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# CHALLENGES AND OPPORTUNITIES OF CO<sub>2</sub> CAPTURE AND STORAGE FOR THE IRON AND STEEL INDUSTRY

**Report: 2011/17**

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## INTERNATIONAL ENERGY AGENCY

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## DISCLAIMER AND ACKNOWLEDGEMENTS

IEAGHG supports and operates a number of international research networks. This report presents the results of a workshop held by one of these international research networks. The report was prepared by Jasmin Kemper and Stanley Santos of IEAGHG as a record of the events of that workshop.

The 1<sup>st</sup> IEAGHG Workshop: Challenges and Opportunities of CO<sub>2</sub> Capture and Storage for the Iron and Steel Industry was held at the Steel Institute – VDEh Auditorium in Düsseldorf, Germany on the 8<sup>th</sup> and 9<sup>th</sup> November 2011.

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## **EXECUTIVE SUMMARY**

The iron and steel industry is one of the largest industrial sources of CO<sub>2</sub>. Globally, it accounts for about 6% of anthropogenic CO<sub>2</sub> emissions from energy use. One of the leading options being considered by the steel industry stakeholders to reduce CO<sub>2</sub> emissions from steel mills (specifically from integrated steel mills) is CO<sub>2</sub> capture and storage (CCS). Development of this technology for application in iron and steel production is still on-going.

In line with the goal of promoting the implementation of CCS in the industry, the IEA Greenhouse Gas R&D Programme initiated and organised the 1<sup>st</sup> Iron and Steel Industry CCS Workshop. This was held at Düsseldorf, Germany, on the 8<sup>th</sup> and 9<sup>th</sup> of November 2011. The aim of this workshop was to gather key industry stakeholders and provide a forum for discussion. The workshop was chaired by Prof. Dr.-Ing. Gunnar Still, Corporate Adviser on Environment of ThyssenKrupp AG.

The main objectives of the workshop were:

- To address and discuss the difficulties of the iron and steel industry to enable the implementation of CCS.
- To understand the various issues and factors in the evaluation of the cost of CCS in an integrated steel mill.

The workshop brought together 74 participants from industry, research institutes and academics coming from 13 different countries worldwide. This workshop comprised of 20 presentations and covered a broad field including:

- Global role of CCS in reducing greenhouse gas emissions from industry,
- CO<sub>2</sub> breakthrough technologies for the iron and steel industry (including CCS),
- Addressing the market competitiveness when implementing CCS in the iron and steel industry,
- Techno-economics of CO<sub>2</sub> capture, transport and storage.

The key messages from the workshop were:

- Technologies using CCS to reduce CO<sub>2</sub> emissions from an integrated steel mill are technically feasible.
- Large scale demonstration projects are needed to validate performance and cost.
- Public acceptance, market competitiveness and project financing should be part of the discussion when implementing CCS to the steel industry sector.
- More engineering work on techno-economic evaluation is necessary to understand the cost dynamics of producing steel with CCS.

For CCS in the steel sector to be viable, an international commitment is required to establish a level playing field to guarantee competitiveness in the global steel market.



# Challenges and Opportunities of CO<sub>2</sub> Capture and Storage for the Iron and Steel Industry

Steel Institute – VDEh Auditorium,  
Düsseldorf, Germany  
8<sup>th</sup> and 9<sup>th</sup> November 2011

## 1. INTRODUCTION

The iron and steel industry is one of the largest industrial sources of CO<sub>2</sub>. Globally, it accounts for about 6% of anthropogenic CO<sub>2</sub> emissions from energy use. Current World Steel Association indicators noted that 1.8 tCO<sub>2</sub> arising from the use of 20.8 GJ/t of crude cast steel. However, there is wide variance in country-by-country data. It was widely reported that steel mills via BF-BOF route emit between 1.6 - 2.2 tCO<sub>2</sub>/t of steel, whereas the EAF route using scrap metal emits 0.6 - 0.9 tCO<sub>2</sub>/t of steel, and the EAF route using DRI emits 1.4 - 2.0 tCO<sub>2</sub>/t of steel. One of the leading options being considered by the steel industry stakeholders to reduce CO<sub>2</sub> emissions from steel mills (specifically from integrated steel mills) is CO<sub>2</sub> capture and storage (CCS). Development of this technology for application in iron and steel production is still on-going.

This is the first workshop initiated and organised by the IEA Greenhouse Gas R&D Programme with an aim of gathering key industry stakeholders and providing a forum for discussion. This workshop is chaired by Prof. Dr.-Ing. Gunnar Still, Corporate Adviser on Environment of ThyssenKrupp AG.

The main objectives of the workshop were:

- To address and discuss the difficulties of the iron and steel industry to enable the implementation of CCS.
- To understand the various issues and factors in the evaluation of the cost of CCS in an integrated steel mill.

The IEA Greenhouse Gas R&D Programme would like to acknowledge and thank Steel Institute and German Steel Federation (VDEh) for hosting this workshop.

## 2. WORKSHOP OVERVIEW

The Iron and Steel Industry CCS Workshop was held in Düsseldorf, Germany, from 8<sup>th</sup> to 9<sup>th</sup> November 2011. The meeting started with a welcome address by Hans-Jürgen Kerkhoff (Steel Institute and VDEh) and John Gale (IEA Greenhouse Gas R&D Programme). This was then followed by two keynote addresses presented by Nathalie Trudeau (IEA) and Prof. Dr.-Ing. Gunnar Still (Thyssenkrupp AG).

This has set the scene for the workshop discussions which covered:

- Global role of CCS in reducing greenhouse gas emissions from industry,
- CO<sub>2</sub> breakthrough technologies for the iron and steel industry (including CCS),
- Addressing market competitiveness when implementing CCS in the iron and steel industry,
- Techno-economics of CO<sub>2</sub> capture, transport and storage.



This workshop consists of 20 presentations and the meeting was concluded with a discussion forum on the techno-economics of CCS for the iron and steel industry sector. This report summarises the different issues discussed during the workshop.

The workshop brought together 74 participants from industry, research institutes and universities from 13 different countries worldwide. The delegate list is appended as Annex I, a list of abbreviations is presented in Annex III.

