre-combustion technology, a partial oxidation process that can convert any hydrocarbon into H_2 and CO (synthesis gas) and presented the elements of the IGCC scheme with CO_2 removal and the volumes of H_2 obtained. He finished the part on capture technologies by presenting the elements of the oxy combustion scheme and the concentrations obtained after the process.

Mr. Delgado Calvo continued by describing how the CO_2 properties (density, critical point, diffusivity, vapour pressure, triple point, viscosity and the Joule-Thompson coefficient) are affected by the impurities and he ended his first lecture with the consequences of the impurities in terms of health and safety, integrity of the pipe, design construction and operation and hydrates formation.

The second part of Mr. Delgado Calvo's lecture focused on the "*CIUDEN Transport Rig*". After a few introductory words on CIUDEN organisation that includes a Clean Combustion Technologies Centre in Cubillos del Sil (Leon) and a CO_2 Geological Storage Centre in Hontomin (Burgos), Mr. Delgado Calvo proceeded to a detailed description of the Clean Combustion Technologies Centre and its main component parts: the fuel preparation system, the combustion island (including the CFB – circulated fluidized bed - boiler and the PC – pulverized coal - boiler) with the BFB – bubbling fluidised bed - gasifier, the flue gas cleaning system, the compression and purification unit and the transport rig. The transport experimental facility (3,000 m piping length that can use captured, as well as commercial, CO_2) and the laboratories and the control room have been described in details. Mr. Delgado Calvo's second lecture was finished with CIUDEN's recent projects and capabilities.

The final presentation of Mr. Delgado Calvo was titled "*Effects of Impurities on CO_2 Transport: Last Experiences at CIUDEN*" and focused on presenting the research done by CIUDEN in the IMPACTS project (consisting in the studying the effects of impurities on materials and the depressurization in a semi-industrial scale installation) by using the CIUDEN'S transport rig and of some of the preliminary results that have been obtained.

3.9 Session 8: Chemical and physical effects of impurities on CO_2 storage

The fourth day of the CCS course began with **Dr. Juan Andres Marin Vidal** from CIUDEN who prepared his lecture in three (3) parts. The first one concerned the "*CO_2 Geological Storage: Operational Parameters during the Injection*" and he started it by introducing to the audience the principles of CO_2 geological storage in terms of reservoir complex, porosity and permeability and the processes that are happening during storage. He talked about the phases of CO_2 in which it can be stored and the various CO_2 geological storage types. Dr. Marin Vidal gave a detailed explanation of the four mechanisms of CO_2 geotrapping in the reservoir rock: structural trapping that allows no upward migration due to caprock, residual trapping, when CO_2 is trapped in capillaries, dissolution in formation water where CO_2 is having a downward movement and mineral trapping when CO_2 enters in reaction with the rock forming minerals.

After going briefly through the reservoir parameters that need to be considered when doing CO_2 storage, he presented the main factors that must be known for the CO_2 geological sites, namely capacity, injectivity and retention, which are depending on the characteristics of the geological structure in which the CO_2 is injected. Other criteria that must be known are: environment, infrastructures, legislation, public perception and costs. Dr. Marin Vidal compared the different reservoir parameters for the storage sites in Hontomin-Spain and Ketzin-Germany. He ended the first part of his lecture by describing the constructive characteristics of a CO_2 injection well, the operation of the CO_2 injection facility installed in the Hontomin storage plant and their CO_2 supercritical injection strategy.

On the second part of his lecture, Dr. Marin Vidal presented "*CIUDEN's Storage Site: Hontomin Pilot Plant*", which is on-shore deep saline aquifer CO_2 storage at 1,500 m depth. He informed the trainees on the beginnings of the pilot plant, how the site location was selected and what geophysical campaigns have been done before decision making. Dr. Marin Vidal showed the pilot plant layout by indicating and depicting its main components. He went into details about the construction of the two (2) (injection and monitoring) wells, the engineering design of the CO_2 injection facility, water conditioning facility and the seismic and hydrogeological control networks and concluded about the future challenges regarding the operation of the Hontomin pilot plant.

Dr. Marin Vidal finalised his lecture with the presentation "*Short-term Effects of Impurities on CO_2 Storage*" where he addressed the topic of impurities in the CO_2 stream from the CO_2 storage point of view. He mentioned the typical impurity components in the CO_2 stream and the physical and chemical effects that they have on the storage process. Finally, he presented the lab scale and the field scale tests that can be done for observing the effects of impurities on CO_2 storage and delivered information on the results of the real scale test (CO_2 injection-extraction experiment) that has been carried out during the IMPACTS project.

The interest shown by the trainees in the CO_2 storage has been high, this becoming clear in the questions and issues raised. Particular attention was paid to the technology used for CO_2 injection in dense state, as well as the strategies used to storage it in the underground geological structure in secure conditions and ensuring the sealing conditions through the different control methods in surface.

3.10 Session 9: Risk assessment of CO_2 transport and storage infrastructure

The ninth session of the CCS course was covered by **Ingrid Raben** from TNO. She has prepared her lecture on risk assessment of CO_2 transport and storage infrastructure in two parts. The first part consisted in an "*Introduction to Quantitative Risk Assessment (QRA)*". After making a short presentation of TNO and its innovation areas, Ms. Raben introduced the audience into a brief history of industrial safety by presenting a few industrial accidents that happened in the world over the years. All these accidents led to awareness in Europe that measures need to be taken to protect the public. Ms Raben underlined that this is how the Seveso Directive, named after an industrial accident in Seveso Italy in 1976, has been adopted at European level and explained the purpose of doing quantitative risk assessment (QRA).

She continued by comparing consequence analysis versus risk analysis. The methodology, the relevant parameters and the risk criteria involved in performing the QRA have also been presented. As there are many parameters that need to be considered for QRA, there are some guideline books on how to do it. Ms Raben presented the content of these books in the Netherlands and how to be used when performing QRA. She ended the first part of his lecture with a detailed presentation of the procedure for performing a risk assessment analysis.

The final part of Ms Raben's lecture addressed the "*Impact of CO_2 Quality on QRA*" and consisted in a presentation on how the impurities in a CO_2 stream influence risk, namely: they can alter thermodynamic behaviour of CO_2, they can change failure frequencies and they can be toxic or flammable. She made a classification of impurities in terms of their properties and showed which can be flammable, explosive, toxic, asphyxiating or damaging in other ways. The conclusions were that the concentration of flammable substances is not sufficient to pose additional risk and CO, NO_2, SO_2 and H_2S can be present in sufficiently high concentration to pose additional risk to external safety.

3.11 Session 10: IMPACTS recommendations

The final lecture of the day belonged to Dr. Amy Brunsvold from SINTEF. The main objective of her final speech was to make a brief summary of the topics presented during the course and to talk about the recommendations resulting from the research done in the IMPACTS project for optimised operation of safer and more efficient handling of CO_2 with impurities along full CCS chains. She emphasized that the presented results and recommendations are preliminary and they are subject to change before the end of the IMPACTS project or after as more results are obtained.

Dr. Brunsvold informed the audience that the input provided by the project's WPs will be synthesised and a report summarizing IMPACTS recommendations will be prepared based on the knowledge and tools developed in IMPACTS. For a better understanding of the IMPACTS outcomes, she has summarized of the results that have been generated during the project: an inventory of CO_2 mixtures that defines the framework for characterization of impurities impact on CCS systems; experimental work measuring accurate property data for explaining thermophysical behaviour of CO_2 mixtures, model development to simulate the transient flow of CO_2 mixtures in pipelines (TREND2 model), tools for benchmarking CO_2 flow simulation, experimental work on the effect of CO_2 supercritical mixtures on corrosion of pipeline materials, lab scale and semi-industrial scale tests of effect of impurities on operation and materials and field scale activities. The recommendations report will likely include: guidelines on the need for upstream conditioning of CO_2 streams, guidelines on the transient operation of pipelines, guidelines on the need for anti-corrosion measures in the CCS chain, guidelines on the operation and integrity of injection wells, guidelines on the choice of storage site and on assurance of reservoir integrity and stability, guidelines on the trade-offs between CO_2 composition, CCs system performance target, and the design and cost of the CCS chain, rules of thumb for mixing different of CO_2 qualities in a multi-user transportation system and a framework for risk assessment of CCS considering CO_2 stream with impurities.

Concluding, Dr. Brunsvold tried to answer the question "What does it take to make CCS happen?" considering that there are no support measures to promote CCS as there are for other clean energy investments. She showed the global CCS status and the key barriers for CCS identified by Global CCS Institute. As examples of best practice she presented three business cases of CCS developed in Norway: the Sleitner field started in 1996 and operated by Statoil, the Snohvit Melkoya project started in 2008 and operated by Statoil ASA, Petoro AS (Norwegian state direct interest), Total E&P Norge AS, GDF Suez E&P Norge AS, Norsk Hydro and Hess Norge and Technology Centre Mongstad (TCM), the world's largest facility for testing and improving CO_2 capture technologies. She mentioned also that Norway intends to have a full-scale CCS project within 2020.

In the end she delivered some information on the methodology and toolbox for consistent and transparent assessment of CCS chains that has been developed by SINTEF in order to handle uncertainties, the complexity and multi-dimensionality inherited in CCS chains and generate relevant future perspectives.

4 WRAP-UP MEETING

The final day of the IMPACTS CCS course was dedicated to an analysis of the outcomes of the course and to the identification of follow-ups. To this end a wrap-up meeting between lecturers and representatives of ISPE was organized in the fifth day of the event. The meeting took place in Sinaia at the conference room of Caraiman Hotel. The participating lecturers have been Amy Brunsvold and Geir Skaugen from SINTEF and Charles Eickhoff from PEL. From ISPE's side, Claudia Tomescu, Camelia Vasile and Gloria Popescu have participated.

In the beginning, an analysis of the audience structure and of the responses received from the participants based on the circulated opinion survey questionnaires has been done.

The CCS course gathered 54 participants, out of which 43 trainees that were:

- MSc and PhD students and representatives of academia;
- researchers and scientists from public or private RDI entities;
- oil and gas industry representatives;
- power sector representatives;
- representatives from the institutional - regulatory authority in the field of mineral resources.

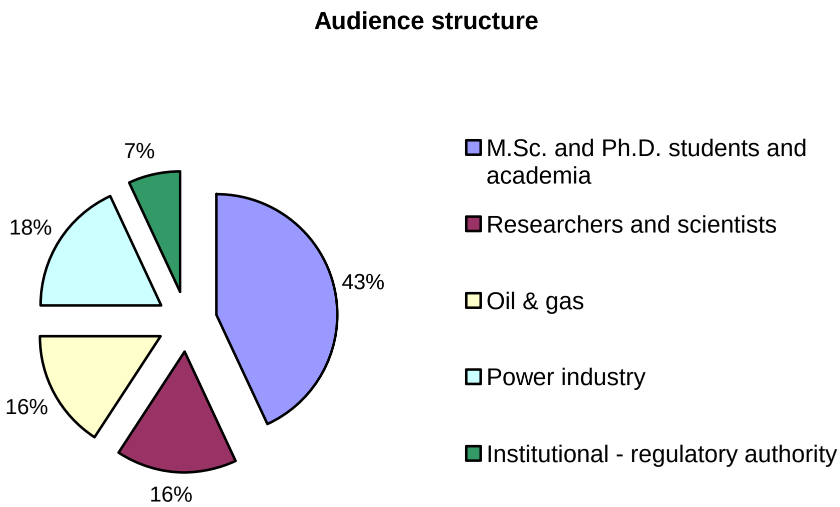


Figure 4-1: IMPACTS CCS course audience structure

56% were male trainees and 44% female trainees.

