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The work and preliminary results of the C^4U project on advanced carbon capture for steel industries integrated in CCUS clusters

Richard T. J. Porter[a,*], J. Carlos Abanades[b], Alvaro Amieiro[c], Syed z. Abbas[d], Silvian Baltac[e], Solomon Brown[f], Marco Cano Bertiz[g], Elena Catalanotti[a], Shaoyun Chen[h], Paul Cobden[i], Eric De Coninck[j], Heleen de Coninck[k], Vincent de Gooyert[k], Jude O. Ejeh[f], Milan Elkerbout[l], José Ramón Fernández[b], Gemma S. Grasa[b], Jérôme Hebrard[m], Thomas Hennequin[k], Zahra Janipour[k], Navid Khallaghi[d], Robert A. W. Kok[k], Francisco J. Lago Fernández[g], Michael Lechner[n], Haroun Mahgerefteh[a], Giampaolo Manzolini[o], Sergey B. Martynov[a], Amelia Mitchell[e], J. A. Z. (Jean-Pierre) Pieterse[p], Christophe Proust[m], Monisha Rastogi[q], Dorothee Rebscher[n], Sara Rosendahl[i], Fabio Rugerri[r], Vincenzo Spallina[d], Floris Swennenhuis[k], Jean-Yves Tilquin[q], Siebe van der Veer[s], H. A. J. (Eric) van Dijk[p], Rosalie van Zelm[k]

[a]*Department of Chemical Engineering, University College London, London WC1E 7JE, United Kingdom*
[b]*INCAR-CSIC, Spanish Research Council, Oviedo 33011, Spain*
[c]*Johnson Matthey Technology Centre, Reading RG4 9NH, United Kingdom*
[d]*Department of Chemical Engineering and Analytical Science, The University of Manchester, Manchester M13 9PL, United Kingdom*
[e]*Element Energy, Cambridge CB5 8AQ, United Kingdom*
[f]*Department of Chemical & Biological Engineering, University of Sheffield, Sheffield, S1 3JD, United Kingdom*
[g]*ArcelorMittal Global R&D Asturias, Aviles 33400, Spain*
[h]*Dalian University of Technology, Dalian 116024, People's Republic of China*
[i]*Swerim AB, Luleå SE-971 25, Sweden*
[j]*ArcelorMittal, Ghent 9042, Belgium*
[k]*Radboud University, Nijmegen 6525 XZ, The Netherlands*
[l]*Centre for European Policy Studies (CEPS), Brussels 1000, Belgium*
[m]*INERIS, Verneuil-en-Halatte, BP 2 60550, France*
[n]*Federal Institute for Geosciences and Natural Resources (BGR), Hannover 30655, Germany*
[o]*Politecnico di Milano, Milan 20133 Milano, Italy*
[p]*TNO, Energy Transition, 1755 ZG, Petten, The Netherlands*
[q]*Carmeuse Reasearch and Technology, Louvain-la-Neuve 1348, Belgium*
[r]*Wood PLC, Milan 20094, Italy*
[s]*Kisuma Chemicals B.V., Veendam 9641 KZ, Netherlands*

Abstract

This paper provides an overview of the aims, objectives and preliminary findings of the C^4U holistic interdisciplinary project, which addresses all the essential elements required for the optimal integration of CO_2 capture in the iron and steel industry as part of the Carbon Capture, Utilisation and Storage (CCUS) chain. The project's scope spans pilot-scale demonstration of two highly

* Corresponding author. Email *address:* r.t.j.porter@ucl.ac.uk

efficient CO_2 capture technologies at TRL7 designed for optimal integration into an iron and steel plant along with detailed consideration of the safety, environmental, societal, policy and business aspects for successful incorporation of CCUS into the North Sea Port industrial cluster. The new sorbent-based CO_2 capture technologies in C^4U are known as DISPLACE (high temperature sorption-DISPLACEment process for CO_2 recovery) and CASOH (Calcium Assisted Steel-mill Off-gas Hydrogen production). Both approaches involve high-temperature gas-solid separation processes that reduce the exergy penalty associated with CO_2 capture. The progress made on the design and construction of pilot-scale CO_2 capture test facilities for assessing the technologies' performance is presented, along with results of uniquely developed mathematical models and laboratory-scale tests performed for gaining understanding of the physical and chemical phenomena underpinning the processes. The use of these results to establish the full-scale design of the technologies for deployment in an integrated steel-mill using process simulation techniques while quantifying the techno-economic and environmental performance in comparison to reference technologies (e.g. amine based CO_2 capture) is also discussed. Analysis undertaken to help interface the technologies with CO_2 transport and storage infrastructure is described with particular regard to requirements to meet target compositional specifications, operational safety of CO_2 pipelines while also carrying impurities and mathematical tools required for the design and operation of a CCUS cluster in view of future expansion. The development of novel business models for facilitating deployment so that the long-term business case can be established through consideration of the concerns of a multitude of various stakeholders and identification of optimal scenarios for overcoming financial risks is discussed. Progress on evaluating societal readiness and public support for CCUS through just transitions in industrial clusters is also presented. The project's work is expected to demonstrate CO_2 capture from an integrated steel-mill in safe and economic CCUS value chains while establishing viable pathways to rollout of CCUS in industrial clusters.

Keywords: Steel sector; pilot-scale demonstation; process simulation; cost analysis; CO_2 quality; pipeline transport; utilisation and storage; just transition; business model.

1. Introduction

The internationally agreed global climate deal reached at the Paris Climate Conference in 2015 is intended to limit the increase in global average temperatures to 'well below' 2 °C above pre-industrial levels [1]. This is re-enforced by the EU's ambition for net-zero emissions by 2050 in order to avoid irreversible climate change [2]. Most scenarios indicate that CCUS is essential for achieving such ambitious reductions [3], particularly in curtailing CO_2 emissions from the main energy intensive industries.

With average emissions being 1.83 tonnes of CO_2 per tonne of steel [4] and with more than 1.8 Gt of steel produced per year, the iron and steel sector is the single largest industrial contributor to global CO_2 emissions at 8 % [5]. According to the IPCC SR1.5 [6], global industry, including iron and steel, would have to reduce emissions by, on average, 42% in 2030 and 79% in 2050 compared to 2010 if we want to limit warming to 1.5 °C.

Iron and steel plants have specific societal characteristics. Steel mills often play a central role in a region; they employ thousands of people and instil the region with a sense of identity and industrial pride. The fear of losing this industry because of ambitious climate policy may be grounds for climate scepticism and resistance against climate policy. On the other hand, implementing CCUS is comparatively undisruptive from a societal point of view, and may therefore be favourably looked upon.

Technologically, steel plants are also special. A unique feature of the current steel making processes is the large scale production of residual off-gases with low energy content but very high carbon content such as Blast Furnace Gas (BFG, with about 50% $CO+CO_2$ and >45% N_2, LHV 3.2 MJ/Nm^3), which are inherent to the steel making process. These residual gases are often used as fuel to produce power or combined heat and power to sustain the most energy demanding steps in the metallurgical processes, thereby increasing the specific carbon emissions of these process steps. Otherwise, the gases are combusted at the mouth of the furnaces, or through flaring after gas cleaning in furnaces.

A broad range of CO_2 capture technologies to reduce emissions from iron and steel production have been proposed [7-10] and are under development at different Technology Readiness Levels (TRLs). Substantial cost saving opportunities may arise when combining suitable capture technologies with the energy and material requirements in the steel making plant. In particular, there is great interest in using steelworks off-gases to produce value added products or implementing efficient strategies to extract the thermal value from them, while producing a CO_2 product stream suitable for further utilisation or geological storage.

Given the urgency of the requirement for emission reductions, the very different characteristics of the CO_2 containing streams emanating from steel plants and the huge quantities of CO_2 involved, a portfolio of promising CO_2

capture technologies must be developed. In addition, they must be practically tested to high TRL to identify the optimal integration solutions that deliver the minimum cost and energy consumption.

Responding to the above challenge, the Horizon 2020 project C^4U is elevating from TRL5 to TRL7 (i.e. lab-scale to pilot scale) two highly energy-efficient high-temperature solid-sorbent CO_2 capture technologies for decarbonising BFG and other carbon containing gases present on a steelworks. The new CO_2 capture technologies in C^4U are known as:

- DISPLACE – high temperature sorption-DISPLACEment process for CO_2 recovery, and
- CASOH – Calcium Assisted Steel-mill Off-gas Hydrogen production.

For the first time, in combination, the two C^4U technologies will target up to 90% of the total emissions that come from a variety of sources on a steel plant for CO_2 capture. C^4U analyses the optimal design for full-scale integration of such technologies in industrial plants operated by the world's largest iron and steel manufacturer, ArcelorMittal. Using a whole system approach, we account for the impact of the quality of the captured CO_2 on the safety and operation of the CO_2 pipeline transportation and storage infrastructure whilst exploring utilisation opportunities based on integration into the North Sea Port CCUS industrial cluster.

This paper provides an overview of the aims, objectives and preliminary findings of the C^4U project. Section 2 discusses industrial experiments for demonstrating the CASOH and DISPLACE advanced capture technologies at TRL7 for optimal integration into the steel plant, involving designing and commissioning the pilot capture units using state-of-the-art chemical and mechanical engineering modelling and simulation tools. Section 3 covers work towards optimal integration of technologies at large-scale for cost-effective processing of the steelworks off-gases while producing a CO_2 stream of suitable quality for subsequent transportation and storage or further utilisation. Section 4 discusses the development of an infrastructure optimisation model which uses a combination of experimental, computational and desktop literature review studies to define the operational, safety and cost constraints for CO_2 pipeline transport, utilisation and storage in an industrial cluster. Business model and societal acceptance work is presented in Sections 5 and 6, respectively, followed by Conclusions in Section 7.

2. Advanced CO_2 capture technologies testing and demonstration at TRL7 and integration in steel plants

A major aim of C^4U is to elevate the DISPLACE and CASOH CO_2 capture technologies from TRL5 to TRL7 and design for optimal integration in the steel industry. The objectives for the technology demonstration at TRL7 are:

- To significantly improve the performance of the two promising TRL5 high temperature solid sorbent CO_2 capture technologies (DISPLACE and CASOH) in accordance to credible Key Performance Indicator (KPI) targets shown in Table 1 for their optimal integration in industrial steel mills;
- To experimentally validate at TRL7 the reliability and cost effectiveness of the optimised C^4U capture demonstration units through accumulation of 4000 hours of operational time in TRL7 pilots;
- To scale-up to TRL9 the design of the two CO_2 capture processes when integrated in the full-scale steel plant together with determination of the fixed and operating costs under state-of-the-art commercial data.