The agenda of the meeting (also appended as Annex II) and copies of the presentations can be downloaded from the IEA Greenhouse Gas R&D Programme website.

The link to the presentations:

<http://www.ieaghg.org/index.php?/20110609257/ccs-in-the-iron-and-steel-industry.html>

### **3. PRESENTATION OVERVIEW**

#### ***Welcome Address by the Host of the Workshop***

*Hans-Jürgen Kerkhoff, Steel Institute VDEh, Germany*

Hans-Jürgen Kerkhoff of Steel Institute VDEh opened the workshop by welcoming the participants and clearly indicating that the German steel market is still growing from strength to strength. He also noted that decreasing the European blast furnace emissions to meet a climate target of 30% below the agreed benchmark set by the European Commission seems to be far out of reach for the steel industry. The upcoming costs from energy and climate policy threaten the German steel industry; this includes cost on ETS, carbon tax, renewable energy policy, closure of nuclear energy, etc... As a case in point, the amendment of the Renewable Energy Law could easily double the annual cost burden of producing steel. Finally, he concluded that German steel industry in 2009 has already achieved significant CO<sub>2</sub> emissions reduction of ~10 Mt compared to the level in 1990. The steel industry has already reached the thermodynamic limit of reducing energy intensity and consequently reducing CO<sub>2</sub> emissions.

#### ***Welcome Address by the Organiser of the Workshop***

*John Gale, IEA Greenhouse Gas R&D Programme, UK*

John Gale underlined in his welcoming address that it is about time to begin the dialogue with the steel industry. The IEA Greenhouse Gas R&D Programme (IEAGHG) as an independent organisation already has experience in facilitating international collaboration between researchers and industry, managing networks and evaluating technology options related to CCS. Therefore, IEAGHG could assist the iron and steel industry with the development and implementation of technologies further reducing greenhouse gas emissions from steel production sites.

#### ***Carbon Capture and Storage in Industrial Applications***

*Nathalie Trudeau, International Energy Agency, France*

The presentation provided an overview of the International Energy Agency's (IEA) perspective on industrial CCS application. A strong legal framework and a global assessment are needed for the implementation of CCS and thus the iron and steel sector must have a high number of demonstration projects deployed during the next years. The total additional costs the iron and steel sector will have to face between 2010 and 2050 are estimated to be \$1200



billion and are highest compared to other sectors. In order to advance the deployment of CCS in the different industrial sectors, IEA recommends stimulating further research into the most cost-effective and energy-efficient capture techniques and equipping at least 75% of the new iron and steel plants in OECD countries with CCS by 2030.

### ***Iron and Steel Industry Perspective on CO<sub>2</sub> Capture and Storage***

*Prof. Dr.-Ing. Gunnar Still, ThyssenKrupp AG, Germany*

The presentation discussed the challenges faced by the steel industry in any implementation of CCS. Prof Still highlighted that unlike power plants, where CO<sub>2</sub> is emitted from a single source, an integrated steel mill has multiple sources of CO<sub>2</sub>. The emissions are located at several stacks and occur from start to end of the iron and steel production. Prof. Still re-emphasised that over the past decade, the steel industry has achieved to reduce the energy intensity of steel production near to its thermodynamic limits. Breakthrough technology is needed to further reduce CO<sub>2</sub> emissions. Development in ULCOS would have CCS as a critical piece of technology needed to achieve that breakthrough. He presented a timeline in the development of the Blast Furnace technology which took a century to achieve the current state of the art. Analogously he noted what ULCOS has already achieved in developing a carbon-lean blast furnace technology in the past 10 years and illustrated challenges it will have to face over the next 10 years to achieve the level advancement needed by the steel industry. Prof. Gunnar Still concluded his presentation by underlining that CCS carries an added cost to the steel production that could impact competitiveness. Implementation of CCS in the steel industry would require a worldwide solution that would provide a level playing field – which is critical to make CCS in the iron and steel industry viable.

### ***Steel, CO<sub>2</sub> Mitigation, CCS and ULCOS - Ultra-Low CO<sub>2</sub> Steelmaking***

*Jean Pierre Birat, Arcelor Mittal, France*

This presentation provided an overview of the ULCOS programme. As the iron making process accounts for roughly 70-80% of CO<sub>2</sub> emissions in an integrated steel mill and in order to achieve the necessary reduction in emissions, this process should be made carbon-lean. It was emphasised that the steel industry simply cannot use the technologies developed by other sectors, it has to develop its own solutions for CO<sub>2</sub> capture. Amine technology, for instance, may not be the right solution for a broad application in the steel sector. For this reason the European steel industry has launched the ULCOS programme, which has been the largest and most comprehensive approach to cut CO<sub>2</sub> emissions in the steel sector. Four process routes were considered most promising: ULCOS-BF based on oxy-blast furnace technology, HIsarna based on smelting reduction technology, Ulcored based on direct reduction of iron, and Ulcowin based on iron production using electrolysis. It was noted that ULCOS-BF cuts the CO<sub>2</sub> emissions by 50% and the coke consumption by 25% while simultaneously a 20-30% increase in productivity can be realised. The next step is to continue working on the pilot and build a demonstration plant within 5 years in which the operation period should be at least 10 years in order to obtain reliable data. Mr Birat suggested that current cost data could only be reliable if a demonstration plant will be operational and recommended that cost data should only be published once the demonstration plant is in place to make it more meaningful. Finally, the presentation concluded that ULCOS has addressed the technological issues. However, beyond these issues, it is necessary to address the political and economic issues in a larger geopolitical scale to make CCS in the iron and steel industry a reality.