Analysing the answer to the "Opinion Survey" questionnaire (see Appendix 4) the following conclusions have been extracted:

- Q1, Q2 - 86% of the trainees consider climate change an issue of high importance and concern both at national and international levels;
- Q3, Q4 – the trainees consider that reduction of CO_2 emissions is of high importance (95%), the major impact being definitely attributed to the transport sector (95%), power sector (81%), metallurgy and oil & gas industries (79%);
- Q5 - the role of CCS technology was relatively well evaluated for reducing the GHG emissions (86%), polar caps melting (84%) and probably ozone layer thinning (65%);
- Q6 – when estimating the impact of CCS implementation in Romania the trainees agreed on its positive influence on the environment (95%); the economic impact is split between the technology high investment rate (51%) and the horizontal economy development (49%);
- Q7 – regarding the CO_2 quality impact on CCS technology chain, in terms of operation processes and equipment materials during CO_2 transport and storage components, 95% of the trainees understood and deducted, during the course, the importance of this aspect;
- Q8 – although there were many discussions during the course regarding the high costs of CCS, 84% would support the implementation of CCS technology in Romania;
- Q9, Q10 – when asked if they consider that CCS deployment is supported by EU policy and if they know about any such developments in Europe, only 67% had a positive answer;
- Q11 – 77% of the trainees consider that developing a future CCS project in Romania would be appropriate and necessary.

Furthermore, the feedback received based on the course “Assessment Questionnaire” has been analysed. 96% of the trainees appreciated the IMPACTS CCS course of high level (very good - 60% and good - 36%).

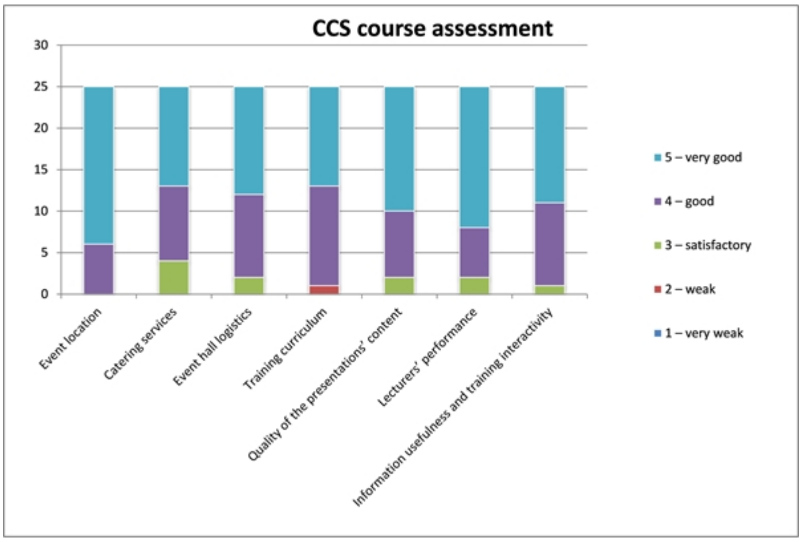


Figure 4-2: IMPACTS CCS course evaluation

The event location and logistics, as well as the lecturer's performance, information usefulness, presentations quality and course interactivity were very well appreciated. There were only few comments regarding the dense structure of the training curriculum (they considered that it was a lot of new information condensed in a short time).

The lecturers have also expressed their opinions regarding their interaction with the trainees, the questions raised during the course and the discussions that they had with them.

Mr. Eickhoff considered that at the beginning some of them were a bit reticent to engage with the course, but this improved during the week as more discussion took place. He found the general level of knowledge amongst the trainees very good and that they had no particular difficulties following the course content. Some very useful questions have been asked during the talks and also around the subjects in discussions in the breaks. In his opinion the trainees were genuinely interested in the subject of CCS in the context of the environment, but probably found the focus of IMPACTS just on the changes to the CCS chain from impurities quite specific. Many of the questions related to the level of overall cost of CCS and the impact such costs might have in Romania in particular. He thought the venue and structure for the course was good and the ability to discuss more informally over breaks and lunch was useful.

Mr. Skaugen’s opinion was that although it was a large variety in the trainee’s background and they did not seem to have worked deeply within CCS, they had a very strong interest in the CCS topic in general. Some of them considered the CCS technology to be expensive and were concerned of how much would the price of MW be increased if CCS would be implemented for the Romanian coal power plants.

At her turn, Dr Brunsvold said that, in her opinion, the trainees seemed to be a balanced mix of students and industry representatives, although she was surprised to actually find more people from industry than she was expecting. Based on the discussions, it was clear that the audience was quite interested in CCS, but some were skeptical about how CCS could be implemented on a large scale in Romania. She thinks that once they understood that the IMPACTS project was there simply to provide information about the challenges of transporting and storing CO_2 with impurities (and not trying to convince them that CCS should be forced upon Romania’s power and industry plants), they became more positive about the lectures. She thought that Filip Neele's presentation on the need for CCS in general was a very good overview discussion to have to put CCS in a larger perspective. The participants seemed eager to participate in the group work. She considered that there were quite a few interesting discussions in the plenum and she enjoyed some nice conversations with the students during the breaks.

The general conclusion of the wrap-up meeting was that, taking into account the positive feedback received, the IMPACTS CCS course was a successful event and its objective of facilitating knowledge sharing and disseminating the main results from IMPACTS has been reached.

5 CONCLUSIONS

As part of the IMPACTS project, a CCS course on “The impact of the quality of CO_2 on transport and storage behaviour” was arranged by the Institute for Studies and Power Engineering at the International Conference Center and Central Library of the University Politehnica of Bucharest, Romania, on 19-23 October 2015.

The main goal of the course was to facilitate knowledge sharing and make the results from IMPACTS project available to students and people from industry. The base for the training course material was: the main achievements from IMPACTS research, the IMPACTS toolbox and the IMPACTS recommendations.

The attendants have been multidisciplinary, being formed by engineering students, researchers and experienced industry professionals from public and private companies. All groups proved to have extensive knowledge in the field of energy and environmental protection and were well informed about the existing industrial technology, mainly the CO_2 capture. Key stakeholders that were involved in the Getica CCS Demo Project were more informed on carbon capture and storage technology compared with the younger attendees.

The lecturers had a good interaction with the audience during the course. The trainees were interested in the presented lectures and the questions that were raised showed that they had a good understanding of the addressed topics.

Considering the positive feedback received, the IMPACTS CCS course was a successful event and its objective of facilitating knowledge sharing and disseminating the main results from IMPACTS has been reached.

Romania is one of the most important coal producers in Europe and about 30% of its energy production is based on coal. The power industry understands that carbon capture and storage could be a good solution for saving coal power plants from closure. That is how Getica CCS Demo Project was born. However, CCS technology isn’t very well known in Romania. Intensive knowledge sharing and public awareness campaigns on low carbon technologies with focus on CC(U)S are needed, with specific communication tools developed by the type of public / stakeholders addressed.

Romanian academia and industry have showed great interest in research results disseminating events, such as the IMPACTS CCS course. Therefore, there is a real openness in Romania for future similar events, which, by easing the transfer of specific knowledge, could be relevant in supporting and proving the existing CCS technology and in demonstrating it on a large scale integrated CCS project.

Figure 5-1: Photos from the IMPACTS CCS course

APPENDIX 1: AGENDA

IMPACTS

The Impact of the Quality of CO_2 on Transport and Storage Behaviour

IMPACTS CCS Course
19-23 October 2015, Bucharest - Romania

AGENDA

Monday, the 19th of October 2015

Hour	Session/Lecture	Lecturer
09.00-09.30	*Participants registration*	
09.30-10.00	Welcome Addresses and Introductions	**George Darie** – Prorector of University Politehnica of Bucharest (UPB), Romania **Claudia Tomescu** – Institute for Studies and Power Engineering (ISPE), Romania **Amy Brunsvold** – SINTEF Energi, Norway
Session S1	***Models on thermodynamic properties and equilibrium***	
10.00-11.00	**Fluid Property Calculations in the 21st Century with Multiparameter Fundamental Equations of State** (part 1)	**Stefan Herrig** – Ruhr University of Bochum (RUB), Germany
11.00-11.20	*Coffee break*	
11.20-12.20	**Fluid Property Calculations in the 21st Century with Multiparameter Fundamental Equations of State** (part 2) - **exercises**	**Stefan Herrig** – Ruhr University of Bochum (RUB), Germany
12.20-12.30	*Break*	
12.30-13.30	**Fluid Property Calculations in the 21st Century with Multiparameter Fundamental Equations of State** (part 3)	**Stefan Herrig** – Ruhr University of Bochum (RUB), Germany
13.30-15.00	*Lunch break*	
15.00-16.00	**Fluid Property Calculations in the 21st Century with Multiparameter Fundamental Equations of State** (part 4) - **exercises**	**Stefan Herrig** – Ruhr University of Bochum (RUB), Germany
16.00-16.20	Discussions / Q&A	
16.20-17.30	**Visit to the UPB Research Facilities**	University Politehnica of Bucharest (UPB)

Tuesday, the 20th of October 2015

Hour	Session/Lecture	Lecturer
Session S1	***Models on thermodynamic properties and equilibrium***	
9.00-9.40	**Measurements of Impurities and Equilibria in CO_2**	**Jacob Stang** – SINTEF Energi, Norway
9.40-10.00	Discussions / Q&A	
Session S2	***Typical CO_2 mixtures and operating conditions, transport and storage gap analysis, classification of CO2 impurities***	
10.00-11.00	**Typical CO_2 Mixtures and Operating Conditions, Transport and Storage Gap Analysis, Classification of CO_2 Impurities**	**Filip Neele** – TNO, the Netherlands
11.00-11.20	Discussions / Q&A	
11.20-11.40	*Coffee break*	
Session S3	***Typical CCS chains***	
11.40-12.40	**Choice of Benchmark CCS Chains for Illustrating CO_2 Quality** (part 1)	**Charles Eickhoff** – Progressive Energy Limited (PEL), UK
12.40-14.10	*Lunch break*	
14.10-14.55	**Choice of Benchmark CCS Chains for Illustrating CO_2 Quality** (part 2)	**Charles Eickhoff** – Progressive Energy Limited (PEL), UK
14.55-15.05	*Break*	
15.05-15.50	**Choice of Benchmark CCS Chains for Illustrating CO_2 Quality** (part 3)	**Charles Eickhoff** – Progressive Energy Limited (PEL), UK
15.50-16.10	Discussions / Q&A	
Session S4	***Corrosion of pipeline steels caused by CO_2 mixtures***	
16.10-16.40	**Corrosion Resistance of C Steels Linepipe in Presence of CO_2 Mixtures: Literature Review**	**Amy Brunsvold** – SINTEF Energi, Norway
16.40-17.00	Discussions / Q&A	

IMPACTS

Wednesday, the 21st of October 2015

Hour	Session/Lecture	Lecturer
Session 55	*The influence of CO_2 mixture composition*	
09.00-10.00	The Effect of Impurities for Pipeline and Tanked Transport of CO_2	Geir Skaugen – SINTEF Energi, Norway
10.00-10.20	Discussions / Q&A	
Session 57	*Techno-economic analyses of impacts of CO_2 quality*	
10.20-11.20	Techno-Economic Analysis of CO_2 Quality Impact on CCS Chains (part 1)	Charles Eickhoff – Progressive Energy Limited (PEL), UK
11.20-11.40	*Coffee break*	
11.40-12.40	Techno-Economic Analysis of CO_2 Quality Impact on CCS Chains (part 2)	Charles Eickhoff – Progressive Energy Limited (PEL), UK
12.40-13.00	Discussions / Q&A	
13.00-14.30	*Lunch break*	
Session 56	*Operational and material effects of impurities in CO_2 streams*	
14.30-15.30	CO_2 Transport: the CO_2 Stream Composition depends on the Capture Process	Miguel Angel Delgado – Fundación Ciudad de la Energía (CIUDEN), Spain
15.30-15.40	*Break*	
15.40-16.10	CIUDEN's Transport Rig	Miguel Angel Delgado – Fundación Ciudad de la Energía, Spain
16.10-16.40	Effects of Impurities in CO_2 Transport: last experiences at CIUDEN	Miguel Angel Delgado – Fundación Ciudad de la Energía, Spain
16.40-17.00	Discussions / Q&A	