Table 1. C^4U DISPLACE and CASOH capture technology KPI targets.

Key Performance Indicators		Benchmark technologies		DISPLACE		CASOH		C^4U IMPACT
		MEA	MDEA	absolute	improvement	absolute	improvement	
Carbon captured [a]	**%**	**27%**	**50%**	**34%**		**55%**		**89%**
SPECCA [b]	**$MJ_{LHV}/kg_{CO2,cap}$**	**4.8**	**2.8**	**2.0**	**−58%**	**1.2**	**−57%**	**1.5**
CO_2 avoidance cost	**€/$tonne_{CO2}$**	**65.0**	**50.6**	**38.8**	**−40%**	**42.2**	**−17%**	**41.0**

[a] Calculated as the % of carbon captured with respect to the total carbon emissions from the different sections of the steel plant

[b] Specific Primary Energy Consumption for CO_2 Avoided

Both DISPLACE and CASOH technologies involve high temperatures gas-solid separation processes that reduce the exergy penalty associated with CO_2 capture. This is due to their ability:

- To recover heat at very high temperatures that can be used for energy demanding processes in the steel plant (i.e. reheating furnaces and CO_2-free power generation), and
- To co-produce H_2/N_2 fuel gases that can lead to decarbonisation of energy consuming processes in the steel mill or the manufacture of high value products.

Both technologies have therefore shown significant potential cost savings for decarbonising a variety of steel mill off-gases by shifting their chemical energy content towards H_2 and/or by allowing efficient thermal integration of their high temperature off-gases in the steel making process, while generating a separate CO_2 stream for utilisation or permanent storage. The combined use of the C^4U technologies can tackle up to 94% of the sources of CO_2 in a steel mill, resulting in an overall CO_2 emission reduction of 89%. Fig. 1 is a conceptual process representation of the DISPLACE and CASOH C^4U capture technologies.

The DISPLACE process removes CO_2 from combusted off-gases arising from iron and steel processing, i.e. gases with no residual chemical energy, and only residual heat energy like the sinter plant and reheating ovens. In this case, oxyfuel combustion of BFG is used to provide process heat to reheating ovens, followed by the novel application of a high temperature sorption-displacement process using hydrotalcites for CO_2 sorption and recovery/recycle of adsorbed $H_2O_{(v)}$. CASOH is a Ca-Cu looping process for Sorption Enhanced Water Gas Shift (SEWGS) of BFG (and/or other fuel off-gases) using CaO as CO_2 sorbent, while generating concentrated streams of CO_2 during regeneration, by burning a fuel gas using CuO (an oxygen carrier with high exothermic reduction enthalpy). The following sections review the methodology and the project progress made in the development of these technologies.

2.1. DISPLACE process for reheating ovens

DISPLACE is a high temperature sorption-displacement process using hydrotalcites for CO_2 sorption and recovery of steam. The general process scheme for DISPLACE is represented in Fig. 2 and follows a sequential/cyclic operation of reactors with well-established principles in commercial Pressure Swing Adsorption (PSA) systems. The specific demonstration at TRL7 for DISPLACE will be for reheating applications, and it is also applicable for sinter grate off-gases and hot-stove exhaust amongst other gas streams with no residual chemical energy content. These constitute around 35% of the carbon emissions at a typical integrated steelworks [11].

The nominal process operates at constant pressure, feeding either the hot off-gas into the system or steam. The combination of displacement and competitive adsorption interactions of steam and CO_2 on the sorbent are such that mixing of these two gaseous components is much reduced in the gas phase above the sorbent. This gives the

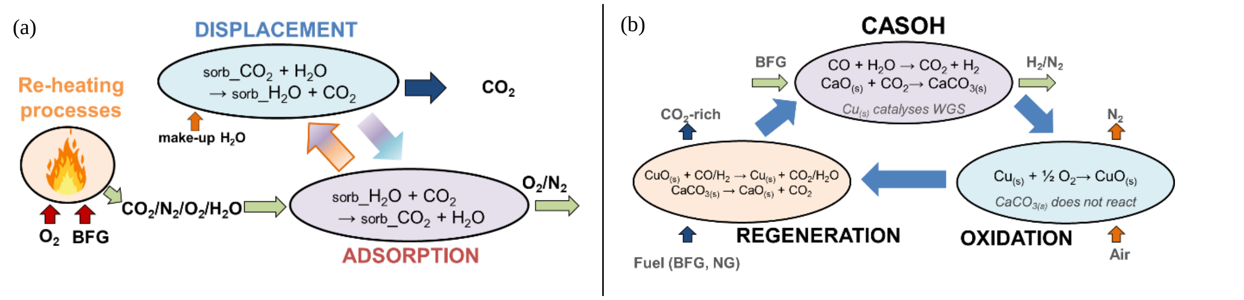

Fig. 1. Conceptual representation of two examples of application of the C^4U high temperature solid looping technologies for steel mills: (a) DISPLACE; (b) CASOH.

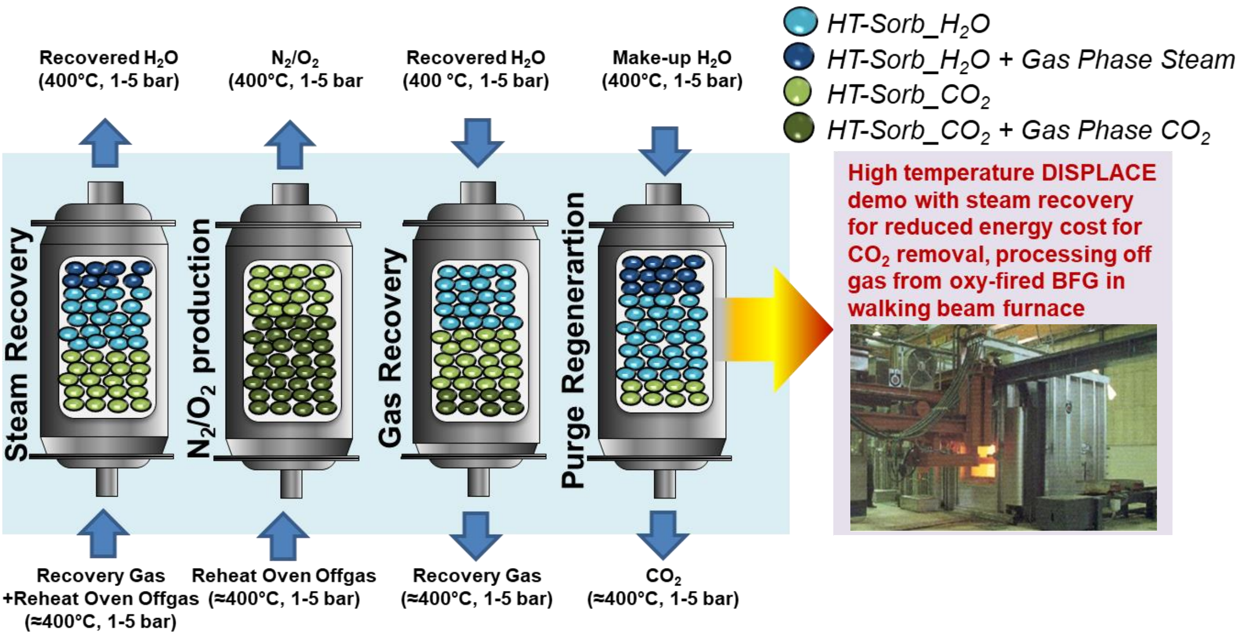

Fig. 2. The general process sequence of stages for the DISPLACE process applied to off-gases from reheating furnaces.

opportunity to develop a cycle with four steps to separate CO_2 from other gases that are inert for the sorbent, i.e.mainly N_2 and O_2 in iron and steel processes. In step 1, a CO_2 containing gas is fed into the sorbent bed, as CO_2 adsorbs, H_2O is replaced and pushed into the gas phase ahead of the CO_2 adsorption front. Initially the gas evolving at the top of the bed is steam which was transferred into the bed in step 4, and the evolving steam in step 1 is directed to step 3 of the cycle. In step 2, feed is continued, and until such time as the adsorption front has moved to the end of the bed, the other inert gas components (N_2/O_2) leave the top of the bed. Moving into step 3, the recovered steam from step 1 is fed into the top of the bed, quickly displacing the interstitial gas that built up in the bed during step 2. This interstitial gas has a CO_2 content slightly lower than the feed gas, as the CO_2 has a greater residence time. This gas is mixed into the feed of step 1. Finally, make-up steam is added to the top of the reactor, which displaces the majority of the CO_2 built up in the bed, producing a high concentration CO_2 stream. The DISPLACE pilot is being developed at Swerim's demonstration site in Luleå, Sweden, where it is integrated in pilot CO_2 capture facilities designed, built and operated through Swerim–TNO collaborations in previous European Union funded Horizon 2020 projects, STEPWISE [12] and FReSMe [13]. The DISPLACE facilities comprise a 600 m pipeline connecting industrially sourced BFG to supply

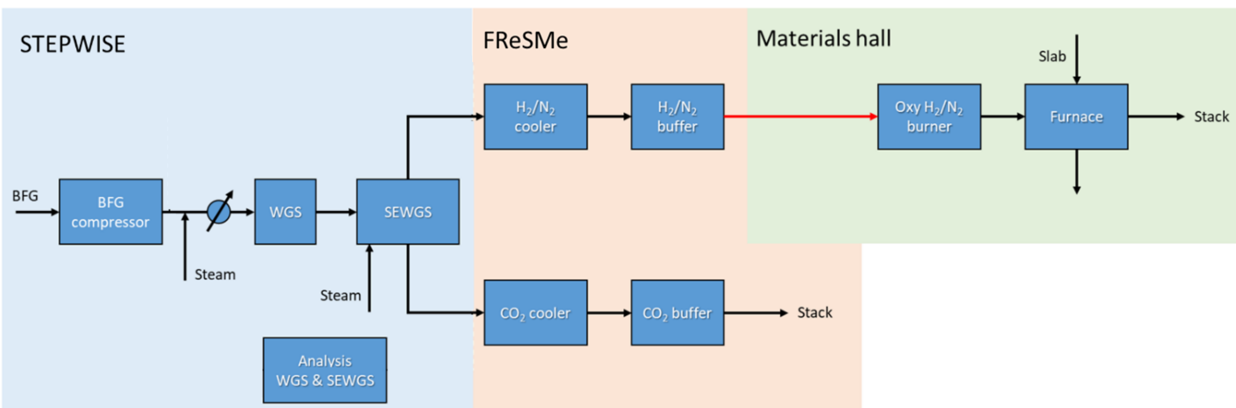

Fig. 3. Campaign 1: N_2/H_2 – SEWGS campaign.