## ***CO<sub>2</sub> Storage – Challenges to the Iron and Steel Industry***

*John Gale, IEA Greenhouse Gas R&D Programme, UK*

Although geological storage of CO<sub>2</sub> is not a new technology, the iron and steel industry has no experience in transport and storage so far. There are also currently no “storage companies” on the market, to which the transport and/or storage process could be handed over. Experience from demonstration projects in the power sector has shown that the storage part is the highest source of risk within a CCS project. Moreover large up-front costs, lack of financing by the governments during the start-up phase, and public opposition regarding the safety of storage have been identified as major issues. The iron and steel industry has its own set of challenges for the transport and storage of CO<sub>2</sub> that is significantly different to other industrial sectors including the power generation industry. It should be noted that the steel industry, in addition to have multiple sources of CO<sub>2</sub> within a steel mill, also requires handling of large volumes of CO<sub>2</sub> (estimated at 10 - 30 MtCO<sub>2</sub>/yr per site), which at this scale has not yet been demonstrated.

## ***Development of High Throughput and Energy Efficient Technologies for Carbon Capture in the Integrated Steelmaking Process***

*Masao Osame, JFE Steel Corporation, Japan*

The COURSE50 project in Japan aims at reducing the CO<sub>2</sub> emissions from BF's by considering existing capture technologies like chemical absorption, physical adsorption, membrane processes, and combustion with nearly pure O<sub>2</sub>. A main objective of the project is the development of chemical, amine-based solvents to reduce the energy consumption for CO<sub>2</sub> capture. The prospective absorbents are tested for industrial application, especially regarding long-term stability and corrosion, in a 30 tCO<sub>2</sub>/d plant. The results clearly indicate a much lower amine loss related to degradation and also a much lower corrosion rate compared to the conventional amine MEA. With an energy consumption of 2.5 GJ/tCO<sub>2</sub> the most promising solvent performs better than other solvents that have been published in the literature. Further reduction of the energy demand to the project target of 2.0 GJ/tCO<sub>2</sub> can be achieved by optimization of the capture unit and improvements in the steelmaking process. On-going research also includes sensible heat recovery from slag which has been confirmed through lab-scale experiments but has to be proven on bench-scale in the future. However, questions concerning price and availability of the newly designed chemical solvent have not been answered at this stage of the project.

## ***Development of the Oxy-BF for CO<sub>2</sub> Capture Application in Iron Making***

*Jan van der Stel, Tata Steel, The Netherlands*

This presentation was also related to the ULCOS programme and provided an overview of the ULCOS-BF developments as well as results from the Experimental Blast Furnace (EBF) test campaigns. Three different concepts of operation with varied conditions for the recycled gas injection have been developed and investigated. During the EBF tests no safety issues have been recorded and the whole operation has been very smooth. The good results also include a constant productivity, a good metal quality, a high thermal stability, and nearly no equipment failure. Conventional burden materials can be used and recovery of the BF after shutdowns has been reported as easy. Similarly, the VPSA operated without any failure and with the required gas quality, i.e. high top gas recycling rates of 90% have been achieved. In conclusion the results from the test campaign demonstrate that a carbon saving of 24% per tHM and a CO<sub>2</sub> reduction of 15% per tHRC are feasible. This refers to a possible 60%



reduction of CO<sub>2</sub> emissions when a capture process is applied to the steel plant and again underlines the technical feasibility of CCS.

***CO<sub>2</sub> Capture from BFG Stream Using Aqueous Ammonia Aided by Waste Heat Recovery***  
*Chi Kyu Ahn, RIST, South Korea*

The implementation of a national CCS Master Plan set by the Korean government has put in place an ambitious objective of becoming one of the leading countries to develop CCS technology and achieve deep reduction in greenhouse gas emissions. The cost target has therefore been set at \$30/tCO<sub>2</sub>. In the iron and steel sector, one of the numerous projects deals with the development of an aqueous NH<sub>3</sub> process for CO<sub>2</sub> capture from Blast Furnace Gas. NH<sub>3</sub> offers some advantages compared to conventional MEA solvents in terms of lower regeneration energy demand, lower absorbent cost, and less corrosion. The NH<sub>3</sub> process can use medium and low temperature waste heat of iron and steel plants, which have not yet been recovered due to economic feasibility, for the supply of regeneration energy. This will lead to a significant improvement in process economics. One of the most important limitations of NH<sub>3</sub> processes is the high volatility of the absorbent resulting in high solvent losses. To overcome the drawbacks of NH<sub>3</sub> based CO<sub>2</sub> capture integrated studies have been carried out, including the evaluation of additives, the determination of the ion and salt speciation, and the introduction of an absorber side stream to suppress NH<sub>3</sub> vaporization. However, the NH<sub>3</sub> make-up has not been quantified at this stage of the project. During the field pilot tests a 9 mass% NH<sub>3</sub> solution provided the best performance, achieving a CO<sub>2</sub> removal efficiency of 90%, a CO<sub>2</sub> purity of 98%, and an energy consumption of less than 3.0 GJ/tCO<sub>2</sub>. The high purity specification of the study led to a subsequent discussion on the purities required for transport and storage. Several participants underlined that they would consider a purity of about 90% as sufficient and suggested future studies should use this number as specification.

***Development of BF Plus Technology for CCS Application***  
*Michael Lanyi, Air Products, USA*

BF Plus is a step-wise, near-term, economics-driven approach to mitigate CO<sub>2</sub> from iron making. One of the main objectives of the technology developers is to lower the cost of hot metal and to maximise the energy production simultaneously. This is mainly achieved by increasing the top gas calorific value and employing an efficient power production through a combined cycle where the gas is cleaned, compressed, and fed to a turbine which is equipped with a heat recovery steam generator. As the top gas calorific value increases with the O<sub>2</sub> content in the BF, a cold blast injection of about 60% is considered favourable. Although BF Plus is a technology that is realisable today, it still offers room for further improvements, e.g. ambient temperature cold blast, coke rate reduction, and increased O<sub>2</sub> content. Application of a CO<sub>2</sub> capture unit and a preceding shift reactor will decrease the net power export but at the same time CO<sub>2</sub> emissions are cut by more than 50%. The conversion rate in the shift reactor is assumed to easily reach up to 90% and for the capture unit a physical solvent is recommended due to the process pressure of 30 bar. Each part of the process is designed for a step-wise retrofit so that risks and capital outlays are minimised. Even if the BF Plus flow sheet may not fit in all places, e.g. where a complex infrastructure process already exists, the presentation has undoubtedly demonstrated that BF Plus is a promising approach for the iron and steel industry.