Thursday, the 22nd of October 2015

Hour	Session/Lecture	Lecturer
Session 58	*Chemical and physical effects of impurities on CO_2 storage*	
09.00-10.00	CO_2 Geological Storage: Operational Parameters during the Injection	Juan Andres Marin – Fundación Ciudad de la Energía (CIUDEN), Spain
10.00-10.10	*Break*	
10.10-10.40	CIUDEN's Storage Site	Juan Andres Marin – Fundación Ciudad de la Energía, Spain
10.40-11.10	Short-term Effects of Impurities on CO_2 Storage	Juan Andres Marin – Fundación Ciudad de la Energía, Spain
11.10-11.30	Discussions / Q&A	
11.30-11.50	*Coffee break*	
Session 59	*Risk assessment of CO_2 transport and storage infrastructure*	
11.50-12.50	Risk Assessment of CO_2 Transport and Storage Infrastructure Part 1: Introduction to Quantitative Risk Assessment (QRA)	Ingrid Raben – TNO, the Netherlands
12.50-14.20	*Lunch break*	
14.20-15.20	Risk Assessment of CO_2 Transport and Storage Infrastructure Part 2: Impact of CO2 Quality on QRA	Ingrid Raben – TNO, the Netherlands
15.20-15.40	Discussions / Q&A	
Session 510	*IMPACTS recommendations*	
15.40-16.40	IMPACTS Recommendations	Amy Brunsvold – SINTEF Energi, Norway
16.40-17.00	Discussions / Q&A	
17.00-17.20	Diploma Awarding Ceremony	

Friday, the 23rd of October 2015

Hour	Session	Chairperson
Wrapping-up the CCS course (only for the lecturers) - Meeting between lecturers and organisers		
08.00-09.30	Departure to Sinaia, Romania	
09.30-13.30	Round Table on the outcomes of the course; discussions regarding: - structure of the audience (academia, industry, etc.) and questions received during the course; - which of the debated topics were of most interest for the attendees; analysis of the attendees' knowledge evaluation questionnaires; - feedback received from the participants based on the training assessment questionnaires; - identification of follow-ups	Claudia Tomescu – Institute for Studies and Power Engineering (ISPE), Romania
13.30-14.30	*Lunch break*	
14.30-16.00	Return to Bucharest – departure of lecturers	

APPENDIX 2: PARTICIPANTS LIST

IMPACTS

The Impact of the Quality of CO_2 on Transport and Storage Behaviour

IMPACTS CCS Course
19-23 October 2015, Bucharest - Romania

LIST of PARTICIPANTS

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IMPACTS

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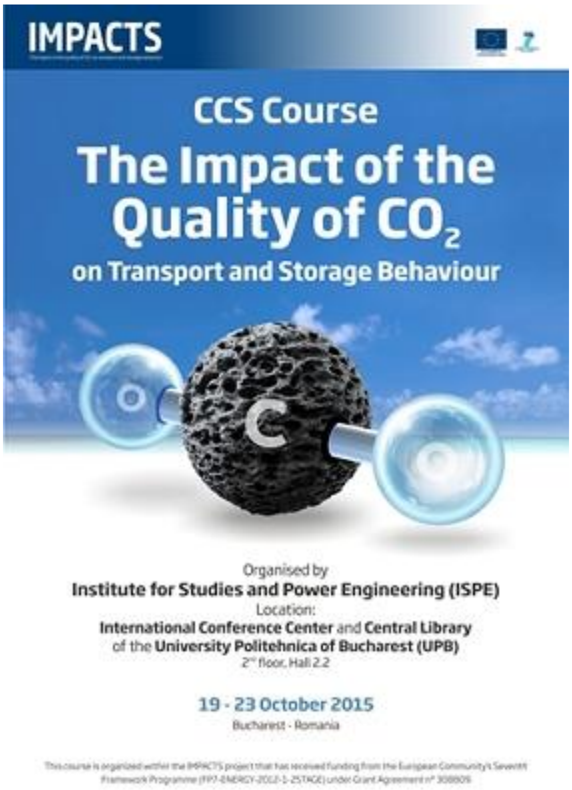
APPENDIX 3: PROMOTION MATERIALS



APPENDIX 4: QUESTIONNAIRES

IMPACTS

The impact of the quality of CO_2 on transport and storage behaviour

CCS OPINION SURVEY

Please fill in the following questionnaire related to the CCS technology:

A1. Gender

❑1	Female	❑2	Male

A2. Please indicate the type of institution you belong:

Education	❑ 1
Research	❑ 2
Public company (utility providers)	❑ 3
Private company – Energy Ind.	❑ 4
Private company – Oil & Gas Ind.	❑ 5
Private company – Metallurgical Ind.	❑ 6
Private company – Chemical Ind.	❑ 7
Public institution	❑ 9
Other institutions.______________	❑ 10

Q1. How important is the “climate change” issue at global, European and national level, in your opinion?

❑ 1	Very important	❑ 2	Important	❑ 3	Less Important	❑ 4	No significant	❑ 5	DK/NA[1]

Q2. How important are the environmental and energy issues in Romania?

❑ 1	Very important	❑ 2	Important	❑ 3	Less important	❑ 4	No significant	❑ 5	DK/NA

Q3. CO_2 concentration increased alarmingly during the last years. What is your opinion about the impact of the following activities?

Activities	❑ 1 Increases CO_2	❑ 2 Decreases CO_2	❑ 3 Has no impact
❑ Road vehicles			
❑ Power plants			
❑ Nuclear power plants			
❑ Wind power plants			
❑ Tree planting			
❑ Metallurgy & oil and gas			
❑Other activities.___________			

[1] Don't Know/ No Answer

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Q4. How important is CO_2 emissions reduction in your opinion?

❑ 1	Very important	❑ 2	Important	❑ 3	Less Important	❑ 4	No significant	❑ 5	DK/NA

Q5. Which of the following environmental issues can be mitigated by using CCS?

	❑ 1 Can be reduced	❑ 2 Cannot be reduced	❑ 3 DK/NA
Toxic waste			
Thinning of the ozone layer			
Greenhouse effect			
Acid rain			
Melting of the polar caps			

Q6. How do you estimate the economic, social and environmental impact of implementing CCS technology in Romania?

	❑1 Positive	❑2 Negative
Social		
Economic		
Environment		

Q7. How do you estimate the CO_2 quality impact on CCS technology chain, in terms of operation processes and equipment materials, focusing the CO_2 transport and storage components?

❑ 1	Very important	❑ 2	Important	❑ 3	Less Important	❑ 4	No significant	❑ 5	DK/NA

Q8. If you agree to the statement that the implementation of CCS technology has positive results, will you support such a project in Romania?

❑ 1	Yes	❑ 2	No	❑ 3	DK/NA

Q9. Do you know if CCS projects have been developed in the EU?

❑ 1	Yes	❑ 2	No	❑ 3	DK/NA

Q10. Do you think that the EU policy supports CCS technology deployment?

❑ 1	Yes	❑ 2	No	❑ 3	DK/NA

Q11. Do you consider developing a CCS project in Romania would be appropriate and necessary?

❑ 1	Yes	❑ 2	No	❑ 3	DK/NA

Thank you!

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IMPACTS

The impact of the quality of CO2 on transport and storage behaviour

ASSESSMENT QUESTIONNAIRE

Please assess the following items related to the CCS Course which you attend, by choosing a rate from 1 to 5, according to:

1 – very weak 2 – weak 3 – satisfactory 4 – good 5 – very good

	1	2	3	4	5
Event location					
Catering services					
Event hall logistics					
Training curriculum					
Quality of the presentations' content					
Lecturers' performance					
Information usefulness and training sessions' interactivity					
Please give a general rating for this training session					

Thank you!