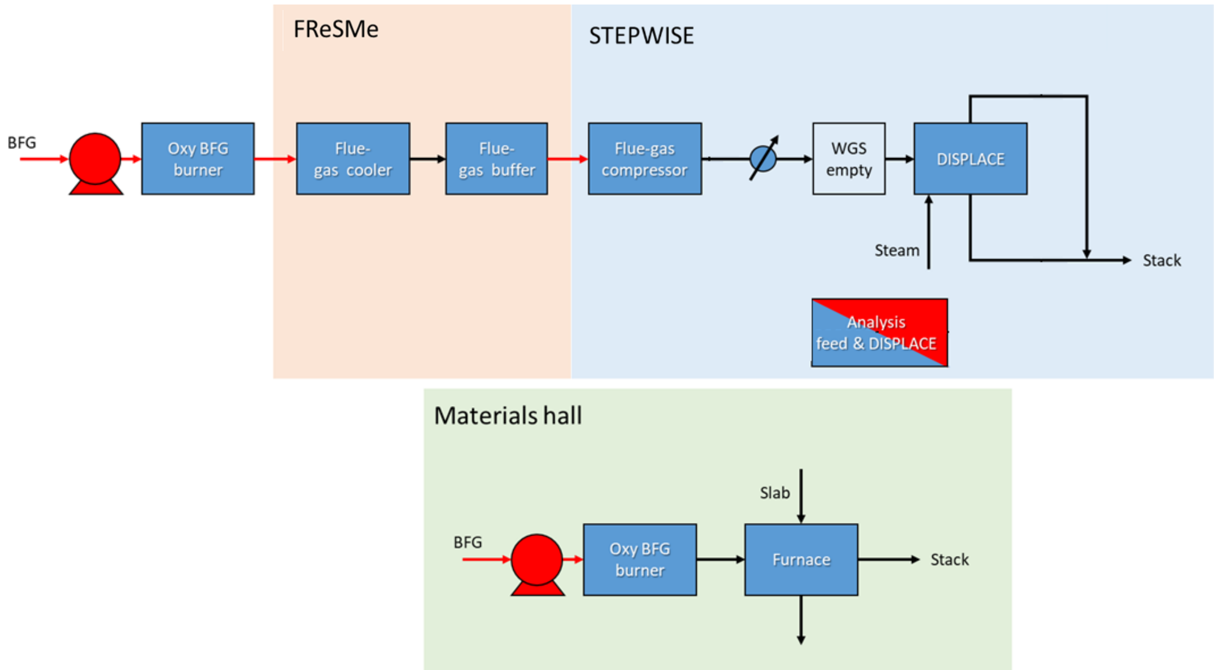

Fig. 4. Campaign 2: Oxy-BFG-DISPLACE campaign.

the experimental facilities at Swerim, a Water Gas Shift (WGS)/Guard bed reactor and an 800 Nm^3/hr dry gas sorbent bed for DISPLACE experimental activities inside an ATEX zone. The DISPLACE pilot testing activities are carried out in two campaigns. The first called the C^4U-SEWGS campaign is illustrated in Fig. 3 and benchmarks at TRL7 the use of an N_2/H_2 mixture derived from industrial BFG with pre-combustion removal of CO_2 in a Chamber Reheating Furnace in a 1000 hrs continuous campaign, and includes experimental validation of the effect on the steel quality. These results also validate N_2/H_2 product usage from the CASOH technology. The process for the C^4U-SEWGS campaign includes the WGS reactor (Fig. 5(a)), a large 10 m single column that can be used for SEWGS and DISPLACE and contains around 3 tonnes of Mg/Al/K-based sorbent (Fig. 5(b)) and a syngas cooler (Fig. 5(c)). Captured CO_2 is transferred to a buffer unit. The second campaign is called the Oxy-BFG-DISPLACE campaign, the block flow diagram is illustrated in Fig. 4. In this campaign, the DISPLACE CO_2 capture pilot plant is operated on oxy-combusted BFG from the chamber furnace, also using a 3 tonne steel/hr rated Walking Beam Furnace (WBF) for reheating applications fitted for oxy-combustion of BFG from a steel mill. Prior to oxy-combustion, BFG is first compressed to 6 bar. This campaign captures CO_2 continuously for 1000 operational hrs and also includes validation on the effect of this process on steel quality. A second part of campaign 2 called C^4U-WBF investigates oxy-firing in the WBF for understanding resulting gas composition.

In the first two years of the C^4U project, the activities for the DISPLACE pilot revolved around the engineering and construction phases. A Basis of Design document set and refined the scope for all the activities that will be performed over the project duration; for example, determining where equipment will be built, the size of all units and which project partners will be responsible for the different parts of the operation and delivery of materials. Basic and detailed engineering has been undertaken to define the exact size and shape of all the equipment that will be needed. A process HAZOP (hazard and operability study) was undertaken and all process equipment has been procured. The sorbent material has been produced by Kisuma and is available at Swerim's site while the WGS catalyst is supplied by Johnson Matthey. The first experimental runs were achieved for oxyfuel combustion of BFG in a WBF (C^4U-WBF) in March 2022. The experimental campaign for pre-combustion capture from BFG to produce a decarbonised gas fuel comprised of N_2/H_2 is scheduled to take place from August to September 2022.

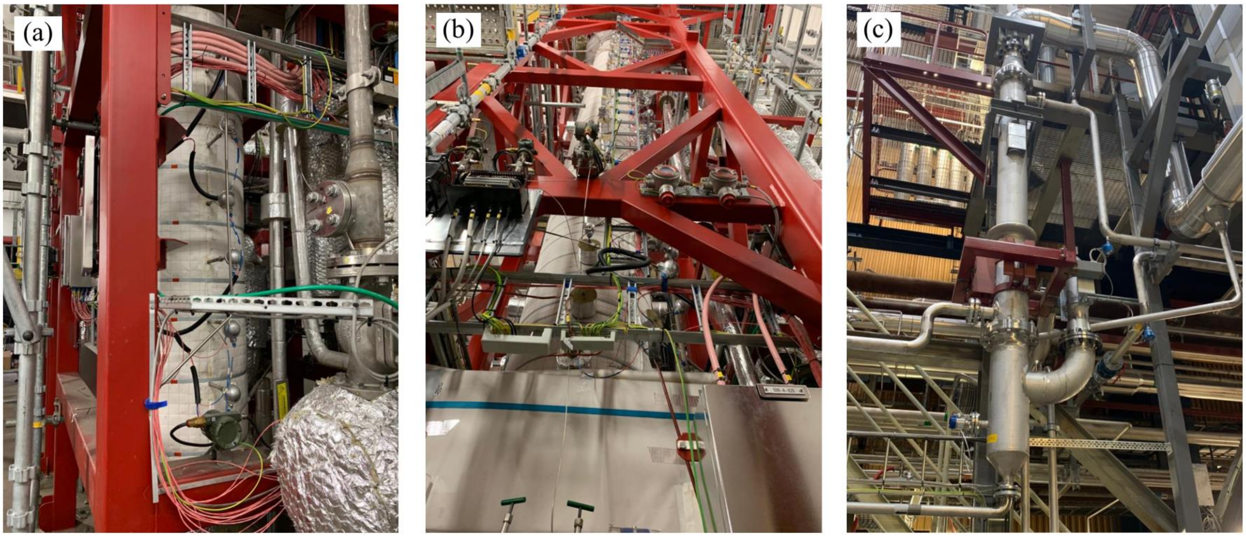

Fig. 5. DISPLACE CO_2 capture equipment: (a) WGS reactor for C^4U-SEWGS campaign; (b) single column DISPLACE capture unit; (c) syngas cooler.

2.2. Calcium Assisted Steel mill Off-gas Hydrogen (CASOH) process for blast furnace gas

The CASOH process is originated by the previously proposed Ca-Cu H_2 production process for power plant applications developed at lower TRL in the European Union FP7 funded project, Ascent [14,15]. A schematic example for BFG steel mill off-gases during 5 processing steps is given in Fig. 6. This is conceived as a combination of sorption enhanced reactions by CaO (to produce $CaCO_3$) and chemical looping combustion technologies in packed bed reactors, using CuO/Cu-based oxygen carrier materials, as these are the only oxygen carriers disclosing high exothermic enthalpies of reduction when reacting with fuel gases (that oxidise into CO_2 and H_2O and drive the decomposition of $CaCO_3$ to CaO during the sorbent regeneration stage). A sequence of three main reaction steps takes place involving air, steam and fuel gases following well established principles in other PSA/TSA processes and regenerative heat transfer processes, when it comes to the dynamic evolution of reaction and heat transfer fronts.

In the main CASOH step, a H_2-rich gas is obtained through a CaO-assisted WGS reaction of the CO contained in BFG, while CO_2 reacts with $CaO_{(s)}$ to form $CaCO_{3(s)}$; this process allows the conversion of up to 99% of the inlet CO to H_2 at intermediate temperature (650 °C), because the continuous removal of CO_2 in solid phase shifts the WGS thermodynamic equilibrium towards H_2. Following a heat removal stage using N_2, the Cu-based solid is subsequently converted to $CuO_{(s)}$ during the OXIDATION step with air maintaining moderate temperature to minimise the premature calcination of $CaCO_3$ (i.e., the CO_2 slip during this stage). The fourth stage (the REGENERATION step) involves the combination of endothermic reaction of calcination of $CaCO_{3(s)}$ and the exothermic gas-solid reduction of $CuO_{(s)}$ to $Cu_{(s)}$ using a gaseous fuel (e.g. CH_4, CO or H_2) producing a highly concentrated stream of CO_2 and $H_2O_{(v)}$. After the REGENERATION, the excess of heat accumulated in the reactor is blown out in a subsequent heat removal stage consisting of flowing N_2 through the bed at a suitable temperature to initiate a subsequent CASOH stage (i.e. 500-600 ºC). Then, N_2 is discharged at temperatures close to 850 ºC, cooled down to 500-600 ºC, and finally recirculated to the reactor in a closed loop. The heat recovered may be used to produce steam for the CASOH process, for power generation or to preheat gaseous feedstock.