### **Air Separation and CO<sub>2</sub> Capture Units for Blast Furnace**

Jean-Pierre Tranier, Air Liquide, France

Air Liquide offers a worldwide portfolio of CO<sub>2</sub> reduction technologies and has also been involved in the ULCOS programme. As the economic feasibility of an amine process like aMDEA® depends on the cost of steam, cryogenic separation and PSA are more suitable for CO<sub>2</sub> separation when the steam cost exceeds €5/t. Test campaigns in the MEFOS pilot plant demonstrated the feasibility of (V)PSA for CO/CO<sub>2</sub> separation from a BF top gas. A stable operation has been observed throughout the experiments and the simulation tool has been verified. Even under challenging operating conditions, the trials have been completed successfully. The next step is to demonstrate the top gas recycle at commercial scale. In the meantime a new ASU dedicated to top gas recycle oxy-Blast Furnace that could also reduce power consumption by the factor of 2 has been developed. The presentation concluded that more detail evaluation is still necessary to further improve energy consumption and costs for the whole (V)PSA process for CO<sub>2</sub> capture. This should also require a large scale demonstration to validate cost and performance.

### **Cleaner Steel Production**

Volker Göke, Linde AG, Germany

Linde is adopting a dual approach in developing relevant mitigation technologies for the iron and steel sector. In regions where storage options are not available or the public is opposed to sequestration, they intend to convert CO and H<sub>2</sub> containing by-product gases into useable by-products, which would in parallel provide partial capture of CO<sub>2</sub> from the steel mill. For this purpose, Linde presented their work on the integration of a MeOH plant into the steel mill and highlighted that chemical utilisation of the coke oven gas (COG) and converter gas (CG or also known as basic oxygen furnace gas - BOFG) is only an add-on and not the overall solution to reduce CO<sub>2</sub> emissions. Increasing CO<sub>2</sub> certificate prices would obviously favour the proposed fuel/chemicals utilisation and it is a strength that the technology is in principle already available. Furthermore, MeOH is expected to play an important role in the future European fuel market. In contrast the purification of the COG and CG to catalyst specifications and the impact on energy balance remain a challenge. It is also not yet clear how the CO<sub>2</sub> emission can be accounted for in the EU Emissions Trading Scheme.

### **Process Evaluations and Simulations of CO<sub>2</sub> Capture from Steel Plant Flue Gases**

Andrew Tobiesen, SINTEF Materials and Chemistry, Norway

The session started with an evaluation of the suitability of amine technology for steel plant and OBF flue gases. A simulation for a conventional MEA based process assuming a total CO<sub>2</sub> recovery of 75% has been done with the in-house tool CO2SIM. The results of the calculations clearly indicate the need for improvements in the capture process, as a high reboiler heat duty of 3.7 GJ/tCO<sub>2</sub> and large dimensions of the process units were obtained. Through optimisation with a new low-energy solvent and heat integration scheme it was possible to bring down the energy requirement for the reboiler to 2.7 GJ/tCO<sub>2</sub>. For the OBF case a MDEA/PZ solvent was chosen because of the high CO<sub>2</sub> partial pressure in the gas. Due to the absence of O<sub>2</sub> in the gas a significantly reduced solvent degradation is furthermore expected. The simulation of an intercooled absorber configuration showed an energy demand of 2.35 GJ/tCO<sub>2</sub>, capture rate of 94%, and reasonable absorber/desorber dimensions. The main message of the presentation was that although MEA is not suitable as a reference solvent for the steel industry, chemical absorption with newly formulated solvents is well



suites for CO<sub>2</sub> capture application in a steel mill. At the end of the presentation some participants suggested the next step must now be the integration of the capture unit into the steel mill and that they would prefer the costs to be the only target function for future optimization studies.

### ***OBF Modelling – System Considerations***

*Lawrence Hooey, Swerea MEFOS, Sweden*

To compare the performance of the conventional blast furnace (BF) against an oxy-blast furnace (OBF) with top gas recycle, an Excel-based model previously used to evaluate the performance of the BF operation has been adapted for the OBF. The BF model is based on the energy and mass balance model for the blast furnace called “MASMOD”. It was developed in the 1980s and has been verified against SSAB operations. This presentation provided an overview of the key results of an on-going study incorporating the MASMOD model in an “Integrated Steel Mill Model” looking at the overall energy and mass balance of a conceptual steel mill producing 4 MtHRC. The current study assumed only coking coal, PCI coal and NG as energy input of the steel mill and that there will be no import or export of energy (i.e. electricity) for a defined system boundary. For the “OBF with CO<sub>2</sub> capture” case a CO<sub>2</sub> capture unit based on the MDEA/PZ solvent, a low purity oxygen plant, and a NGCC power plant have been added to the conceptual “REFERENCE” steel mill (base case). Operating conditions for the OBF were chosen as conservative. The results presented a reduction in coke consumption leading to an overall reduction of direct CO<sub>2</sub> emissions as compared to the Base Case. With a CO<sub>2</sub> capture plant using MDEA/PZ solvent, the study reported a total CO<sub>2</sub> avoidance of 46%. The presentation concluded that optimisation and integration of electricity and heat between power plant and steel mill will become more essential in the development of CO<sub>2</sub> capture technology for an integrated steel mill.

### ***Development in the Air Separation Unit - Addressing the Need of Increased Oxygen Demand from the Oxy-Blast Furnace***

*Paul Higginbotham, Air Products PLC, UK*

As the oxygen demand of the steel mill increases when incorporating OBF technology for CO<sub>2</sub> capture, it is therefore important to understand all technology available. It is the purpose of the air separation unit (ASU) to supply the oxygen, nitrogen and argon needed to the steel mill. This presentation highlights the different ASU configurations that are available to minimise energy consumption. It also illustrated a hybrid ASU that could provide dual purity O<sub>2</sub>: low purity O<sub>2</sub> for the OBF and high purity O<sub>2</sub> for the Basic Oxygen Steelmaking process. Furthermore, the presentation discussed the importance of operational flexibility to supply oxygen based on the steel mill’s demand, and stressed that technological solutions are available. The presentation concluded that the steel mill using OBF would require low purity O<sub>2</sub> at moderate delivery pressure. Thus the use of an ASU based on a three column design with liquid pumps providing the required delivery pressure is recommended. The possibility of using the N<sub>2</sub> at elevated pressure from the ASU for integration into an advanced power plant cycle could further reduce electricity demand by half compared to the conventional ASU used by steel mills worldwide.