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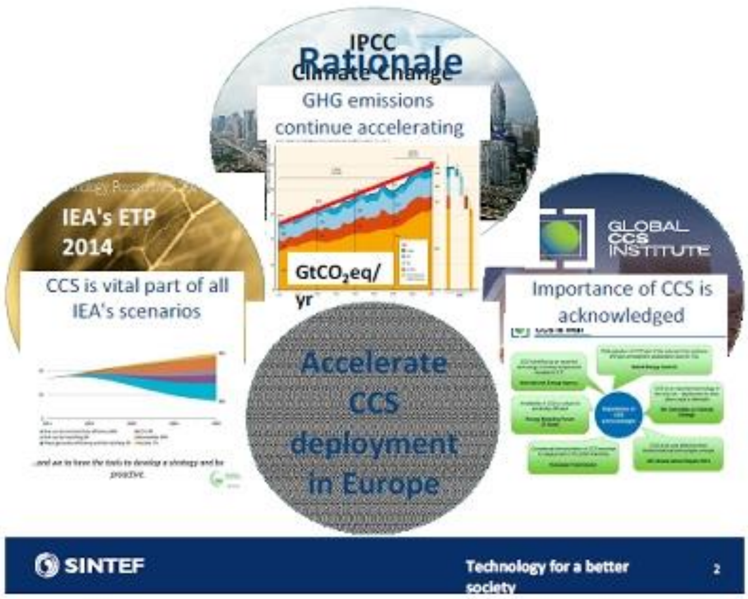
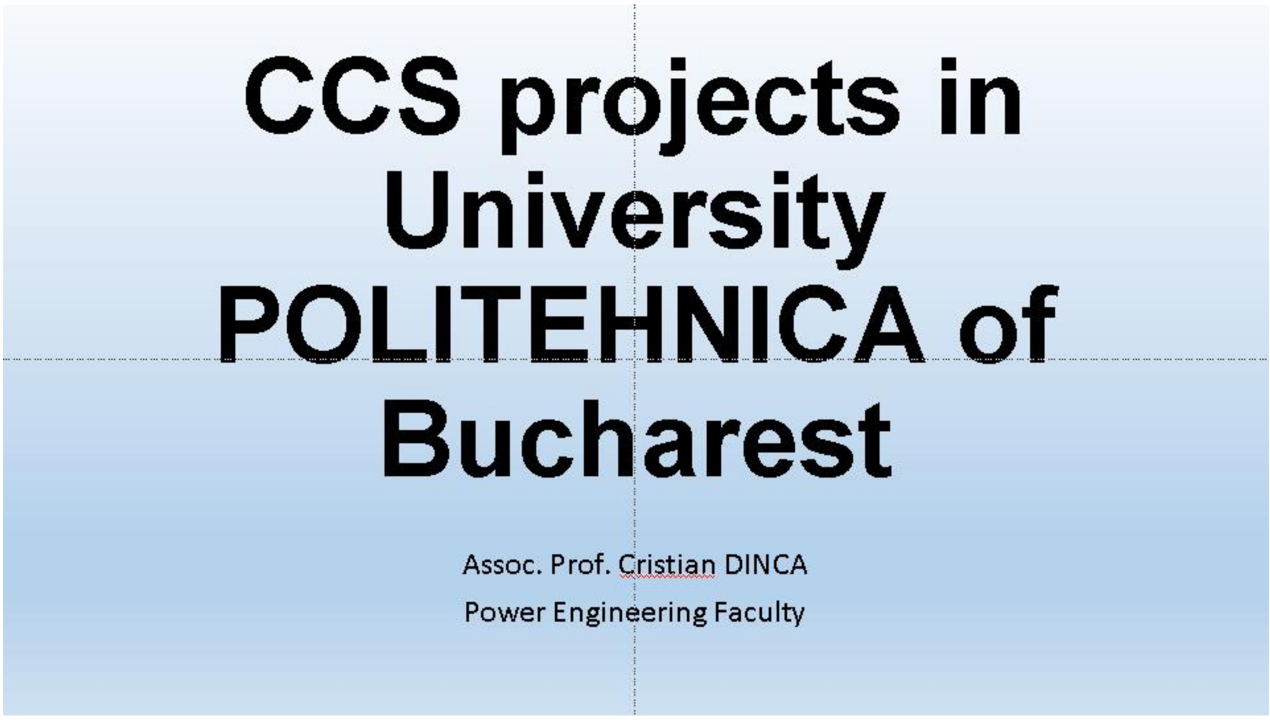
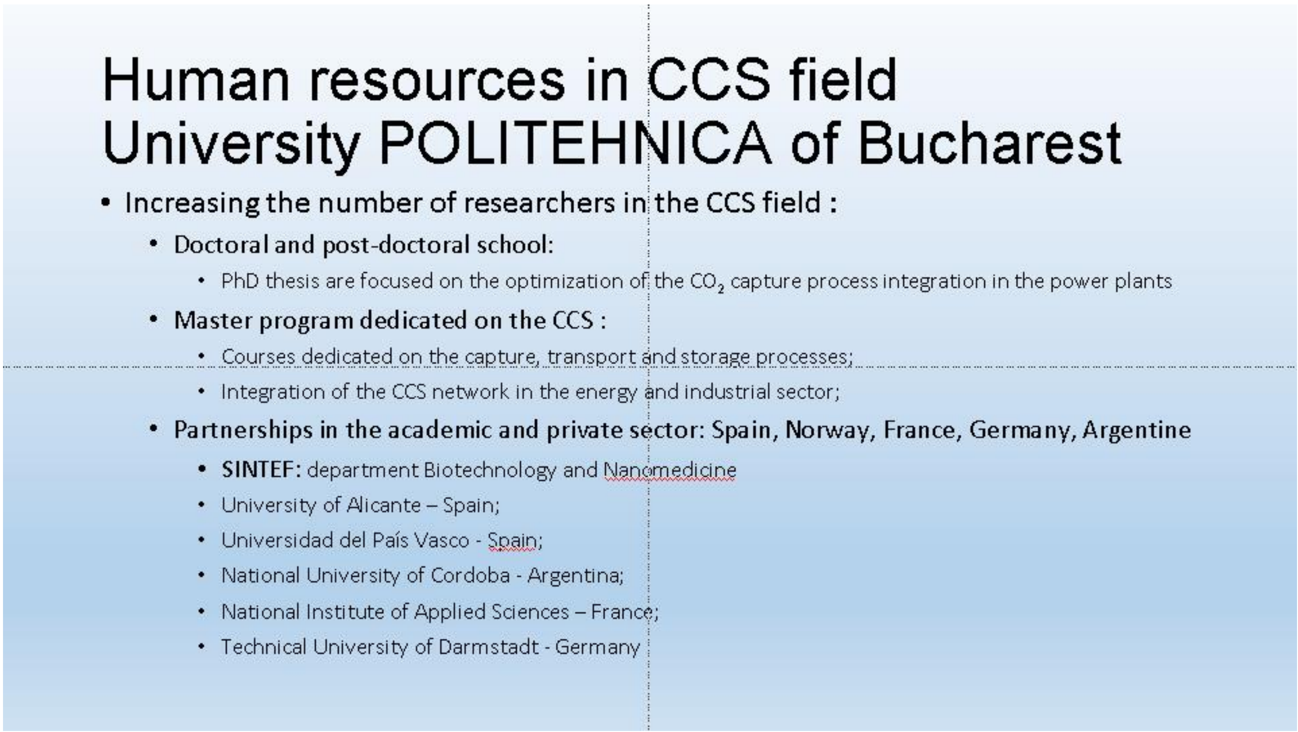
APPENDIX 5: PRESENTATIONS

Opening session




CCS projects in University POLITEHNICA of Bucharest
Assoc. Prof. Cristian DINCA
Power Engineering Faculty


Human resources in CCS field
University POLITEHNICA of Bucharest
• Increasing the number of researchers in the CCS field :
• Doctoral and post-doctoral school:
• PhD thesis are focused on the optimization of the CO_2 capture process integration in the power plants
• Master program dedicated on the CCS :
• Courses dedicated on the capture, transport and storage processes;
• Integration of the CCS network in the energy and industrial sector;
• Partnerships in the academic and private sector: Spain, Norway, France, Germany, Argentine
• SINTEF: department Biotechnology and Nanomedicine
• University of Alicante – Spain;
• Universidad del País Vasco - Spain;
• National University of Cordoba - Argentina;
• National Institute of Applied Sciences – France;
• Technical University of Darmstadt - Germany

Session 1: Models on thermodynamic properties and equilibrium

THERMODYNAMIK

RUHR-UNIVERSITÄT BOCHUM 50 Jahre RUB

Fluid Property Calculations in the 21st Century with Multiparameter Fundamental Equations of State

Roland Span and Stefan Herrig

IMPACTS Training Course, Bucharest, October 2015

50 Jahre RUB

What is a Fundamental Equation of State?

Hypothesis: The second law of thermodynamics yields a complete description of equilibrium states

↳ A complete description of equilibrium states should be possible in terms of the independent variables introduced by the second law of thermodynamics

For pure fluids this approach results in

- Closed systems: $Tds = du + pdv \;\Rightarrow\; du = Tds - pdv \;\Rightarrow\; u = u(s,v)$
- Flow processes: $Tds = dh - vdp \;\Rightarrow\; dh = Tds + vdp \;\Rightarrow\; h = h(s,p)$

- Entropy cannot be measured directly, (practically) has an arbitrary reference state

↳ Nobody wants an equation of state that uses entropy as an independent variable

Span and Herrig | Fundamental Equations of State | Bucharest 2015 2

Measurement of impuritites and equilibria in Co2 mixtures

Jacob Stang
Sintef Energy Research

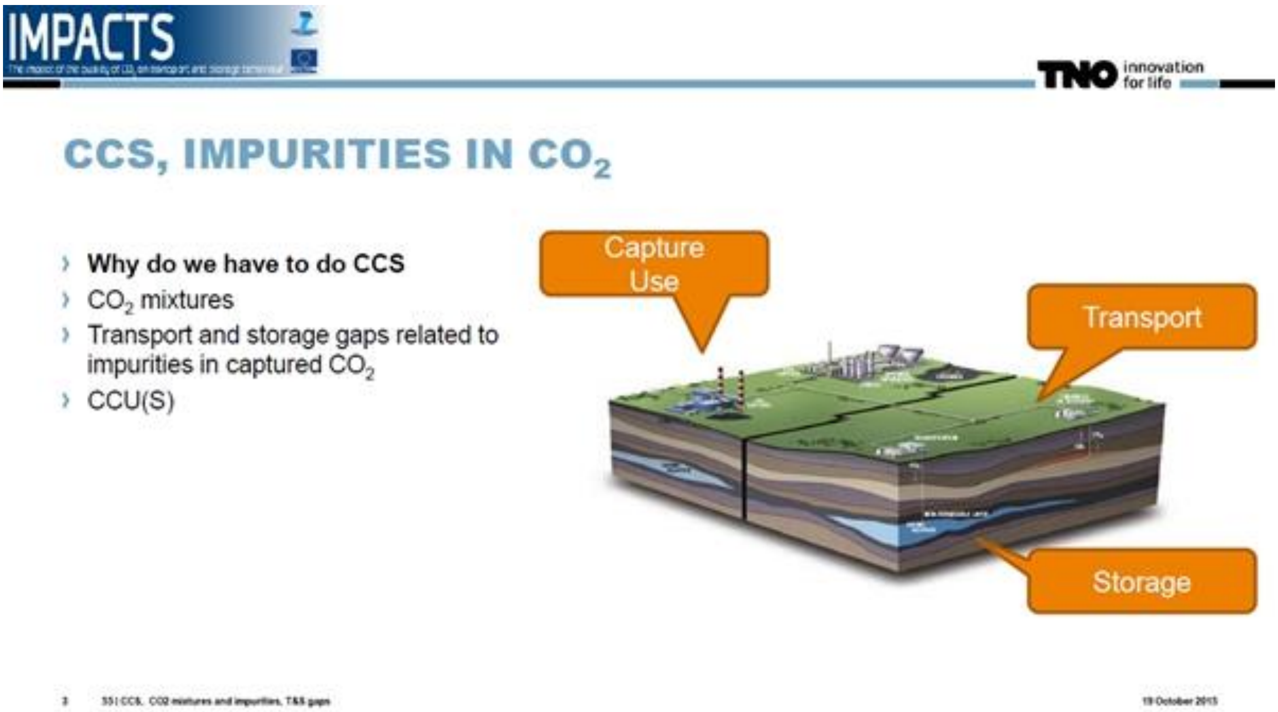
SINTEF   SINTEF Energy Research   1

CO_2 Mixture Properties - Motiviation

- Need for mixture behavior knowledge in CCS for:
  - Safety
  - Efficiency
  - Economy
- Accurate models required for relevant mixtures, conditions, and thermo-physical properties
- Accurate models require accurate experimental data!

SINTEF   SINTEF Energy Research   2

Session 2: Typical CO_2 mixtures and operating conditions, transport and storage gap analysis, classification of CO_2 impurities



Session 3: Typical CCS chains

IMPACTS

The impact of the quality of CO_2 on transport and storage behaviour

Choice of Benchmark CCS chains for illustrating CO_2 quality

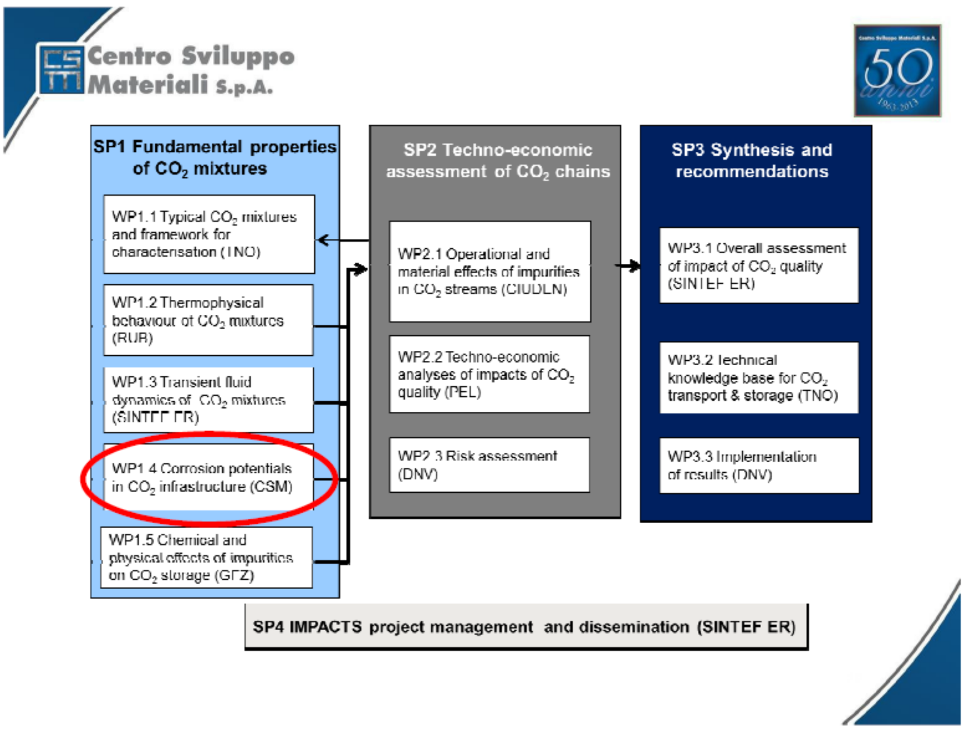
Charles Eickhoff

PEL

Agenda

- Purpose of Benchmark CCS chains
- Chain Elements
- Capture Options
- Transport Options
- Storage Options
- Criteria for Selection
- CCS Benchmark Chains chosen
- Impurity Ranges
- Technology Implications