Other patented processes (i.e. General Electric [16]) combine exothermic metal oxide redox reaction to provide the heat to drive the decomposition of $CaCO_3$ and regenerate the CaO without implementing CO_2 capture. Among common oxygen carriers, only CuO has the necessary exothermic reduction enthalpies with typical fuel gases (e.g. CO, H_2, CH_4) to sustain the CASOH process [15]. In the CASOH process, the sorbent regeneration step is the main innovation with respect to previous processes involving sorption enhanced reactions with CaO [17,18,19]. The large

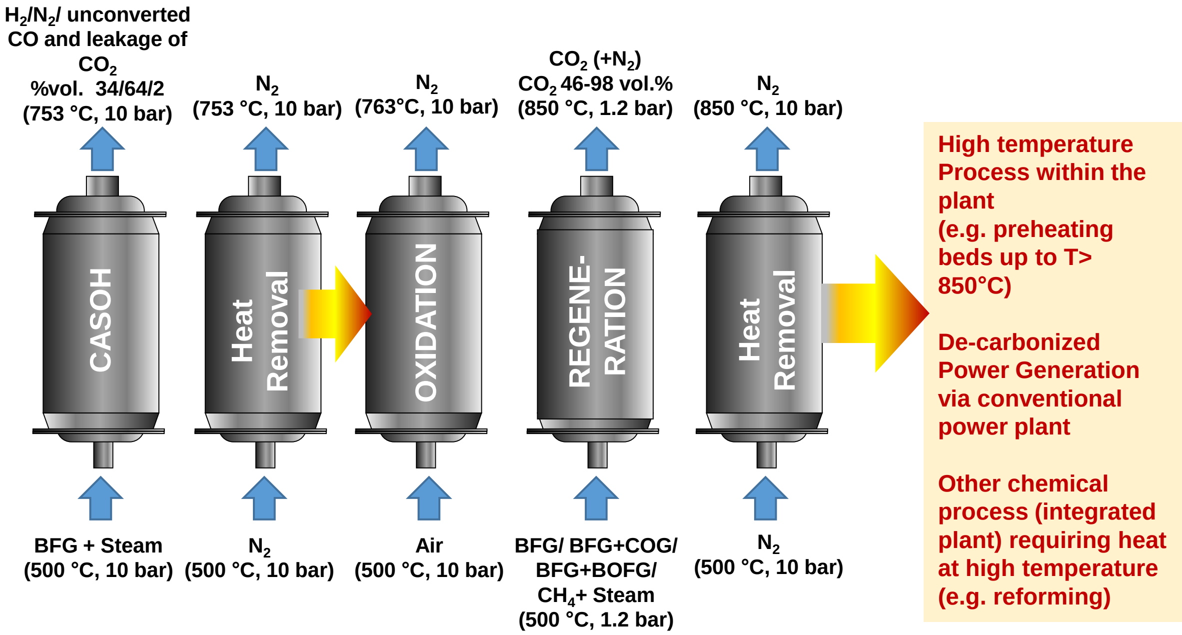

Fig. 6. CASOH scheme reaction network using BFG for both H_2/N_2 production and sorbent regeneration (other low N_2 content fuel gases such as NG, BOFG and COG can be used in the regeneration stage to further increase purity of CO_2).

energy supply needed for calcination is released *in-situ* by the reducing particles of the oxygen carrier, thereby avoiding the need for cryogenic O_2 or large heat-transfer surfaces at very high temperature. A certain Ca/Cu ratio ensures that the heat generated during the fuel gas combustion and CuO reduction is sufficient to decompose completely the calcium carbonate [20]. The novel CASOH process is developed in C^4U with high content of CO in steel mill off gases representing an early opportunity to validate the Ca-Cu packed bed reactor technology up to TRL7, because: i) the Cu-based oxygen carrier is also an excellent catalyst for WGS, facilitating the calcium enhanced reaction towards H_2 during the CASOH stage ii) the high temperature recovery (T>870 °C) from the CASOH process originated by the reduction of CuO with CO could reduce the thermal requirements of other steel mill processes. The process exhibits inherent high energy efficiencies and potential for high purity CO_2 [21].

The process flow diagram of the CASOH pilot is shown in Fig. 7 and the adoption of the design was justified to save on technical constraints on the need for high temperature valves while limiting the operating pressure. In addition to the packed-bed reactor, a gas electric preheater is included to facilitate the conditioning of the inlet gas and the bed of solids for each stage of the process. A water-cooled heat exchanger located downstream of the reactor will bring the product gases down to suitable temperatures for venting or for gas recycle, depending on the reaction stage. The flow diagram also comprises a compressor able to supply air up to 10 bar and two blowers to boost the pressure of the BFG and the recycled gas to around 1.5 bar at the entrance of the gas preheater. Finally, a switching valve set-up (designed to operate at any time at moderate temperatures) needed to synchronise the dynamic operation of the reactor in every stage, instruments (about 30 temperature points and about 10 ΔP probes to monitor axial temperature and pressure profiles) and two gas analysers (for CO_2, CO, CH_4, H_2, O_2) complete the set up.

The general overview of the 3D layout of the pilot components is presented in Fig. 8(a). The pilot is located at ArcerlorMittal Asturias GasLab site in Aviles, Spain, being adjacent to a steel mill that is the source of real industrial process gases on which the technology will be demonstrated at an inspiring scale. The pilot process fits well within the site's space and service-supply constraints. A sufficient 3D design of the reactor was completed to allow the tendering and manufacturing process. The bottom of the reactor is non-standard and has an initial bed of inert material

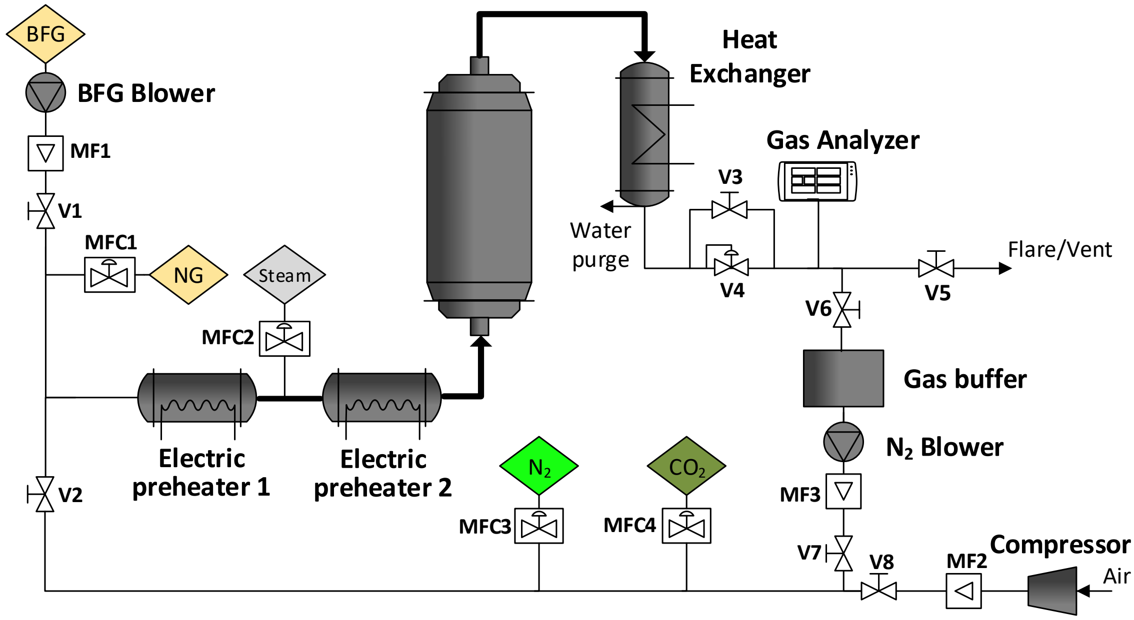

Fig. 7. Simplified process flow diagram of the CASOH pilot.

to distribute gas to the active part of the bed. The top of the reactor is the main access point for instrumentation. The first section of the gas cooler was also designed here. Evacuated gases from the pilot process are burnt in a flare. A photograph of the reactor built on the basis of the design studies and ready for installation is shown in Fig. 8(b). The first experimental results at TRL7 are expected in December 2022. Future scale-up studies by the end of the project will be based on the TRL7 results. In parallel work, extensive testing at lab-scale of selected functional materials for the pilot has been completed, accumulating several thousand cycles in different experimental set-ups at Consejo Superior de Investigaciones Científicas (CSIC) and the University of Manchester for both carbonation-calcination

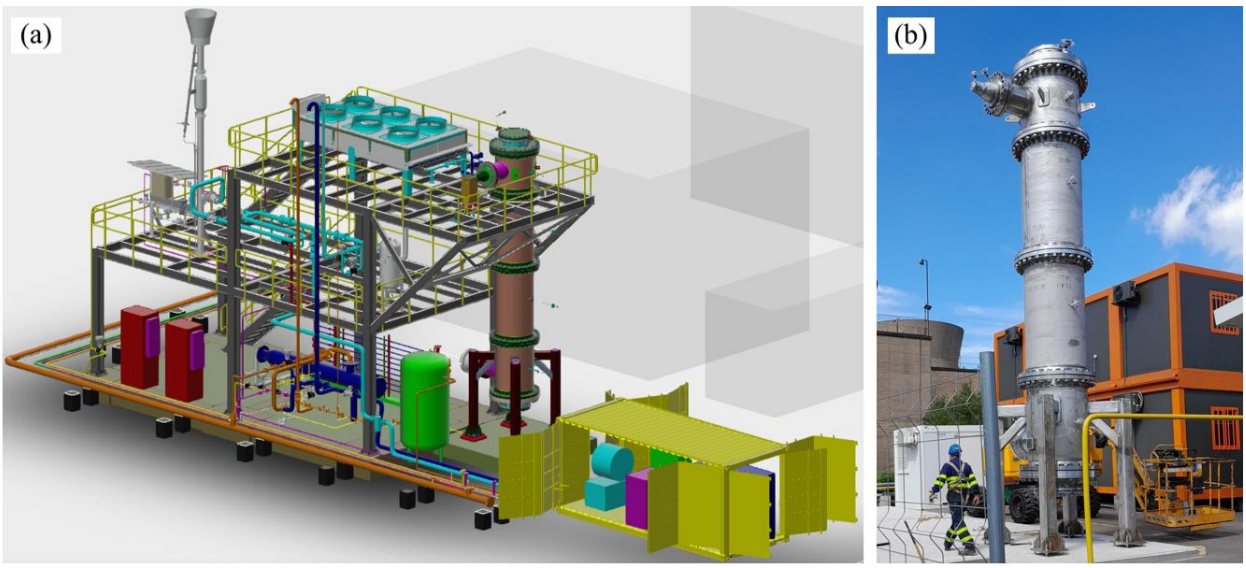

Fig. 8. The main CASOH pilot components: (a) 3D layout of the pilot; (b) the CASOH reactor for TRL7 demonstration.

reactions of Ca-materials supplied by Carmeuse and oxidation-reduction reactions of the Cu-materials supplied by Johnson Matthey. These tests aim to reproduce at lab-scale the cyclic reaction conditions expected for the materials in the pilot. This information is useful for tuning reactor models, anticipate pilot behaviour during experiments and adopt design decisions regarding the future control of the pilot. The University of Manchester has performed experimental campaigns at the largest reactor used so far (TRL4) for the combined beds of Ca-Cu material (see reference [22] for further details). The results confirm that it is viable to convert BFG compositions into a H_2/N_2 gas stream (H_2/N_2: 17%/82%, less than 1% unconverted CO and leakage of CO_2), while carbonating CaO to $CaCO_3$. After a mild oxidation step of Cu to CuO, the CuO reduction clearly promotes $CaCO_3$ calcination at temperatures higher than 850 °C. As such, these are promising results for the TRL7 demonstration of the CASOH process. In addition, 1D Dynamic reactor model for packed beds have confirmed the process viability with known materials and operating conditions [23].