## ***Development of the HIsarna Process – An Alternative Iron Making Technology with CO<sub>2</sub> Capture Potential***

*Christiaan Zeilstra, Tata Steel, The Netherlands*

The development of the HIsarna process is part of the ULCOS programme and covers both the improvement of CCS and the design of new smelting reduction technologies. In the HIsarna process the coal and ore are used directly, so no coking and agglomeration takes place. Benefits of the technology include a 20% reduction in CO<sub>2</sub> emissions and the suitability for combination with CCS to achieve an overall reduction of 80%. The presentation introduced the current pilot plant testing procedures and summarised the results of the 4 completed campaigns. Typical to any pilot testing, the plant initially suffered some teething problems and modifications were made resulting in three successful start-ups and achieving 60% of the full design capacity. The presentation concluded that the HIsarna process is a high risk/high reward innovation that is suitable for CCS and has the potential to improve the sustainability of steel making. HIsarna is not expected to be ready for industrial implementation before 2020, so the next step of the project involves the demonstration of an industrial scale plant.

## ***15 Years of Industrial CO<sub>2</sub> Storage Experience***

*Tore Torp, Statoil, Norway*

The presentation summarised 15 years of industrial storage experience at Statoil. Statoil's CO<sub>2</sub> storage sites include a unique blend of onshore/offshore, shallow/deep, and horizontal/vertical wells. An overview of the major storage projects Sleipner, In Salah and Snohvit was presented. The presentation explained the different trapping mechanisms and how they will increase the storage safety. The risk is generally expected to decrease once the injection process is stopped. In order to address the public concern regarding storage safety, the Svelvik test site has been established to simulate and quantify unforeseen leakage and migration. The investigation of onshore and offshore leakage scenarios in the course of the project is still on-going, so no definite statements are possible at the moment. The presentation ended with a summary of the current status of CO<sub>2</sub> storage with regard to the legal framework development. Furthermore the status of monitoring at Sleipner would help to demonstrate that CO<sub>2</sub> storage is safe.

## ***Lessons Learned: IEAGHG Weyburn-Midale CO<sub>2</sub> Monitoring & Storage Research Project***

*Neil Wildgust, IEAGHG/PTRC, Canada*

The Weyburn-Midale project successfully stored 20 MtCO<sub>2</sub> up to now from EOR operations and thereby proved that industrial amounts of CO<sub>2</sub> can be injected into geological formations. Although long-term storage is still an uncertain concept, the region is comfortable with the CO<sub>2</sub>-EOR activities. Because the influence of one stakeholder or the public can affect the whole project, it is essential to start the communication process early. Besides, cross-border transport has not been experienced as an issue since pipelines are already crossing in this area. One of the main statements from the projects is the unlikelihood of major leakage events if the site is carefully chosen, characterised, and operated. In this regard, a best practice manual is being produced.



## ***Challenges and Opportunities of CO<sub>2</sub> Capture and Storage in the Iron and Steel Industry: Understanding the Overall Perspective***

*Christopher Beauman, European Bank for Reconstruction and Development, UK*

The presentation provided a clear message about the importance of competitiveness and that it could impact the implementation of CCS in the iron and steel industry sector. In this context competitiveness doesn't necessarily mean low cost but also the ability to address the needs and provide the services required by steel industry's customers. Steel is the most traded and carbon-intensive good worldwide. Addressing the reduction of CO<sub>2</sub> emissions from the steel industry should not be limited to OECD countries – as China produces half of the world's iron production. This same principle applies to any implementation of CCS technology to this industrial sector – as CCS would require additional investment and cost that could impact competitiveness. One important question arising from this presentation is whether the burden of CO<sub>2</sub> should only stay on the shoulders of the steel producers. It is very clear that there is an urgent requirement to develop a global climate change related trade policy that would tackle any “carbon leakage” and provide a level playing field. This point unmistakably calls for a fair agreement among all stakeholders.

## ***Techno-Economic Evaluation of Some of the Considered Options of Capturing CO<sub>2</sub> from an Integrated Steel Mill***

*Lawrence Hooey, Swerea MEFOS, Sweden*

A techno-economic assessment (on a scoping level) for some of the considered options of capturing CO<sub>2</sub> from a conceptual “REFERENCE” integrated steel mill was presented. The study was carried out with the aim to develop methodology and provide information that would help understand the cost dynamics of capturing CO<sub>2</sub> from a “REFERENCE” steel mill. The conceptual steel mill assumed in the study would produce 4 MtHRC /yr – situated in the coastal region of Western Europe. It was assumed that the “REFERENCE” steel mill would not import or export energy (i.e. electricity, district heating, etc...) in or out of the defined system boundary. It is supposed to be self-sufficient with its own electricity and coke requirements via its captive coke and power plant. The steel mills with CO<sub>2</sub> capture are evaluated based on three different scenarios. Two of these scenarios are based on two levels of end-of-pipe CO<sub>2</sub> capture from the flue gases of the captive steam boilers (level 1 and 2), hot stove (level 1 and 2), coke plant (level 2) and lime plant (level 2) using standard MEA solvent. The third scenario is based on CO<sub>2</sub> capture from an OBF using MDEA solvent. From the presentation it could be summarised that the OBF-MDEA process provides the better option of capturing CO<sub>2</sub> (at 46% avoidance and cost of ~\$58/tCO<sub>2</sub>) than the other two end-of-pipe cases. In summary, it was presented that the level 1 end-of-pipe case achieving a 50% CO<sub>2</sub> avoidance would have avoidance cost of ~\$82/tCO<sub>2</sub>; whilst the level 2 end-of-pipe case achieving a 60% CO<sub>2</sub> avoidance would have a cost of ~\$72/tCO<sub>2</sub>.