Session 4: Corrosion of pipeline steels caused by CO_2 mixtures



Session 5: The influence of CO_2 mixture composition

IMPACTS CCS Course: 19-23 October 2015, Bucharest - Romania

The Effect of Impurities for Pipeline and Tanked Transport of CO_2

Geir Skaugen, SINTEF ER

SINTEF Technology for a better society 1

Introduction – Content of presentation

- The effect of impurities on the thermodynamic properties of CO_2 relevant for case studies
- Description of two transport cases –compressed gas for pipeline transport of CO_2 and liquid CO_2 for tanked transport (i.e by ship)
- Case studies with respect to impurities
- Results and discussions

SINTEF Technology for a better society 2

Session 6: Techno-economic analyses of impacts of CO_2 quality

IMPACTS

The impact of the quality of CO_2 on transport and storage behaviour

Techno-economic analysis of CO_2 quality impact on CCS chains

Charles Eickhoff

PEL

IMPACTS

Progressive Energy

Agenda

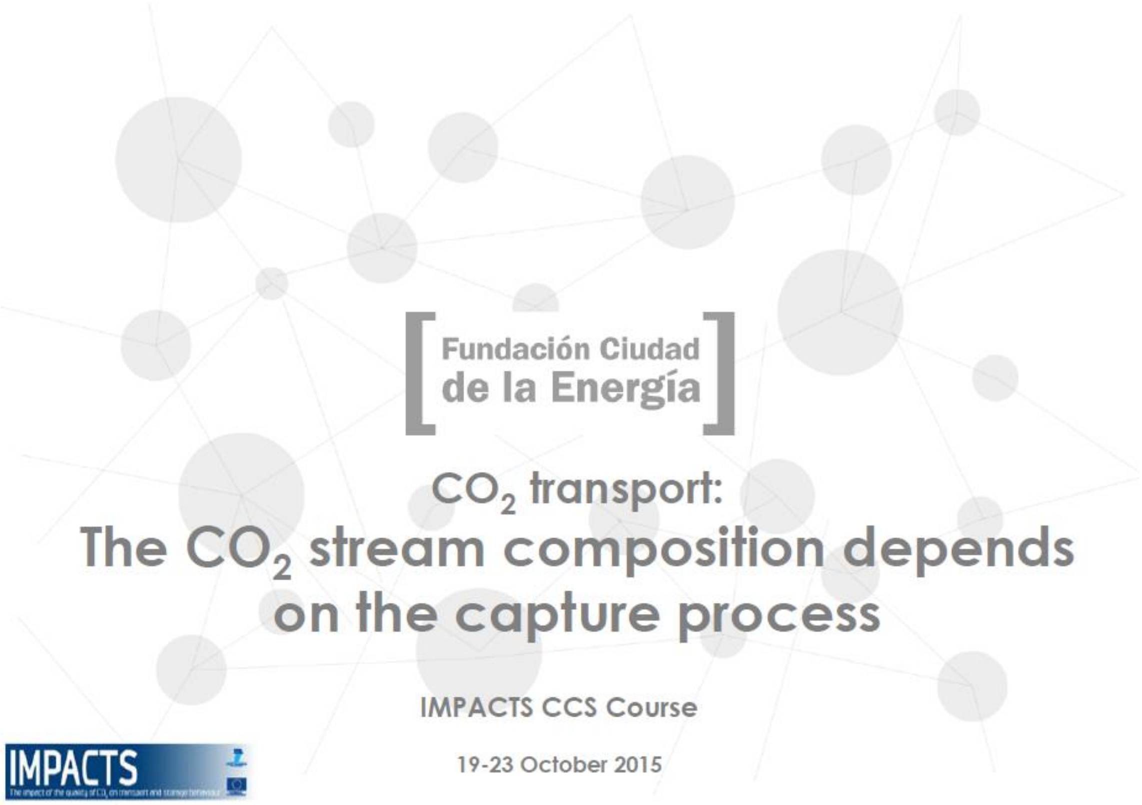
- What is a Techno-economic analysis?
- How have we approached this in IMPACTS?
- Use of cost functions - outline
- TE Model – overview
- Derivation of cost functions
- Examples of cost function results
- Techno-economic trade-offs in CCS chains
- Risk limits

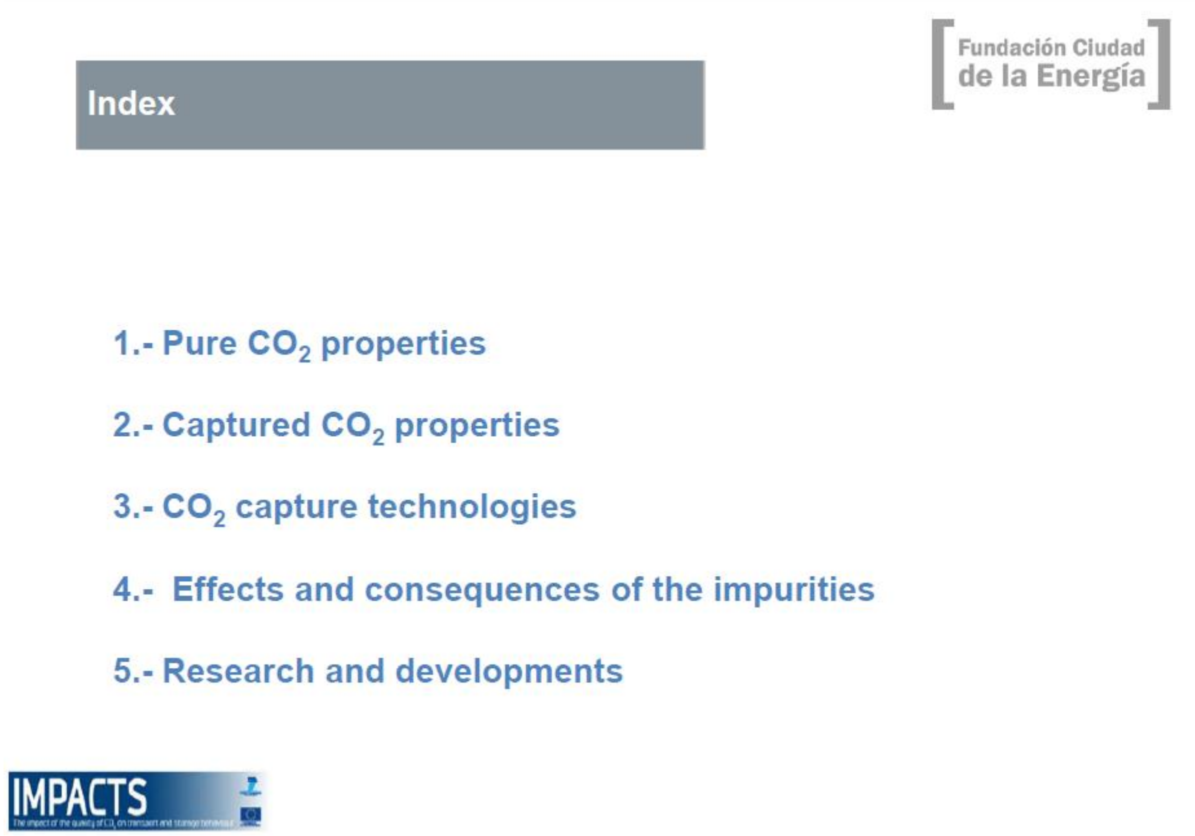
IMPACTS

CONFIDENTIAL

Progressive Energy

Session 7: Operational and material effects of impurities in CO_2 streams





Fundación Ciudad de la Energía

CIUDEN transport rig

IMPACTS CCS Course

19-23 October 2015

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Fundación Ciudad de la Energía

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1.- Who is CIUDEN?