3. C^{4}U capture technology performance and integration in steel plants

The C^{4}U capture processes are being designed at full-scale according to the operating conditions in a case study steel plant and the results obtained from the demonstration at TRL7. For the capture process and actual integration within the integrated steelwork, different options are considered including very different gas sources as represented schematically in Fig.9.

The specific cases considered for technology integration in C^{4}U are:

- DISPLACE base case: This is the case of decarbonised flue gas from oxyfired re-heating ovens in accordance with the demonstration activity for DISPLACE; CO_2 emissions from re-heating ovens are around 5% of the total CO_2 emissions from a primary steelworks (source 1 in Fig. 9). This is an early opportunity for CO_2 capture because pure O_2 is available in the primary steelworks.
- DISPLACE multiple sources: In this case the combination of possible CO_2 sources is considered to explore the full potential of the DISPLACE technology targeting the maximum CO_2 capture rate. The DISPLACE approach is designed to operate any combination of the CO_2 sources mentioned above (sources 1,2,3 in Fig. 9) with an overall CO_2 separation rate of 35% of the current CO_2 emissions from the steelworks.

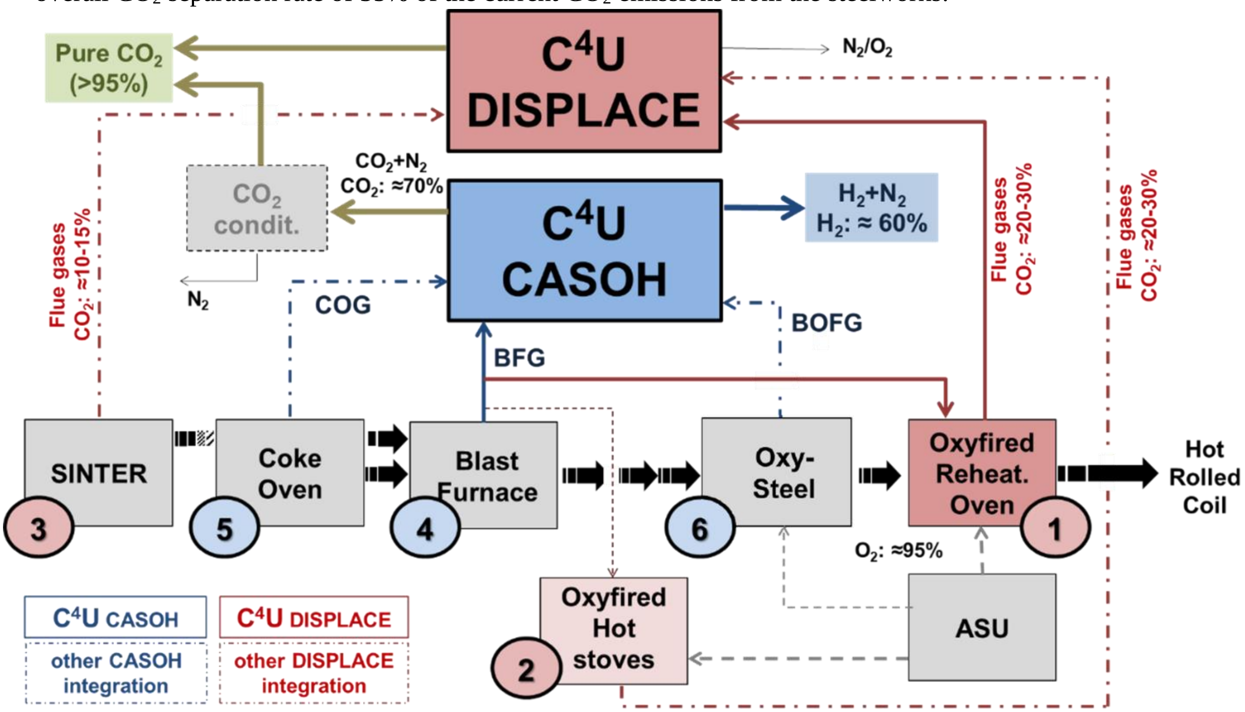

Fig. 9. Block flow diagram of main production units in a steel mill integrated with C^{4}U CO_2 capture technologies.

- DISPLACE for producing decarbonised H_2: In this case, previous research carried out in the STEPWISE project is updated according to the performance of the CO_2 purification unit. This case is complementary to other research in the project because H_2 utilisation within a cluster is considered for the CASOH process;
- CASOH base case: In this is case, only BFG is used as a feedstock according to the results of the CASOH pilot demonstration at TRL7;
- CASOH multiple sources: In this case multiple fuel gases (sources 4,5,6 in Fig.9) will be considered to achieve the full potential of the steel mill decarbonisation using the CASOH process;
- CASOH high CO_2 purity: This is the case where NG will be used in the regeneration step to produce high purity CO_2 (>95%) so that the CO_2 at the regeneration stage is directly suitable for the final utilisation and/or storage (i.e. with minimum CO_2 conditioning other than water condensation before compression).

Advanced process modelling is used to design the C^4U technologies at industrial scale for assessment of the optimal energy and costs of the integrated process in the steelwork plant operation. All the above configurations will be compared with the reference case benchmark technologies based on solvent CO_2 absorption for both post-combustion capture and pre-combustion capture.

For comparison of the C^4U approach to state-of-the-art technologies, reference cases for pre-combustion CO_2 capture from BFG using methyl diethanolamine (MDEA) were simulated and their KPIs calculated. 5 types of KPIs were analysed: 1) CO_2 capture rate (%) – the amount of carbon (CO + CO_2) separated with respect to that generated; 2) Specific Primary Energy Consumption for CO_2 Avoided (SPECCA, MJ/kg_{CO2}) – the amount of primary energy required to separate 1 kg of CO_2; 3) Levelised Cost of Decarbonised Fuel (LCoDF, €/GJ) – defines the cost of producing a H_2 (+ CO) rich stream related using a calculated value for the Total Annualised cost; 4) Cost of CO_2 Avoided (CCA, €/t_{CO2}) – uses the LCoDF to define the incremental cost of capturing 1 tonne of CO_2; and 5) increase in the cost of Hot Rolled Coil (€/t_{HRC}) due to the application of carbon capture. The basis of the calculation uses an industrially defined BFG composition (CO_2 – 21 mol%, CO – 22.7 mol%, H_2 – 2.4 mol%, N_2 - 53.5 mol%, C_2H_4 – 0.2 mol%) and a defined flowrate (125.1 kg/s) that is typical for a usual sized steel mill (3.16 Mt-steel/yr). The first reference case considers MDEA solvent for pre-combustion capture from BFG to produce an H_2 rich gas stream along with a separate CO_2 product. The CO_2 content in BFG is separated in an absorber unit to produce decarbonised fuel

Table 2. Techno-economic performance of the MDEA pre-combustion capture plants for BFG coupled with CCGT power generation [24].

		No capture	MDEA	WGS + MDEA
Steel mill size	[Mt_{HRC}/y]	3.16	3.16	3.16
Thermal input	[MW]	294.7	294.7	294.7
Net electrical output	[MW]	146.96	110.58	71.54
Net electrical efficiency	[%]	49.9	37.5	24.3
CO_2 specific emissions	[kg_{CO2}/MWh]	1941.6	1391.5	675.1
CO_2 capture avoidance	[%]	-	28.3	65.2
SPECCA	[MJ_{LHV}/kg_{CO2}]	-	4.32	6.01
Total direct plant cost	[M€]	165.08	278.99	346.43
Total plant cost	[M€]	218.32	368.96	458.15
Annualised plant cost	[M€/yr]	24.89	42.06	52.23
Total annualised cost	[M€/yr]	81.47	106.18	126.48
LCoDF*	[€/GJ]	5.20	9.73	14.78
LCoE	[€/MWh]	70.32	121.79	224.26
Electricity cost	[M€/yr]	-	14.34	29.73
Δcost of HRC	[€/t_{HRC}]	-	12.36	23.65
CO_2 avoidance cost	[€/t_{CO2}]	-	93.57	121.55

*Indicates costs related to capture only containing mostly CO, H_2 and a small amount of ethylene as fuel components. The CO_2 rich solvent is passed to a desorption regeneration unit where CO_2 comes out of solution through heating and the lean solvent is sent back to the absorber. A second "enhanced" case, incorporates a high-temperature WGS reactor prior to the MDEA absorption and regeneration units, in which CO is converted into CO_2 and H_2 by reaction with steam, thereby resulting in a significantly higher H_2 concentration of around 25% in the decarbonised gas stream [24], with also some residual CO due to incomplete conversion (~6.3 mol%) and unseparated CO_2 (~2.2 mol%). The techno-economic performances of these cases is assessed while integrating the decarbonised BFG for use in efficient power-generation using a Combined Cycle Gas Turbine (CCGT) which incorporates a 3 pressure level steam cycle in which heat is transferred from the gas turbine exhaust gases. These cases are compared to the no-capture case, as shown in table 2.

The performance comparison for decarbonised BFG power generation in Table 2 shows CO_2 avoidance of 28.3 % and 65.2 % for MDEA and WGS + MDEA cases, respectively. The net electrical efficiency drops from the no capture value of 49.9 % to 37.5 % and 24.3 % for MDEA and WGS + MDEA cases, respectively. There are also CO_2 specific emissions that are representative of the CO_2 capture avoidance which reach 42.6 % and 80.8 % maximum. The SPECCA in the enhanced case is about 6.01 MJ/kg_{CO2} capture while it is slightly lower at 4.32 MJ/kg_{CO2} for the MDEA case. In terms of economics, the LCoDF which only accounts for capture and does not consider transport and storage, based on an initial cost of 5.2 €/GJ, an increase in this cost goes to almost double for the MDEA only case and just under a factor 3 higher for the case of WGS + MDEA. The analysis resulted in SPECCA which is still high either 4.32 or 6.01 MJ_{LHV}/kg_{CO2} the CO_2 avoidance cost is ~90 to 120 €/t_{CO2} for the respective MDEA only and WGS + MDEA cases.