## ***Cost of Transport - Large Scale and Post Demonstration***

*Per Arne Nilsson, Panaware AB, Sweden*

The main objective of the EU CCS Demonstration Programme is to enable the commercial availability of CCS. Therefore the capture technology must come down the learning curve, safe and secure storage of CO<sub>2</sub> should be demonstrated, and cost of CO<sub>2</sub> transport should be minimised. This presentation provided an overview of the evaluation done by the EU Zero Emissions Platform (ZEP) on the cost of CO<sub>2</sub> transport. It could be noted that in order to reduce the transport cost, it is vital to have an early strategic planning. Moreover the study led



to the conclusion that massive investment is needed to establish a pan-Europe CO<sub>2</sub> pipeline infrastructure that would serve large scale implementation of CCS. The level of CAPEX required could be prohibitive and carries significant risk. However, a combination between ship and pipeline transport could be able to mitigate some of the economic risk. Finally it was recommended that developing a CO<sub>2</sub> transport hub system would benefit the industry most by achieving cost reduction due to economy of scale.

#### ***The Post-2020 Cost-Competitiveness of CCS - Cost of Storage***

*Wilfried Maas, Shell, The Netherlands*

The presentation provided an overview of the work done by the Zero Emissions Platform (ZEP) on cost assessment of coal and gas fired power plants with CO<sub>2</sub> capture, and cost of CO<sub>2</sub> storage using six different realistic cases with an early commercial phase regime as basis. The ZEP report clearly indicates that CCS applied to power generation could be made cost-competitive compared to other low carbon power generation technologies. CCS is technically feasible but requires a secure environment to allow for long-term investment. It can also be noted that the demonstration phase costs will be significantly higher due to the lack of lifetime and scale effects. But once CCS is applied, the plant is expected to be no longer sensitive towards increasing CO<sub>2</sub>/ETS cost. Later on in the presentation, the results of cost analysis for CO<sub>2</sub> storage were presented. The evaluation of the cost of storage is based on an analysis of 26 different parameters. It was identified that 8 of these parameters could have a significant material impact. Therefore, sensitivity analyses have been undertaken. The presentation concluded that type and location of field is the main determinant of costs; - i.e. - onshore is cheaper than offshore; - Depleted Oil and Gas Field (DOGF) is cheaper than Saline Aquifer (SA), - larger field is cheaper than smaller field, - higher injectivity is cheaper than lower injectivity. Unfortunately, the cheapest forms of storage (big onshore DOGF) are also the least available. The cost of the injection well will cover 40 - 70% of the total CO<sub>2</sub> storage cost. The wide variation in cost is primarily due to geophysical variation of the storage site rather than to the uncertainty of the cost estimate data.

## **4. CONCLUDING REMARKS**

The workshop clearly showed that the technologies needed to reduce CO<sub>2</sub> emissions using CCS from an integrated steel mill are technically feasible. These technologies could be made available or would be mature in the next 10 to 15 years. To achieve the required technological maturity, large scale demonstration is needed to validate and verify the promising results obtained from the different pilot scale experimental works.

The concluding remarks were provided by Nils Edberg (SSAB) and Prof. Gunnar Still (TKS). They have both agreed that presentations during the workshop and subsequent discussions have been interesting, inspiring and challenging at most.

It was concluded that on-going work on CO<sub>2</sub> breakthrough technologies by the steel industry is needed to achieve the goal of commercialisation of these new carbon-lean iron making processes with confidence that they will be reliable. This activity should continue in the form of demonstration activity over the next decade and is expected to result in new technological development for the iron and steel industry.

In parallel, many questions on public acceptance, market competitiveness (including “carbon leakage”) and project financing have to be answered in the near future to allow the decision



to be made for long-term investment on implementing CCS in the iron and steel industry sector.

Evaluating costs for CO<sub>2</sub> capture technologies applied to the steel industry is still done with significant uncertainties. So there is an urgent need for further research and engineering work on cost evaluation and verification. The methodology used for the assessment and reporting of CCS cost should enable a like-for-like comparison of various CO<sub>2</sub> capture technology options for the iron and steel industry.

Finally, Prof. Gunnar Still closed the workshop with a firm recommendation to continue the discussion and collaboration. He noted that the work done by the iron and steel industry on CO<sub>2</sub> capture and storage should be understood and recognized. Moreover, an international commitment is required to establish a level playing field where countries that implement CCS in their iron and steel sector would not lose their competitiveness in the global steel market.

## 5. NEXT STEPS

The workshop has succeeded to provide a forum for the iron and steel industry stakeholders to discuss about the challenges of implementing CCS within the industry. Work is on-going on the development of CO<sub>2</sub> breakthrough technologies (including CCS) to reduce greenhouse emissions from iron and steel production. It was recommended that we need to continue discussion and develop collaboration through dialogues similar to this workshop. Follow-up activities to this workshop will be planned and pursued.

The meeting also provided a feedback to on-going work done by Swerea MEFOS. This project was initiated by the IEA Greenhouse Gas R&D Programme. It is now the aim to complete these reports and have a follow-up meeting to review the results of this study. A round table meeting will be organised, and this will be held in the early part of spring next year.