2.- CIUDEN´s Clean Combustion Technologies Centre

3.- CO_2 Geological Storage Centre

4.- Rear-view-mirror

5.- CIUDEN capabilities

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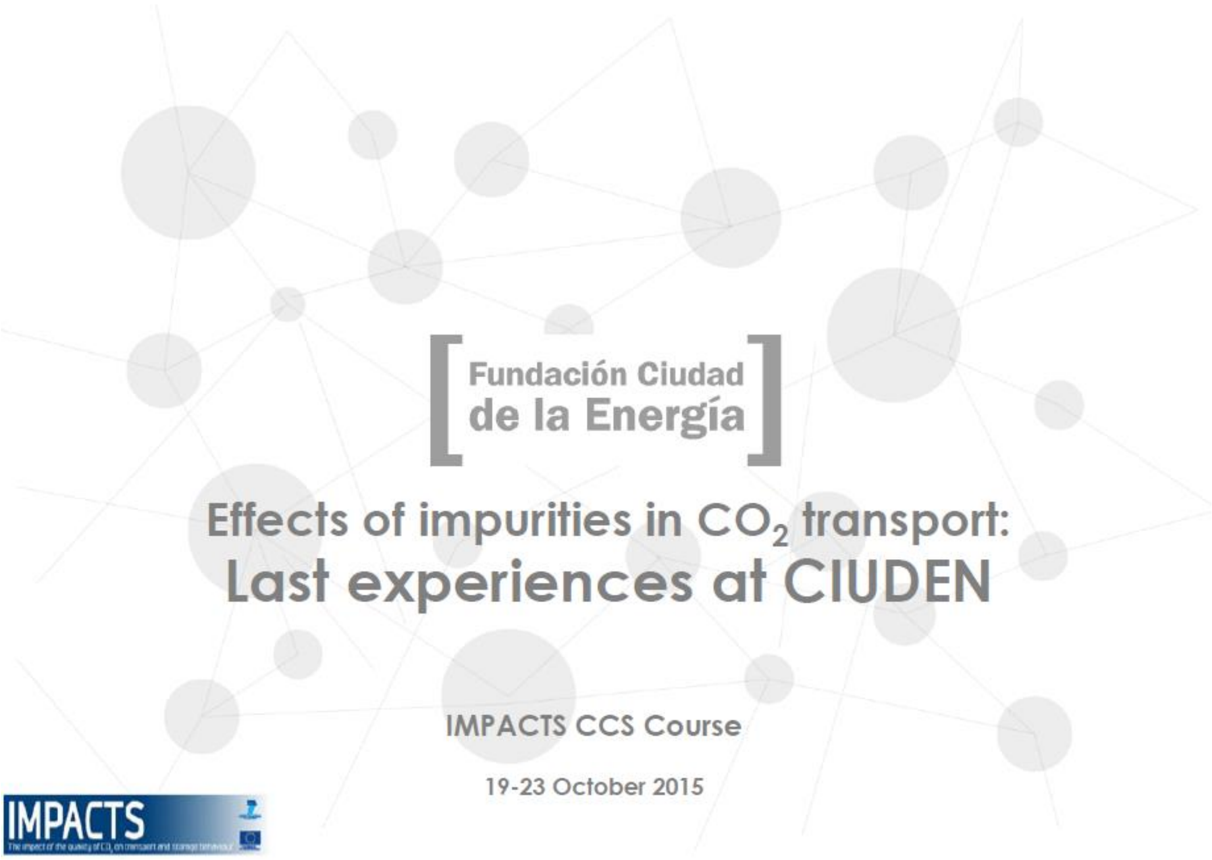
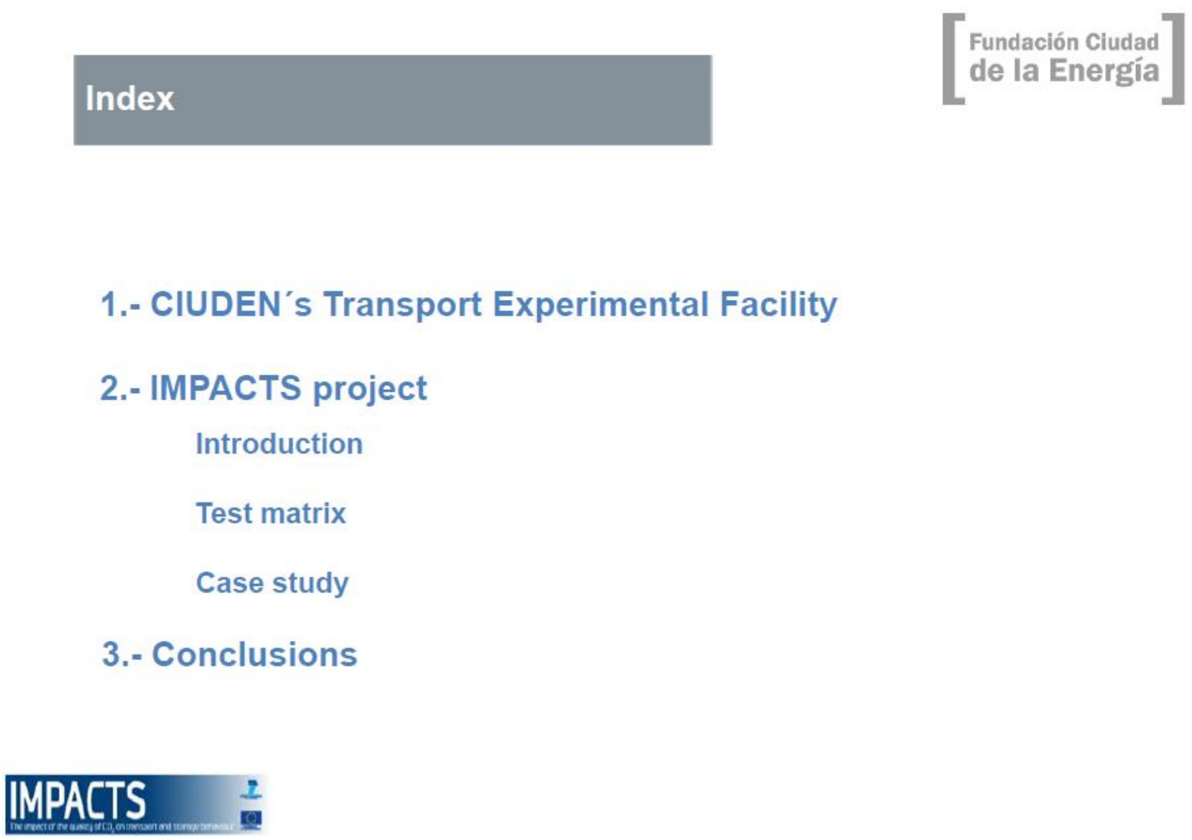
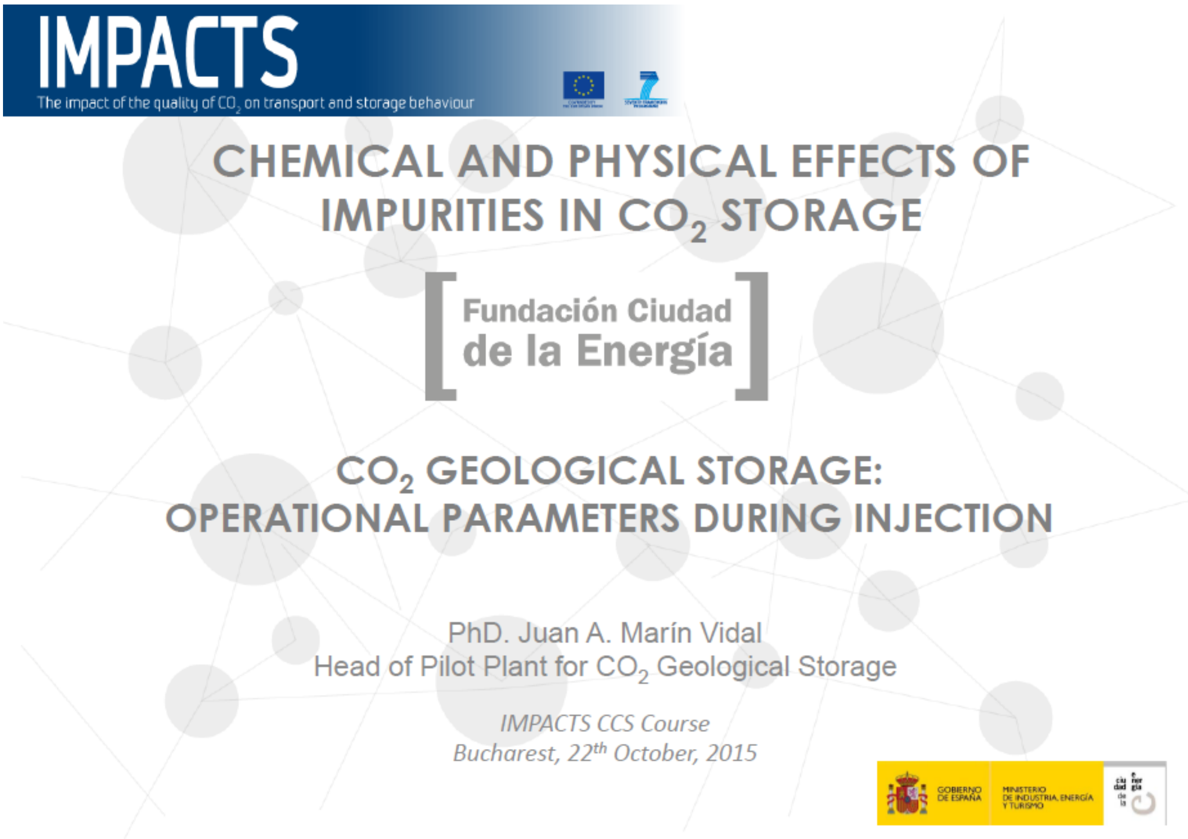
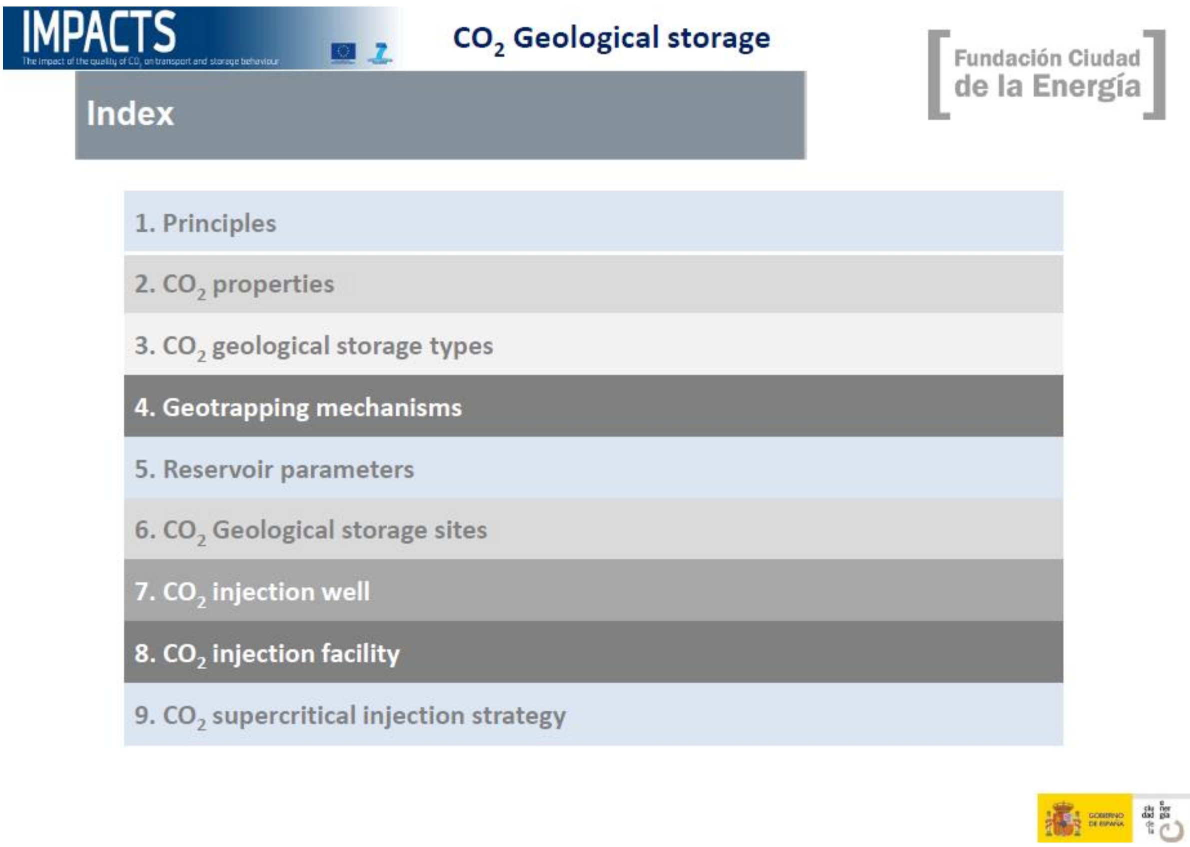
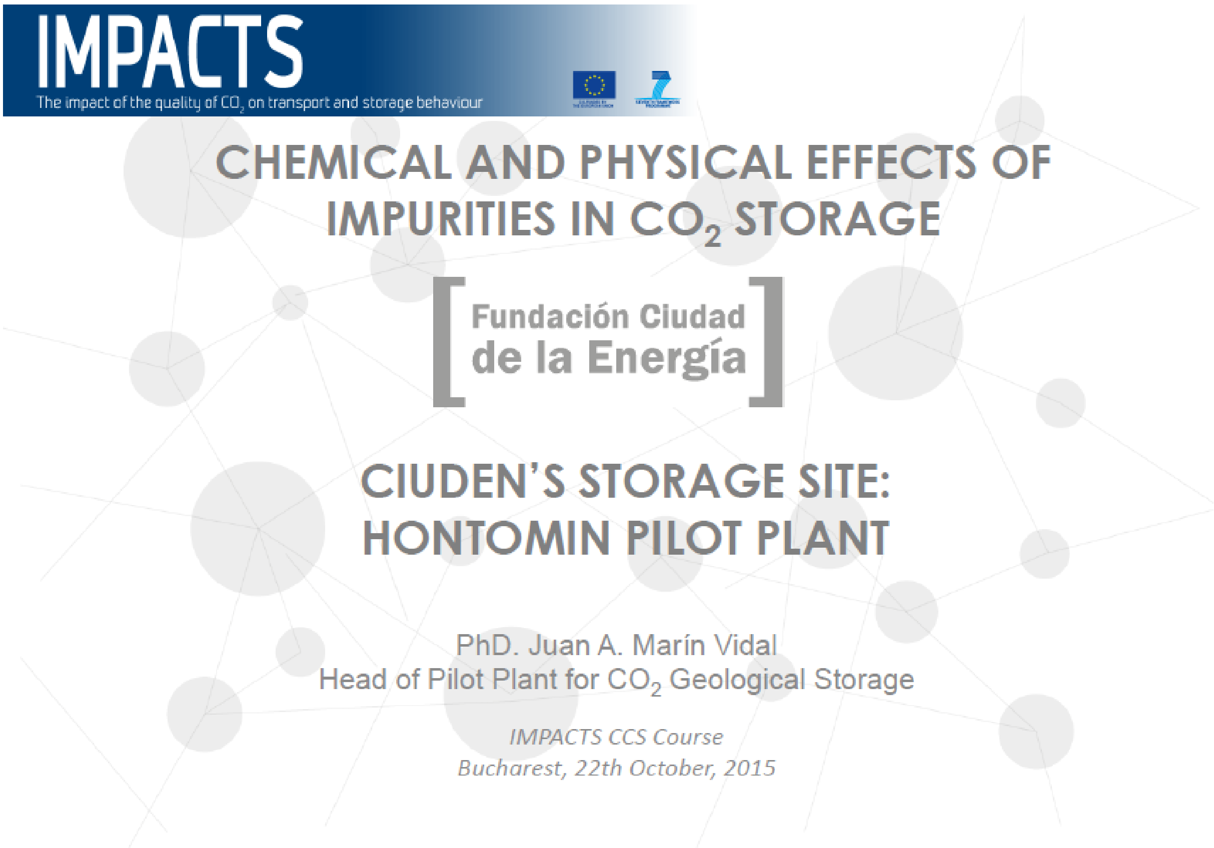