TNO has performed DISPLACE operation modelling for separating CO_2 from oxy-fired BFG (i.e. separating CO_2 from N_2 + O_2) with system optimisation under high carbon capture rate and purity, and low steam consumption constraints. Some work related to DISPLACE feed composition supports the pilot capture campaigns. Isobaric operation vs small-blowdown, column dimensions, feed flow rates and cycle timing are variables for the study. The model is adapted for DISPLACE and C^4U-SEWGS operation. This model is based on characteristics of hydrotalcites derived from mixed oxide sorbents with a variety of adsorption sites. It is an interaction model which works with typical Langmuir interaction/competitive, interaction/exchange and interaction/pore condensation. Only steam and CO_2 can be adsorbed/desorbed onto the sorbent while inert gases cannot, which is important for modelling the cycle behaviour [25]. Compositional constraints are based on matrices for oxy-fired BFG, with O_2 excess for combustion resulting in an O_2 concentrations of 1 and 0.7 vol% for the oxy-fired BFG flue gas. NO_X (NO + NO_2) concentrations of 1000 ppm_v are based on a rough estimation of thermal NO_X produced while SO_2 concentration is based on the sulfur content of the BFG (25 – 30 ppm_v). The capture rate is assumed to be >90% while purity is assumed to be high (>95%) and steam consumption low. The working capacity ratio for H_2O / CO_2 has been calculated as a function of isobaric pressure and a range of concentrations of steam in purge and feed. For the desorption case using steam as a purge gas, the impact in low isobaric pressure regions is large where high values of working capacity ratio for H_2O / CO_2 mean more steam is needed to recover CO_2. Feed saturation variation has a lower impact on the variation of the working capacity ratio.

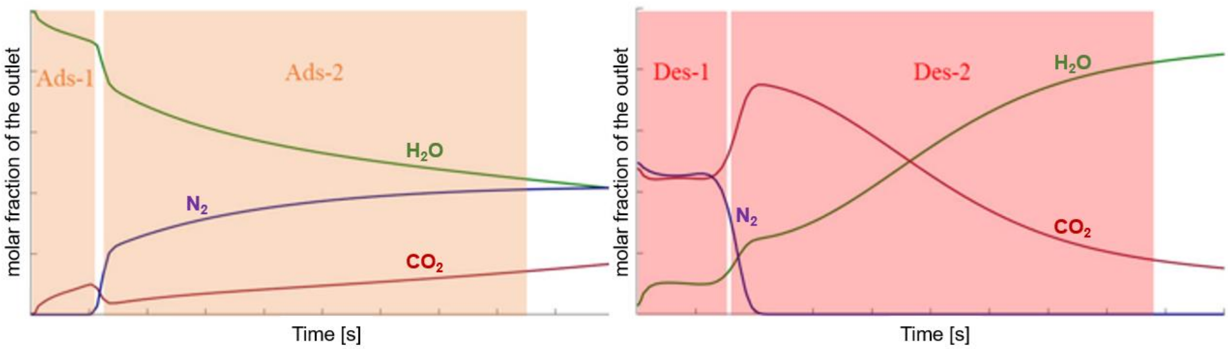

Fig. 10. Representative examples of the DISPLACE column outlet profiles for adsorption (left) and desorption (right).

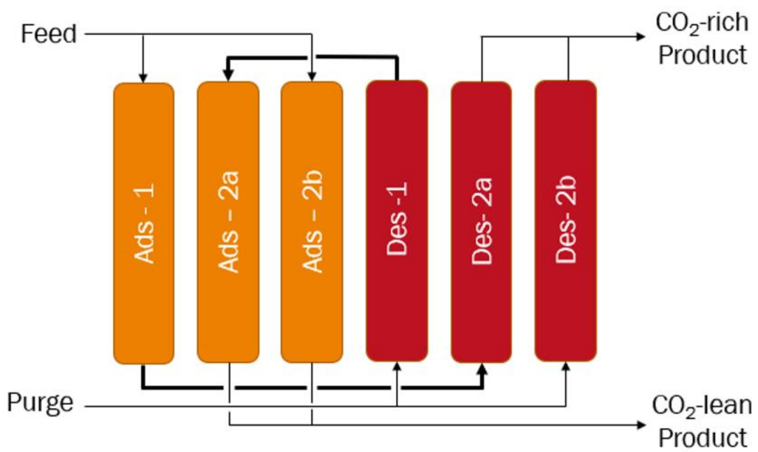

Fig. 11. Example of a DISPLACE column outlet profiles for adsorption (left) and desorption (right).

The DISPLACE cycle design is based on the outlet concentration where columns are fed co-current during adsorption and counter-current during desorption. This change of direction allows for deeper cleaning of the end of the bed, where a cleaner end of bed leads to higher carbon capture rate and purity of the CO_2-lean product. Desorption zones can be split further to improve recovery as illustrated in Fig. 10 which shows the time-dependent evolution of component fractions at the column outlet during adsorption and desorption steps. The first section of the outlet Ads-1 (at near pure H_2O) and Des-1 (at feed composition) represents gas in the void fractions of the column and are useful for recycling. Preliminary designs of the DISPLACE process using a 6 step approach have been assessed, as exemplified in Fig. 11 for the cycle with 6 columns where at any given time 3 columns are in the absorption steps and 3 columns which are in the desorption steps. High steam content in the adsorption-1 zone is useful for recycle with still high steam content in the outlet which can be fed to the adsorption step 2, where the outlet of desorption zone 2 can be recycled to the adsorption step. Other cycle designs are possible such as 5 or 7 step designs. More recycling leads to higher productivity but increased system complexity. With the 6 column approach, Fig. 12 shows the preliminary performance. A full-scale DISPLACE unit, in a real steel plant would result in 6 columns and 8 trains. An initial assessment was performed through incrementally changing the pressure of the feed from 5 bar to 10 bar while maintaining the steam / carbon ratio constant but with the column diameter of the vessel incrementally reduced. Fig. 12 shows that while keeping constant OPEX in terms of steam consumption while CAPEX for the column diameter can be reduced while keeping the constraints on CO_2 purity and capture rate. Sensitivity analysis will assess the impact of system pressure and steam / carbon ratio on the performance. Several optimisation options are available

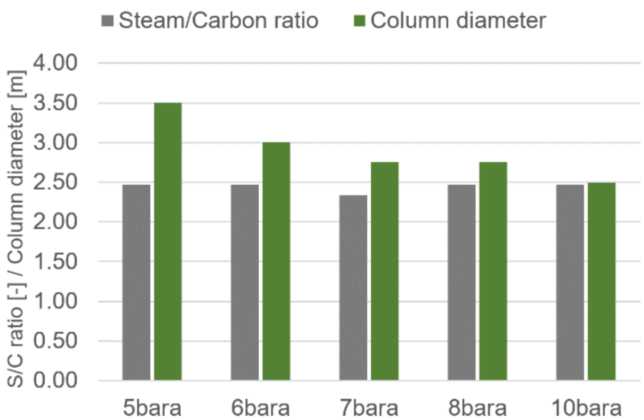

Fig. 12. DISPLACE steam demand and column diameter for different operating pressures at similar CO_2 purity and capture ratio.

Table 3. CASOH CO_2 capture modelling conditions.

Process conditions	**Values**				
Sorbent composition	100% CaO (max. conversion 10%)				
Oxygen carrier composition	30 wt% of Cu-based particles on SiO_2				
Bed composition	60 wt% sorbent + 40 wt% oxygen carrier, overall 275 ton				
Conditions	**CASOH stage**	**HR-1**	**Oxidation**	**Regeneration**	**HR-2**
Initial bed temperature, °C	500	754 / 500	500	763/500	850/800
Pressure, bar	10	10	10	1.2	10
Steam to CO ratio (S/CO)	1.2	-	-	1.2	-
Inlet gas temperature, °C	500	500	500	500	500
Feed flowrate, Nm^3/s	BFG: 15.51	156.9	23.3	BFG: 35.5; H_2O: 10.3	179.3
	H_2O:4.5			COG + BFG: 34: H_2O: 8.4	
				BOFG + BFG: 31; H_2O: 9.5	
				CH_4: 16.6	
Cycle time, s	900	1800	900	900	1800

(operating pressure, steam/ carbon ratio, column diameter) and future results of these will be transferred to the design and preliminary costing of the capture section to identify the most suitable operating regions of this process. The outlook for the DISPLACE modelling activities is to update the model at low pressure and validate the isobaric model with the experimental campaign. The model will also be updated for void space contribution and dispersion effects with selected cycles rerun with the updated model.

A 1-D heterogeneous reactor model of the CASOH process accounting for the mass transfer in gas phase, mass transfer in solid phase, energy balance across the reactor system and reaction kinetics was developed using MATLAB. In this model, it is assumed that; (a) the heat losses are neglected given that the reactor has a large diameter and the system is adequately insulated. (b) The concentration and temperature gradients along the radial direction are negligible, and (c) the size of the catalyst and sorbent are uniform and the porosity of the bed is constant. The model is used to simulate a system representative of large-scale which cycles over the CASOH stages illustrated in Fig. 6 and to develop the heat management strategy of the process. The initial operating conditions for each stage in the model are listed in Table 3.

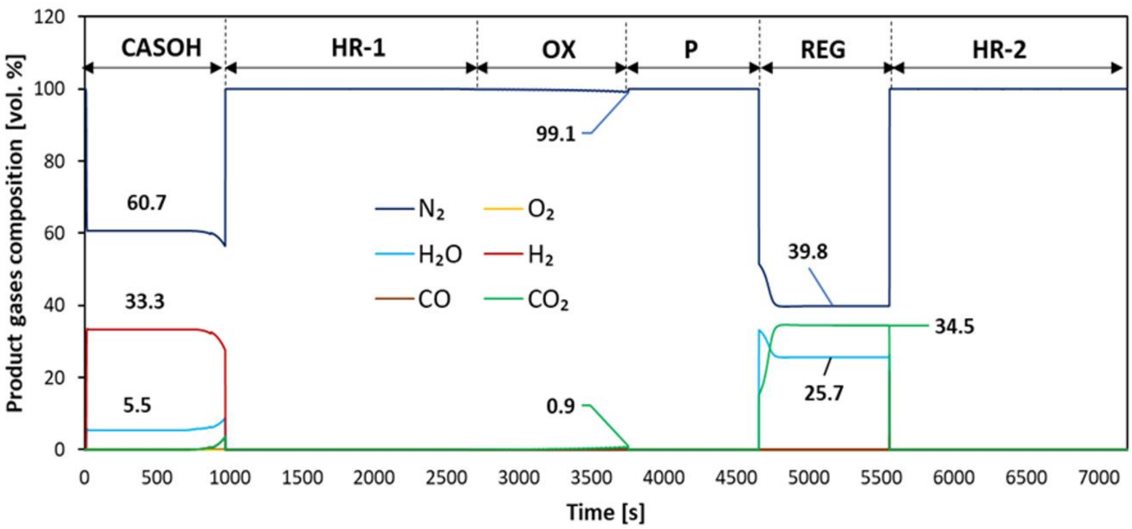

Fig. 13. Simulated gas composition profile during the consecutive stage of CASOH, oxidation, regeneration and in between heat removal [23].