## 6. ANNEX I – DELEGATE LIST

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<b>Andrew Tobiesen</b>	SINTEF Materials & Chemistry
<b>Antti Arasto</b>	VTT Technical Research Centre of Finland
<b>Benedicte Prodhomme</b>	ALSTOM
<b>Bob Peglar</b>	Global CCS Institute
<b>Chi Kyu Ahn</b>	RIST
<b>Christiaan Zeilstra</b>	Tata Steel Europe
<b>Christopher Beauman</b>	European Bank for Reconstruction & Development
<b>Daniel Bouwhuis</b>	Huettenwerke Krupp Mannesmann GmbH
<b>Daniel Jansen</b>	ECN
<b>Elmar Schuster</b>	Voestalpine Stahl Donawitz GmbH&CoKG
<b>David Valenti</b>	EUROFER
<b>Etienne Hubert</b>	Air Liquide
<b>Evin Ekinci</b>	Free University Berlin
<b>Felix Zwiener</b>	KSB Aktiengesellschaft



<b>Gerard Louwerse</b>	Tata Steel
<b>Gerhard Endemann</b>	Steel Institute VDEh - German Steel Federation
<b>Gianluca Di Federico</b>	Alstom Carbon Capture GmbH
<b>Gunnar Still</b>	ThyssenKrupp AG
<b>Hans Bodo Lüngen</b>	Steel Institute VDEh
<b>Hans Peter Domels</b>	ThyssenKrupp steel Europe AG
<b>Hans-Jörn Weddige</b>	ThyssenKrupp AG
<b>Hans-Jürgen Kerkhoff</b>	Steel Institute VDEh
<b>Harsh Pershad</b>	Element Energy
<b>James Battensby</b>	Parsons Brinckerhoff
<b>Jan Van Der Stel</b>	Tata Steel
<b>Jan-Olov Wikström</b>	Swerea MEFOS
<b>Jasmin Kemper</b>	Ruhr-Universität Bochum
<b>Jean Pierre Birat</b>	ArcelorMittal
<b>Jean Theo Ghenda</b>	Steel Institute VDEh
<b>Jean-Pierre Tranier</b>	Air Liquide
<b>Jens Traupe</b>	Salzgitter AG
<b>Jeremy Johns</b>	Tata Steel Consulting
<b>Jin Cao</b>	Air Products and Chemicals, Inc
<b>John Newman</b>	Energy and Environment Consultant
<b>Jonas Helseth</b>	Bellona Europa
<b>Jörgen Grubbström</b>	Alstom Power
<b>Joseph Terrible</b>	Air Products and Chemicals, Inc
<b>Junhong Kim</b>	World Steel Association
<b>Kai Sauerzapfe</b>	Project Management Forschungszentrum Jülich
<b>Karl Meuser</b>	Huettenwerke Krupp Mannesmann GmbH
<b>Kim Kärsrud</b>	SSAB AB
<b>Klaus Lachmann</b>	Schneider Electric
<b>Konstantinos Vatopoulos</b>	EUROPEAN COMMISSION, DG JRC-IET
<b>Kristin Onarheim</b>	VTT Technical Research Centre of Finland
<b>Lawrence Hooey</b>	Swerea MEFOS
<b>Luke Gracias</b>	Carbon Energy
<b>Luke Warren</b>	Carbon Capture and Storage Association
<b>Masao Osame</b>	JFE Steel Corporation
<b>Matthias Kopp</b>	wwf germany
<b>Michael Lanyi</b>	Air Products and Chemicals
<b>Michael Hensmann</b>	ThyssenKrupp Steel Europe AG
<b>Michel Devaux</b>	Air Liquide
<b>Mykola Shestavin</b>	Donetsk National University
<b>Nathalie Trudeau</b>	International Energy Agency
<b>Nils Edberg</b>	SSAB EMEA AB
<b>Paul Higginbotham</b>	Air Products plc
<b>Per Arne Nilsson</b>	panaware ab
<b>Peter Radgen</b>	E.ON



<b>Peter Webster</b>	Parsons Brinckerhoff
<b>Philip Cherukara</b>	Semcon Energy UK
<b>Rainer Klamt</b>	KSB Aktiengesellschaft
<b>Ralph Baessler</b>	Federal Institute for Materials Research & Testing
<b>Sorin Anghel</b>	GEOECOMAR
<b>Stanley Santos</b>	IEA Greenhouse Gas R&D Programme
<b>Tore Andreas Torp</b>	Statoil Research Centre Trondheim
<b>Tuija Nevalainen</b>	Ruukki Metals
<b>Vic Abraham</b>	Tata Steel Consulting
<b>Volker Goeke</b>	Linde AG
<b>Wilfried Maas</b>	Shell Global Solution International B.V.
<b>Wolfgang Bender</b>	VDEh-Betriebsforschungsinstitut GmbH
<b>Ziad Habib</b>	Lhoist Sa

## 7. ANNEX II – AGENDA

### 8th November 2011 (Morning Session)

**08.00 – 09.30**      **Registration and Coffee**

**09.30 – 10.00**      **Opening of the Workshop**  
Prof. Dr. Ing. Gunnar Still, ThyssenKrupp AG, Germany

#### **Welcome Remarks**

**Hans-Jürgen Kerkhoff**  
Chairman Steel Institute VDEh,  
President German Steel Federation

**John Gale**  
General Manager  
IEA Greenhouse Gas R&D Programme, UK

**10:00 – 10.30**      **Presentation 01: (30 minutes)**  
**IEA Perspective on Industry Application on CCS**  
Nathalie Trudeau, IEA, France

**10:30 – 11.15**      **Presentation 02: (45 minutes)**  
**Iron and Steel Industry Perspective on CCS**  
Prof. Dr. Ing. Gunnar Still, ThyssenKrupp AG, Germany

**11.15 – 11.45**      **Coffee Break**

**11.45 – 12.30**      **Presentation 03: (45 minutes)**  
**Overview of the CO<sub>2</sub> Capture Options for Integrated Steel Mills – ULCOS Programme**  
Jean Pierre Birat, Arcelor Mittal / European Coordinator - ULCOS Programme, France