Fundación Ciudad de la Energía
Effects of impurities in CO_2 transport:
Last experiences at CIUDEN
IMPACTS CCS Course
19-23 October 2015
IMPACTS


Index
Fundación Ciudad de la Energía
1.- CIUDEN´s Transport Experimental Facility
2.- IMPACTS project
Introduction
Test matrix
Case study
3.- Conclusions
IMPACTS

Session 8: Chemical and physical effects of impurities on CO_2 storage



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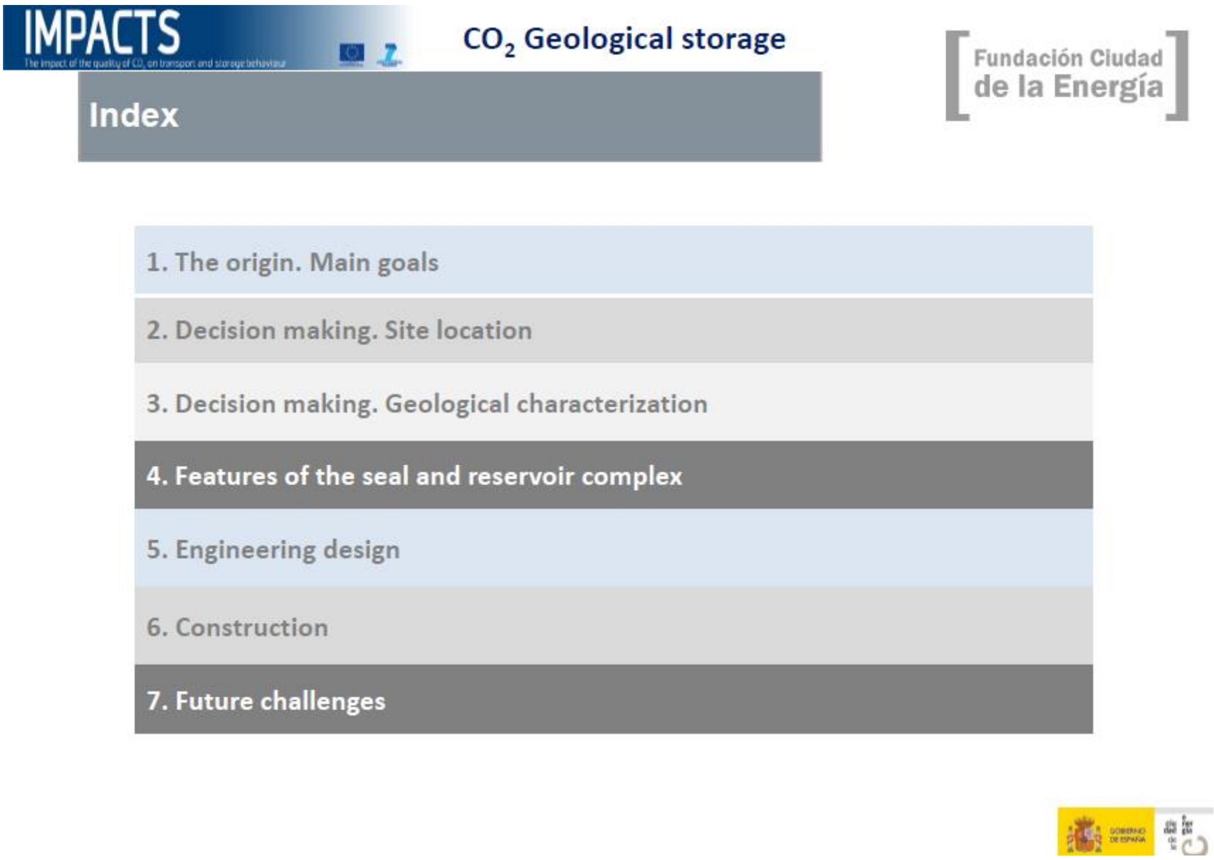
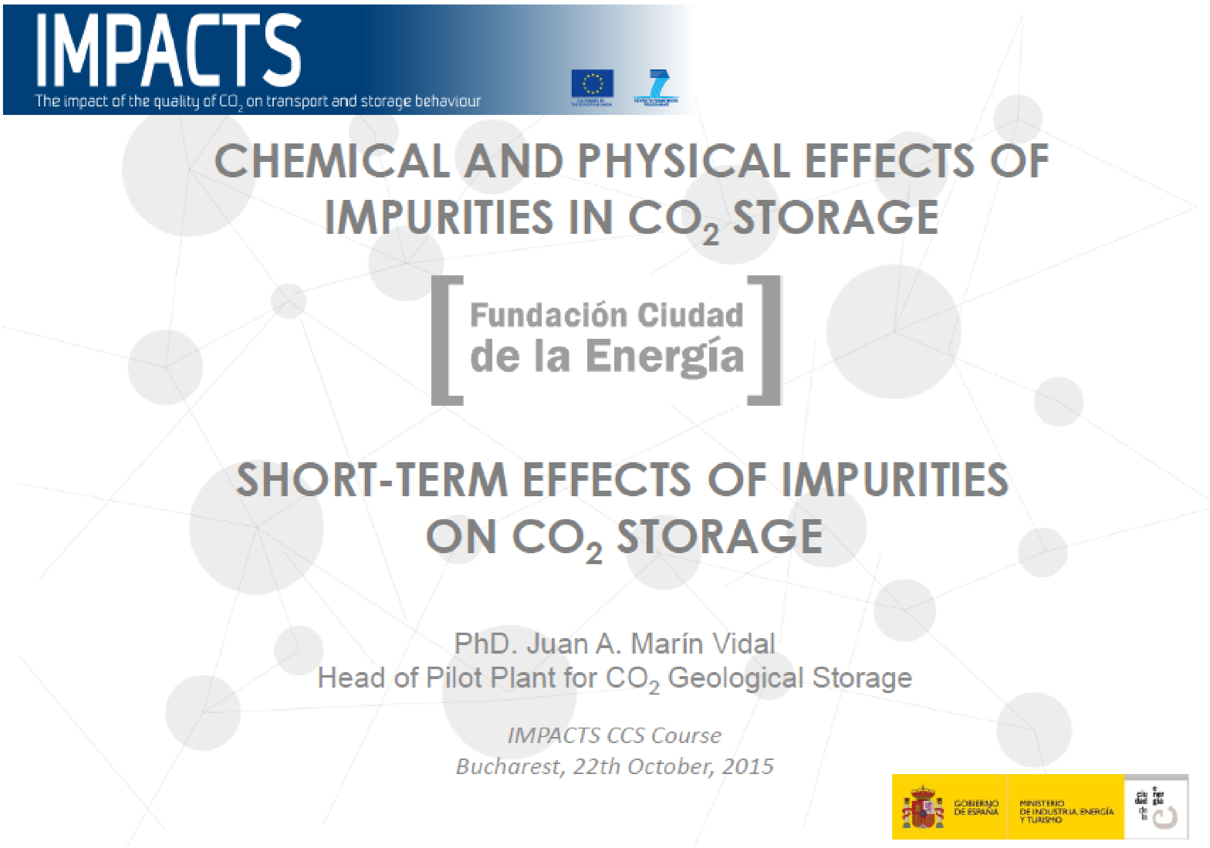
The impact of the quality of CO_2 on transport and storage behaviour
CHEMICAL AND PHYSICAL EFFECTS OF IMPURITIES IN CO_2 STORAGE
Fundación Ciudad de la Energía
CIUDEN'S STORAGE SITE: HONTOMIN PILOT PLANT
PhD. Juan A. Marín Vidal
Head of Pilot Plant for CO_2 Geological Storage
IMPACTS CCS Course
Bucharest, 22th October, 2015


IMPACTS
CO_2 Geological storage
Fundación Ciudad de la Energía
Index
1. The origin. Main goals
2. Decision making. Site location
3. Decision making. Geological characterization
4. Features of the seal and reservoir complex
5. Engineering design
6. Construction
7. Future challenges