Table 4. Summary of main performance results of the CASOH and regeneration stages

Conditions	Case 1	Case 2		Case 3
	BFG	BFG / BOFG / COG		NG
CASOH stage				
H_2-rich flow, Nm^3/s	13.3	17.6		40.1
Regeneration stage		BFG / BOFG	BFG/COG	
N_2 / CO_2 flow, Nm^3/s [dry basis]	32.96	30.3	34.9	33.2
N_2 / CH_4 / CO_2, Nm^3/s [dry basis]	53.6 / 0 / 46.4	48.1 / 0 / 51.9	42 / 0 / 58	0 / 2 / 98
Thermal output, H_2 / N_2 [$MW_{LHV,H2\text{-}rich}$]	48.3	64.1		145
Cold gas efficiency [%]	27.2	23.1 /18.5		19.0
Energy efficiency [%]	75.3	79.5		88
Primary energy efficiency [%]	71.1	77.6		90

The gas compositions (vol. %) at the outlet of reactor during each stage are shown in Fig. 13. During the CASOH stage, complete conversion of CO is achieved and only 0.45% of CO_2 is released at the outlet of the reactor. This stage involves the production of H_2-rich stream (34% H_2 and 60% N_2). The CO_2 captured in the CASOH stage is released during the regeneration stage when the CaO-based sorbent is regenerated by in situ by calcination of $CaCO_3$ when burning a fuel gas containing CO and H2 with the oxygen contained in CuO (ΔH298K = -126.9 kJ/molCO, ΔH298 K = −85.8 kJ/molH_2). In this case where BFG is used as the inlet regenerative gas, the outlet gas is rich in CO_2 (34% CO_2 and 40% N_2), making an additional capture step (i.e. DISPLACE within the C4U project) or a larger compression and separation unit (CPU) downstream necessary to finally dispatch high purity CO_2 for permanent storage or chemical synthesis. In the CASOH process, two different heat recovery units are considered to distinguish the quality of the heat. High-temperature heat (i.e., in the range from 500 to 850 °C) can be used to supply heat directly to some point of the steel mill, thereby reducing the energy demand of the integrated steelworks, as well as for the production of high-pressure steam for power generation. On the other hand, intermediate-temperature heat (i.e., between 200 and 500 °C), which is mainly obtained from the cooling of product gases, can be used to preheat gaseous feedstock, to produce steam required in the CASOH process and to produce additional intermediate-pressure (IP) steam for thermal and electricity generation.

The overall process performance of the CASOH stages discussed above are summarised in Table 4. For the BFG case 1, the process uses a thermal input of 175 MW based on a lower heating value. Thermal output from the process contained in the hydrogen stream from CASOH is ~48.3 MW. Cold gas efficiency is ~27.2%. In consideration of the recovery of high temperature heat, primary energy efficiency is 71.3%, which results by some heat not being recovered with higher efficiency. The results in table 4 include also different ways to operate the regeneration using three different options; 1) BFG only; 2) BFG / BOFG / COG mixtures, with 2 sub-options: (a) BFG / BOFG mixture or (b) BFG / COG mixture; and 3) Natural Gas (NG). These different regeneration gas mixtures have an impact on the CO_2 purity output from the regeneration stage and hence impact the additional costs for further separation and purification downstream of the CASOH unit. Different temperature profiles inside the bed result depending on which regenerative fuel is used as shown in Fig. 14. Estimates of cold gas efficiency indicate the increase in energy consumption when fuels with higher thermal content are used for regeneration.

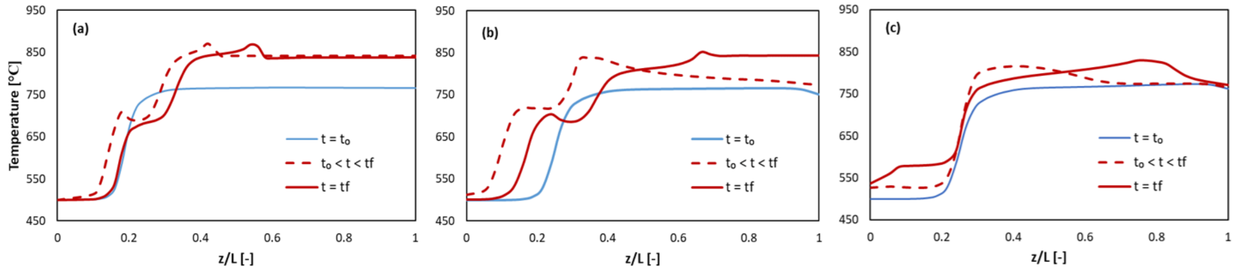

Fig. 14. Evolution of the temperature profiles during the regeneration stage for different regenerative gas mixtures: (a) BFG only; (b) BFG/BOFG/COG; (c) natural gas.

4. Whole system integration: industrial CCUS cluster operation and logistics

In C^4U, the decarbonisation of an entire CCUS industrial cluster is investigated, evaluating performance metrics (economics, energetics, safety and environmental impacts) by considering:

- how to best integrate capture technologies into industrial CCUS clusters at minimum cost and energy penalty;
- how to optimise operation of the CO_2 pipeline transport network and define the CO_2 purity tolerance levels for the different parts of the transport chain given temporal variations in flow rates and quality of CO_2 at emission sources;
- what level of industrial decarbonisation through CCUS will be required to meet the 2050 targets.

Despite significant progress in modelling and planning of CO_2 pipeline networks [26-28] the successful integration of the capture technologies into a CCUS cluster poses challenges due to the lack of reliable optimal solution tools to enable cost-efficient design and operation of a cluster, and managing CO_2 streams of various purity to meet operational and safety constraints for pipeline transport and geological storage [29]. An essential prerequisite in meeting the above objective is the accurate knowledge of the CO_2 flow rate, fluid phase and composition at any point and time along the connecting pipeline network, including the point of injection into the storage site. Transient flow models have been developed to simulate flow dynamics but these are limited to single CO_2 pipelines [30]. Extension of existing steady-state network flow models [26] to transient models capable of predicting the network operation dynamics upon variations in CO_2 stream compositions and flow rates from connected emitters has not been addressed so far.

The work in C^4U involves the development of a rigorous multisource CO_2 pipeline network fluid flow model for case study application to the North Sea Port CCUS industrial cluster connecting the ArcelorMittal steel plant in Ghent and other industrial emitter along its route in the North Sea Port to Terneuzen for ultimate storage in depleted gas fields off the Dutch coast. A key requirement for the above integrated CCUS cluster design is ensuring that the operational envelope respects transport and storage CO_2 quality constraints that are necessary to prevent/ minimise (1) corrosion of pipeline transportation materials, (2) potential pipeline blockages during rapid depressurisation and avoiding two-phase flows, (3) risks of ductile and brittle fracture propagation, and (4) limiting the amount of impurities affecting the CO_2 injection/storage operation, e.g., nitrogen to preserve storage capacity, oxygen - to avoid biofouling, and sulfur compounds on corrosion and health and safety grounds.

Given the enormous computational workload needed to undertake the techno-economic evaluation for an industrial CCUS cluster, the above constraints are described using computationally efficient Reduced-Order Models (ROMs). The ability to mix streams in a shared pipeline allows these constraints to be taken into account at various points in the network and where issues may arise (e.g. at a mixing point or even at an injection point), to propagate it upstream until the ideal location for an intervention (e.g. additional purification stage) is found. This work is spatially explicit, i.e., the layout and nature of the existing cluster is taken into account, comparing its decarbonisation and the distinct design and layout that would correspond to the least cost design of a CCS-ready cluster. Options for the subsequent expansion of the industrial cluster are examined by inclusion of additional sources of CO_2 to match the level of industrial decarbonisation needed to meet the 2050 targets.

To support this work, experimental campaigns on CO_2 pipeline decompression at medium- and large-scale are performed at INERIS and Dalian University of Technology (DUT), respectively, for pure CO_2 and CO_2 mixed with impurities expected from CCS in non-trace amounts to observe their impact on flow and phase-transition behaviour. The information obtained from tests is used for validation of transient CO_2 flow models in a wide range of conditions that examine the possibilities of solid formation in CO_2 pipelines and will enable the provision of recommendations with respect to potentially hazardous situations, in addition to guiding the scope of purification of CO_2 streams or operation of venting scenarios.

INERIS has completed experimental campaigns using CO_2 pipeline containing impurities. Ten tests were performed for depressurisation in a medium-scale pipeline test facility that was upgraded with instrumentation. Measurements of pressure and temperature were performed along with the set-up of a transparent section in the pipeline to observe three-phase flow at incremental times during depressurisation. A comprehensive analysis of these results is underway.

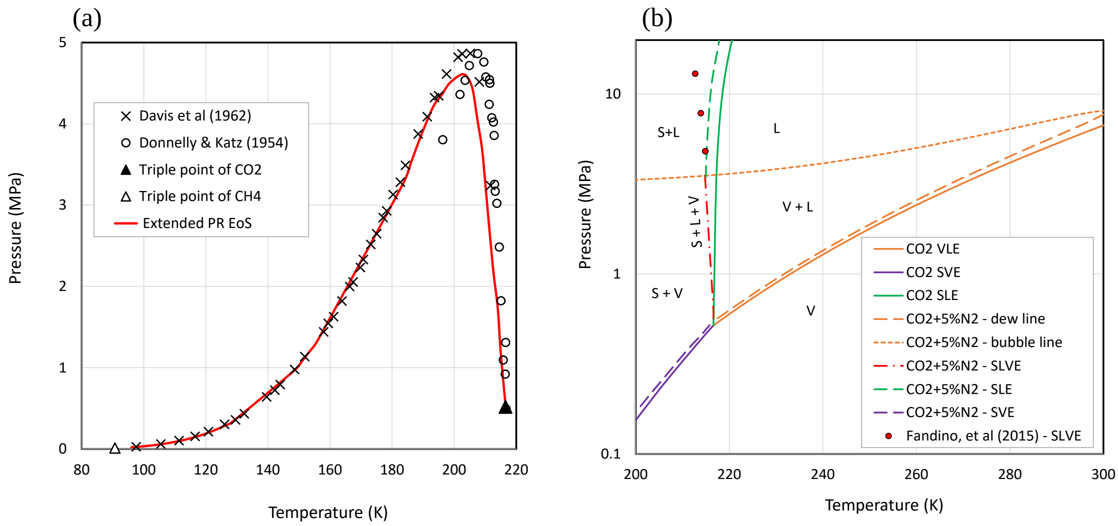

Fig. 15. P-T phase diagrams for CO_2 binary mixtures with impurities [31]: (a) Solid-Liquid-Vapour Equilibria (SLVE) locus for CO_2 + CH_4 system; (b) impact of CO_2 dilution by 5% N_2 on the predicted phase transition boundaries (V – vapour, L – liquid, S - solid).