<b>12.30 – 13.00</b>	<b>Presentation 04: (30 minutes)</b> <b>CO<sub>2</sub> Storage - Challenges to the Iron and Steel Industry</b> John Gale, IEA Greenhouse Gas R&D Programme, UK
<b>13.00 – 13.45</b>	<b>Lunch and Coffee</b>
<b><u>8th November 2011 (Afternoon Session)</u></b>	
<b>13.45 – 14.15</b>	<b>Presentation 05: (30 minutes)</b> <b>Development of High Throughput and Energy Efficient Technologies for Carbon Capture in the Integrated Steelmaking Process</b> Masao Osame, COURSE50 Subproject Leader, JFE Steel Corporation, Japan
<b>14.15 – 14.45</b>	<b>Presentation 06: (30 minutes)</b> <b>Development of the Oxy-BF for CO<sub>2</sub> Capture Application in Iron Making</b> Jan van der Stel, Tata Steel, The Netherlands
<b>14.45 – 15.15</b>	<b>Presentation 07: (30 minutes)</b> <b>Challenges and Opportunities of CO<sub>2</sub> capture and storage in the iron and steel industry</b> Chi Kyu Ahn, Research Institute of Industrial Science & Technology (RIST), S. Korea
<b>15.15 – 15.45</b>	<b>Coffee Break</b>
<b>15.45 – 16.15</b>	<b>Presentation 08: (30 minutes)</b> <b>Development of BF Plus Technology for CCS Application</b> Michael Lanyi, Air Products, USA
<b>16.15 – 16.45</b>	<b>Presentation 09: (30 minutes)</b> <b>Air Separation and CO<sub>2</sub> Capture Units for Blast Furnace</b> Jean Pierre Tranier, Air Liquide, France
<b>16.45 – 17.15</b>	<b>Presentation 10: (30 minutes)</b> <b>Blast Furnace Upgrading and Cleaner Steel Production</b> Volker Göke, Linde AG, Germany

**8th November 2011 (Evening Event)**

<b>19.00 – 22.00</b>	<b>Workshop Dinner – Brewery "Zum Schiffchen"</b> Restaurant Brauerei Zum Schiffchen Hafenstraße 5 40213 Düsseldorf Tel. No.: +49 211 13 24 22 <a href="http://www.brauerei-zum-schiffchen.de/zum-schiffchen-e.php">http://www.brauerei-zum-schiffchen.de/zum-schiffchen-e.php</a>
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## 9th November 2011 (Morning Session)

<b>08.45 – 09.00</b>	<b>Admin Announcement</b>
<b>09.00 – 09.30</b>	<b>Presentation 11: (30 minutes)</b> <b>Design and Application of a Spreadsheet-Based Mass Balance Model of Oxy-Blast Furnace</b> Lawrence Hooey, Swerea MEFOS, Sweden
<b>09.30 – 10.00</b>	<b>Presentation 12: (30 minutes)</b> <b>Process Evaluations and Simulations of CO<sub>2</sub> Capture from Steel Plant Flue Gases</b> Andrew Tobiesen, SINTEF Materials and Chemistry, Norway
<b>10.00 – 10.30</b>	<b>Presentation 13: (30 minutes)</b> <b>Development in the Air Separation Unit – Addressing the Need of Increased Oxygen Demand from the Oxy-Blast Furnace</b> Paul Higginbotham, Air Products, UK
<b>10.30 -11.00</b>	<b>Coffee Break</b>
<b>11.00 -11.30</b>	<b>Presentation 14: (30 minutes)</b> <b>Development of the HiSarna – an Alternate Iron Making Technology with CO<sub>2</sub> Capture Consideration</b> Christiaan Zeilstra, Tata Steel, The Netherlands
<b>11.30 – 12.00</b>	<b>Presentation 15: (30 minutes)</b> <b>Industrial Scale CO<sub>2</sub> Storage Experience in Sleipner, In Salah and Snohvit</b> Tore Torp, Statoil, Norway
<b>12.00 – 12.30</b>	<b>Presentation 16: (30 minutes)</b> <b>Lessons Learnt: IEAGHG Weyburn-Midale CO<sub>2</sub> Monitoring and Storage Research Project</b> Neil Wildgust, PTRC, Canada
<b>12.30 – 13.15</b>	<b>Lunch and Coffee</b>

## 9th November 2011 (Afternoon Session)

<b>13.15 – 15.45</b>	<b>Discussion Forum:</b> <b>“Cost Implication of CO<sub>2</sub> Capture and Storage for the Iron and Steel Industry”</b>
	<b>Presentation 17: (30 minutes)</b> <b>Understanding the Overall Perspective on CO<sub>2</sub> Capture and Storage Cost Implication for the Iron and Steel Industry</b>



Christopher Beauman, European Bank for Reconstruction and Development, UK

**Presentation 18: (30 minutes)**

**Techno-Economic Evaluation of Some of the Considered Options of Capturing CO<sub>2</sub> from an Integrated Steel Mill**

Lawrence Hooey, Swerea MEFOS, Sweden

**Presentation 19: (30 minutes)**

**Cost of CO<sub>2</sub> Transport, large scale and long term - Presentation of the Results of ZEP Programme**

Per Arne Nilsson, Panaware, Sweden

**Presentation 20: (30 minutes)**

**Cost of CO<sub>2</sub> Storage – Presentation of the Results of ZEP Programme**

Wilfred Maas, Shell, The Netherlands

**15.45 – 16.15**

**Concluding Remarks**

Nils Edberg, SSAB, Sweden

Prof. Dr. Ing. Gunnar Still, ThyssenKrupp AG, Germany

## **8. ANNEX III – LIST OF ABRREVIATIONS**

aMDEA®	“activated MDEA” process from BASF
ASU	Air Separation Unit
BF	Blast Furnace
BOF	Basic Oxygen Furnace
BOFG	Basic Oxygen Furnace Gas
CAPEX	Capital Expenditure
CCS	CO <sub>2</sub> Capture and Storage
CG	Converter Gas
COG	Coke Oven Gas
DOGF	Depleted Oil and Gas Field
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EBF	Experimental Blast Furnace
EOR	Enhanced Oil Recovery
ETS	Emissions Trading Scheme
HIsarna	Smelting reduction technology developed by ULCOS Project
HM	Hot Metal
HRC	Hot Rolled Coil
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
MEA	Monoethanolamine
MeOH	Methanol
MDEA	Methyl diethanolamine
NG	Natural Gas
NGCC	Natural Gas Combined Cycle



OBF	Oxy-Blast Furnace
OECD	Organisation for Economic Co-operation and Development
PCI	Pulverised Coal Injection
PSA	Pressure Swing Adsorption
PZ	Piperazin
SA	Saline Aquifer
ULCOS	Ultra Low CO <sub>2</sub> Steelmaking
VPSA	Vacuum Pressure Swing Adsorption
ZEP	Zero Emissions Platform