IMPACTS
The impact of the quality of CO_2 on transport and storage behaviour
CHEMICAL AND PHYSICAL EFFECTS OF IMPURITIES IN CO_2 STORAGE
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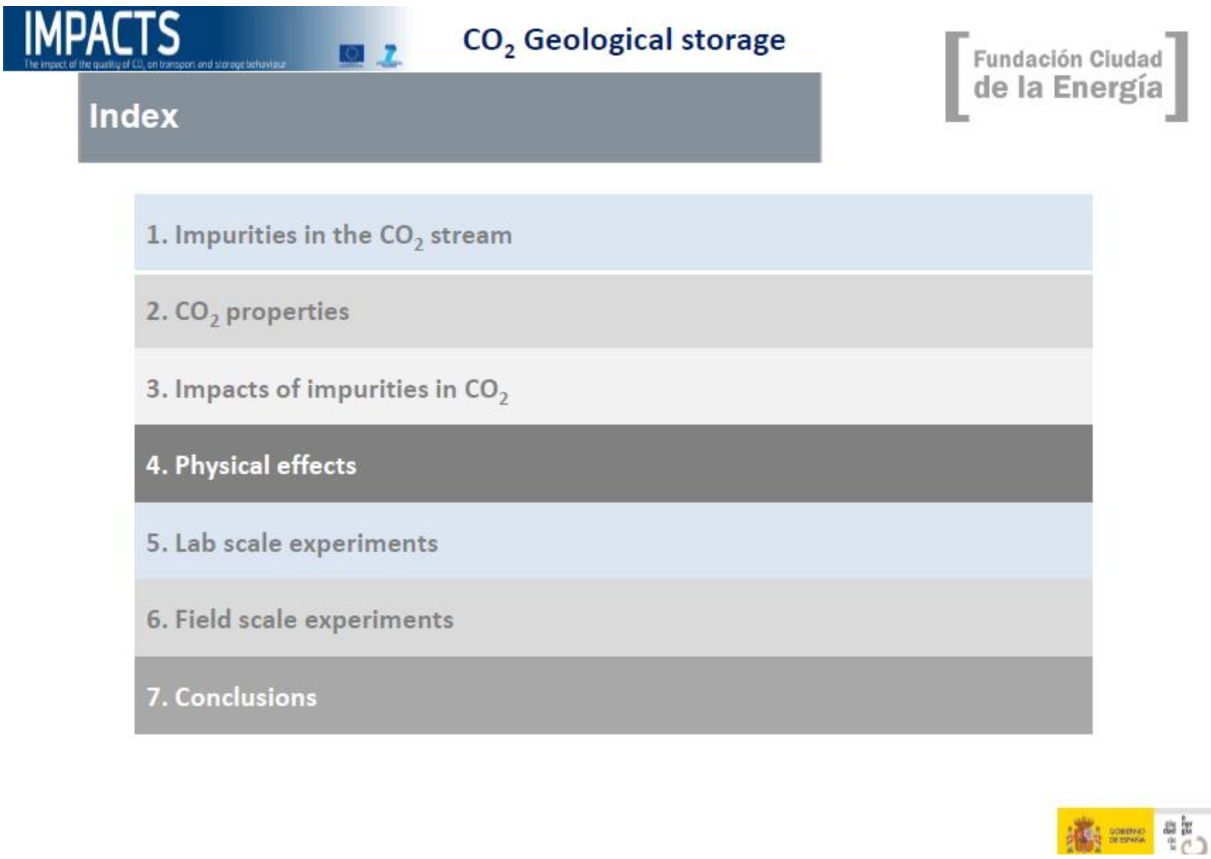
SHORT-TERM EFFECTS OF IMPURITIES ON CO_2 STORAGE
PhD. Juan A. Marín Vidal
Head of Pilot Plant for CO_2 Geological Storage
IMPACTS CCS Course
Bucharest, 22th October, 2015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CO_2 Geological storage
Fundación Ciudad de la Energía
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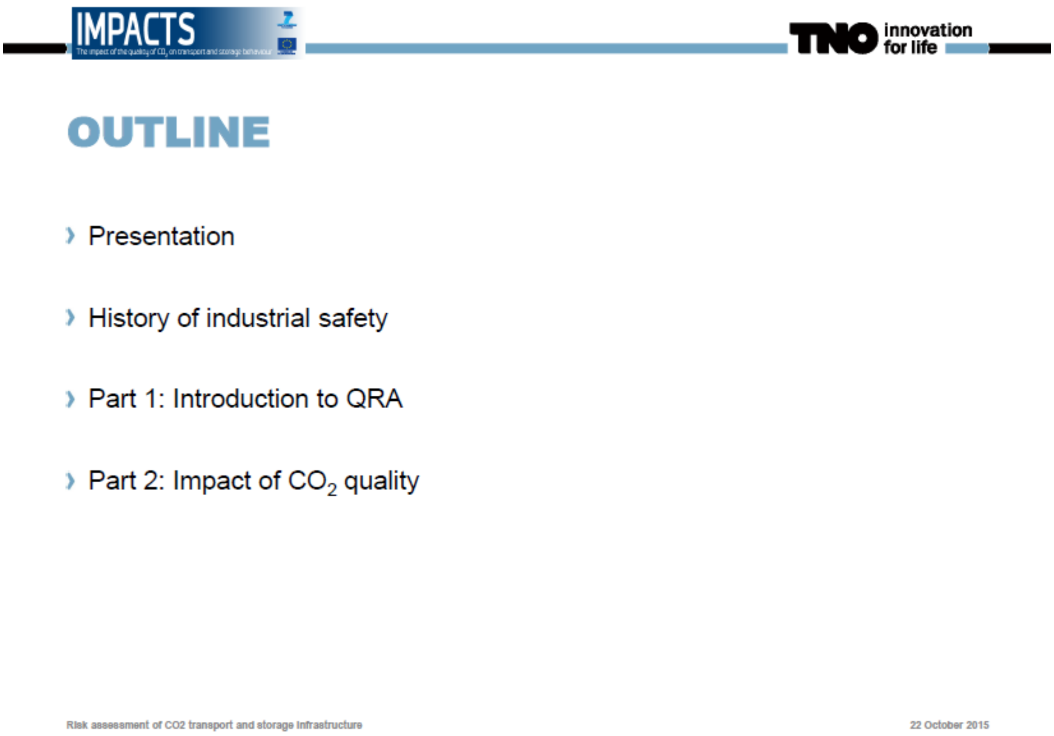
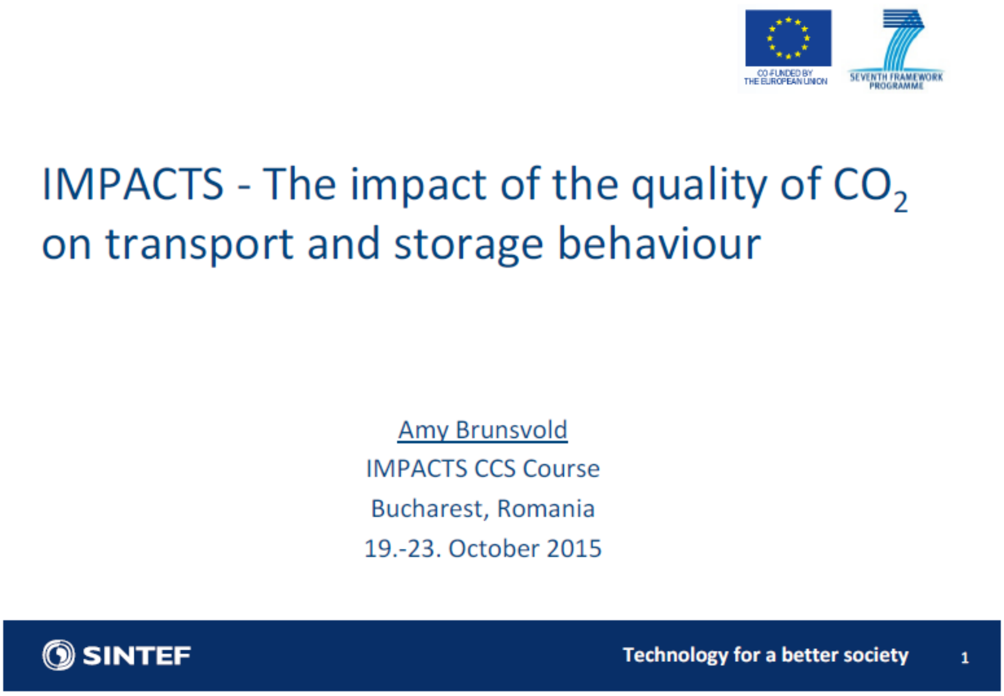
1. Impurities in the CO_2 stream
2. CO_2 properties
3. Impacts of impurities in CO_2
4. Physical effects
5. Lab scale experiments
6. Field scale experiments
7. Conclusions

Session 9: Risk assessment of CO_2 transport and storage infrastructure



Session 10: IMPACTS recommendations

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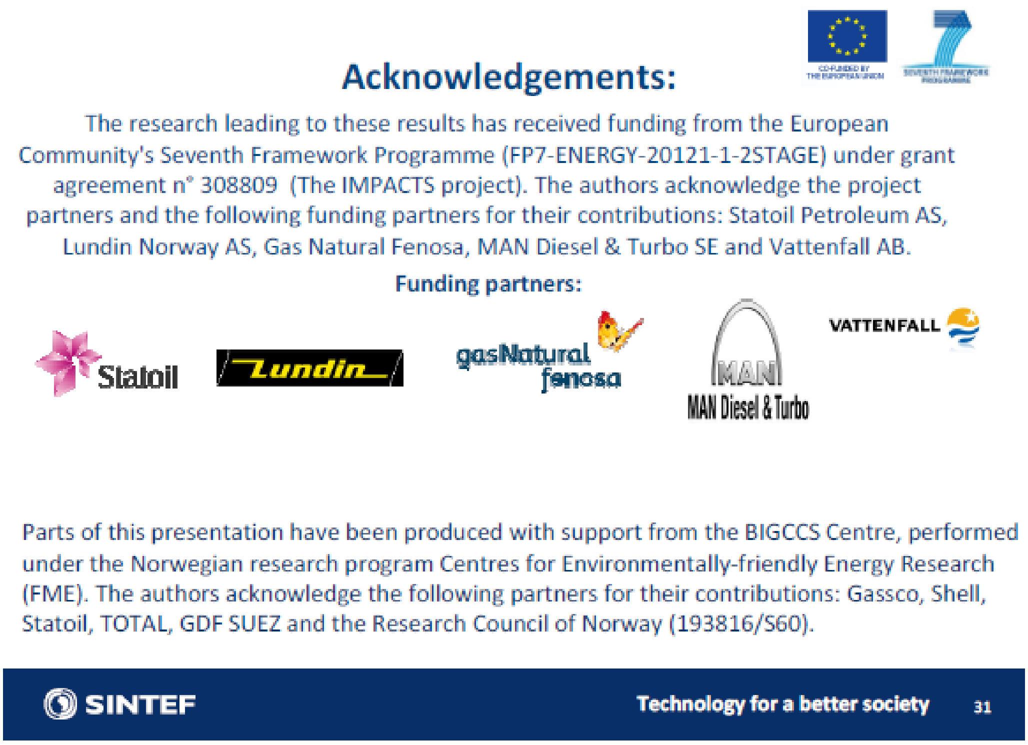
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Funding partners:
Statoil
Lundin
gasNatural fenosa
MAN Diesel & Turbo
VATTENFALL
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APPENDIX 6: SESSION 1 EXERCISES

THERMODYNAMIK

RUHR UNIVERSITÄT BOCHUM RUB

FAKULTÄT FÜR MASCHINENBAU

Institut für Thermo- und Fluiddynamik
Lehrstuhl für Thermodynamik
PROF. DR.-ING. ROLAND SPAN

IMPACTS Training Course, Bucharest, October 2015

Fluid Property Calculations in the 21st Century
with Multiparameter Fundamental Equations of State

Exercise 1

For temperatures in the range 270 K to 450 K the isochoric heat capacity of carbon dioxide can approximately be described by

$$c_v^o(T)/R = 4.7863 - 1.3856\,\tau^2,$$

with $\tau = T_c / T$, $T_c = 304.13$ K and $R = 188.92$ J/(kg K).

For temperatures in the range 330 K to 450 K and densities up to 200 kg/m^3 the residual Helmholtz energy is given by the following empirical equation of state:

$$\frac{f^r(T,\rho)}{RT} = \alpha^r(\tau,\delta) = \sum_{i=1}^{4} a_i \tau^{t_i} \delta^{d_i}$$

τ and R are defined as given above. The reduced density is $\delta = \rho / \rho_c$ with $\rho_c = 467.6$ kg / m^3. The empirically determined coefficients and exponents of the equation of state are:

i =	1	2	3	4
d_i	1	1	2	2
t_i	1	2	−1	3
a_i	0.042033	−1.1933	0.16677	−0.047873

a) Calculate the pressure of carbon dioxide for $T = 380$ K and $\rho = 150$ kg/m^3.

b) Calculate the density of carbon dioxide at $T = 380$ K and $p = 5$ MPa.

c) Calculate the specific isochoric heat capacity at $T = 380$ K and $\rho = 150$ kg/m^3.

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d) Determine a relation for the ideal gas part of the reduced Helmholtz energy,

$$\frac{f^{\circ}(T,\rho)}{RT} = \alpha^{\circ}(\tau,\delta) = \alpha^{\circ}(\tau,\delta_0) + \ln\left(\frac{\delta}{\delta_0}\right).$$

The integration constants have to be determined in a way that the entropy s° and the Enthalpy h° of the ideal gas become zero for $\tau_0 = 1$ and $\delta_0 = 0.003771$ (ideal gas at 304.13 K and ambient pressure).

Exercise 2

A mass flow of 10 kg/s carbon dioxide with the initial conditions $T_1 = 300$ K, $p_1 = 0.1$ MPa is adiabatically compressed to $p_1 = 10$ MPa with an isentropic efficiency of $\eta_{sC} = 0.86$.

Use the provided excel sheet and TREND 2.0 to calculate …

a) … the outlet temperature of the compressor and the entropy of the compressed gas.

b) … the power requirement in case a flow of 90% carbon dioxide, 5% nitrogen, 3% argon, and 2% oxygen is compressed instead of pure carbon dioxide.

APPENDIX 7: CERTIFICATE OF ATTENDANCE

IMPACTS

Certificate of Attendance

this is to certify that

Mr/Ms ....

of ....

has participated to the

CCS Course on

The Impact of the Quality of CO_2 on Transport and Storage Behaviour

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