Tests for pure CO_2 venting scenarios with prolonged duration at large-scale are being performed by DUT [32]. Detailed measurements of pressure and temperature at the different locations inside an instrumented experimental vent section at the end of the pipeline were recorded. Analysis was performed with respect to the impact of the vent configuration on the transition behaviour decrease. With respect to hazard analysis, the minimum temperature that is achieved during depressurisation and its correspondence with associated phase transition (i.e. dry ice formation during) is of prime importance.

To enable calculation of thermodynamic properties of multiphase CO_2 mixtures involving solid phase when simulating the CO_2 pipeline decompression, an extended Peng-Robinson equation of state (EoS) resolving Solid-Liquid Equilibria (SVE) for pure CO_2 was combined with dedicated EoS predicting the Vapour-Liquid Equilibria (VLE) for CO_2 mixtures with non-condensable gases. The Solid-Liquid-Vapour Equilibria (SLVE) and freezing point in impure CO_2 were predicted using established thermodynamics approach, validated against experimental data available for a mixture of CO_2 + CH_4 (Fig. 15(a)). Fig. 15(b) gives an example of the phase boundaries predicted using the developed mode for a mixture of CO_2 with 5% N_2.

For the project's CCUS cluster whole-system modelling and operational logistics work with the aim of evaluating the potential for CO_2 capture technologies in reducing the cost of decarbonisation in an industrial cluster, progress was made on collecting the relevant data and identifying conditions for CO_2 capture and transport within the North Sea Port area. A literature review of the publicly available information on the industries within the cluster region and their current decarbonisation plans was undertaken [34]. The information reviewed included the locations of the major emitters in the North Sea Port along with the locations of current material transport routes by pipeline and ship as shown in Fig. 16(a). Information about the transient operation of the emitting industries in the North Sea port region is required for studies of the operability of the cluster in terms of transport and storage infrastructure design, optimal scheduling and the optimisation of the operation of such a network. In this regard, data from the emission registers about the amounts of CO_2 emitted during the past by major industries in the region was collected, including total CO_2 emitted in the region, and their temporal variation at a resolution of a single year (as shown in Fig. 16(b)) or higher in some cases. Information was also collected on operating schedules for the various regional industries for anticipation of fluctuations of CO_2 emissions in terms of their amplitude and frequency. Fluctuations of industrial CO_2 emissions may also be anticipated through correlation with general economic indicators like GDP.

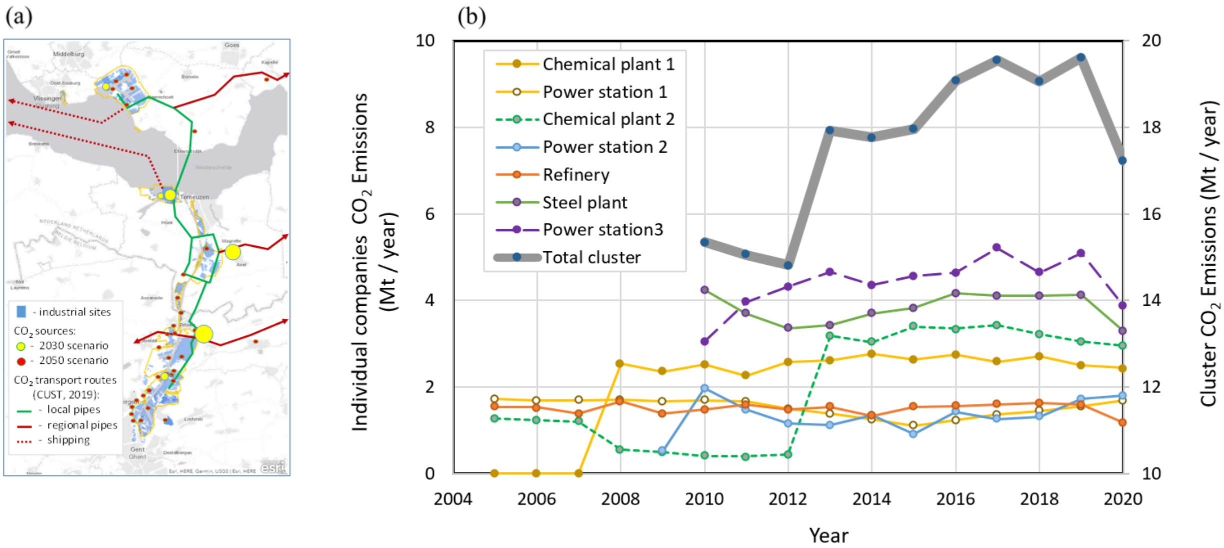

Fig. 16. Characterisation of the North Sea Port industrial cluster: (a) map showing locations of CO_2 emission sources and transport routes by pipeline and shipping [33]; (b) historical CO_2 emission rates for individual emitters and total industrial cluster.

Descriptions of two major scenarios for the cluster based studies in C[4]U are based around assumptions, formulated for each element of the CCUS chain (i.e. purification, transport, compression, storage and utilisation) including lists of emitters who form the composition of the cluster by 2030 and as the cluster expands to the 2050 scenario while adopting C[4]U technologies in the steel plant. This information will provide input to the network optimisation studies and it will also be used to perform the studies on CO_2 storage along with the information about impurities contained in the cumulative stream captured from industries in cluster [35].

5. Societal readiness for CCUS in industrial clusters

Societal readiness is a concept under development that has not been discussed much in the literature for CCS or CCU technologies. The C[4]U project conceptualises societal readiness as including business models, support by stakeholders and end-users, and incorporating the socio-political dynamics. The technical demonstration in C[4]U is therefore balanced with integrated and solution-focused societal readiness research. In both Belgium and the Netherlands, there is a hot debate about what policy instruments are needed to achieve deep emission reductions in industry, and whether CCS is a necessity (CCU receives less commentary). Literature has been indicating that mixes of policy instruments are preferred over the neo-classical economics mantra of one problem – one instrument. C[4]U adopts this notion of policy mixes and work with stakeholders using social-science based methods towards a suitable mix that would work for the North Sea Port CCUS industrial cluster and potentially for other industrial clusters. To investigate conditions for public support for CCUS, we are co-creating engaging narratives for environmentally benign capture technologies and approaches, testing them using system dynamic, with stakeholders around the industrial clusters where our capture technologies are prospective for implementation. Along with the work on business model innovation (described below in section 6), this forms the basis of a policy analysis, leading to recommendations of how CCUS in industrial clusters around steel mills can be effectively incentivised, in-line with business and stakeholder needs. The specific objectives for assessing societal readiness and policy for the North Sea Port Industrial CCUS Cluster in C[4]U are:

- To help understand and improve societal readiness for CCUS in the North Sea Port, and gain insight into the social and political dynamics and performance of CCUS, through system dynamics narrative development in consultation with end-users and local stakeholders;

- To identify and evaluate potential policy instruments for implementation of CCUS in steel plants in industrial clusters as well as governance arrangements, to arrive at an overall assessment of societal readiness.

Social science methods that are used include interviews, focus groups and systems dynamics modelling. These methods are most suitable to investigate the concerns and needs of stakeholders as well as socio-political dynamics when implementing CCUS in industrial clusters, which are always part of a specific context. In the case of C^4U, this context includes a border area with the various socio-economic challenges that tend to generate. Given the actuality of the policy debate on deep emission reductions in industry in both Belgium and the Netherlands, the project assesses policy instrumentation of the industrial system transition, including CCUS, and takes into account the specifics of industrial clusters as well as business models and realities.

During C^4U, Swennenhuis et al. [36] compared impacts of different low-emission technologies for routes to a sustainable steel industry, including CCUS, bio-based and hydrogen-based steelmaking, on society. The study provided a novel conceptualisation of justness for sustainability transitions which is briefly summarised in Table 5. The table shows different dimensions of recognised justness, (e.g. distributional, procedural, restorative etc.) on different aspects such as labour, which is prominent in justness discussions, but also very different aspects to it, like the environment, climate, energy and others. The framework is then applied to the different routes to a sustainable steel industry; i.e., comparing CCUS application to biomass- and hydrogen-based steel production. Here, the research question focuses on whether any of these pathways perform better in terms of justness as compared to each other, thus augmenting the techno-economic comparisons of these different pathways. Making the comparison based only on justice aspects, the study found that impacts on society differ between the different sustainable steelmaking routes, and vary between people or communities in different places. None of the pathways significantly out-perform each other in terms of overall justness but show trade-offs between the different types of justness. For example, hydrogen-based steelmaking can help deal with environmental pollution, but might trigger industry to relocate nearer and cause local employees to lose their jobs. Communities or biodiversity at locations will be impacted by the green electricity production methods for generating hydrogen. Advantages of CCUS belong to the local communities and the labour perspective due to the impacts on job retention. Therefore, it is important to consider societal aspects, and account for the local context of both the communities around the steel plant and those of suppliers.

In system dynamics studies for CCUS, interviews with around 10 NGOs, government, industrial sector and union representatives with stakes in development of CCUS in the North Sea Port. Interviewees are asked about their personal perspectives of CCUS in the sustainability transition, enablers for and barriers to implementation, stakeholder interaction and societal aspects of CCUS. The diagram showing interrelation of enablers and barriers to CCUS

Table 5. Overview of different motives of justice relevant to sustainability transitions.

Motive / *Type*	*Labour*	*Environment*	*Climate*	*Energy*	*Other*
Distributional	Employment	Non-GHG pollution	Climate change impact	Access to energy	Distribution costs and benefits
	Community impact	Environmental risk	Alignment with Paris goals	Affordability of energy	
	Worker's safety	Safety risk			
Procedural	Fair participation employees	Fair participation community	Fair participation vulnerable groups	Energy policy	
Recognitional	Preservation of culture and identity	Acknowledgement of pollution and risk	Recognition of climate impact	Recognition of energy poverty	
			Responsibility for emissions		
Restorative		Addressing pollution and risk	Climate adaptation	Addressing energy poverty	
Other			Carbon lock-in		

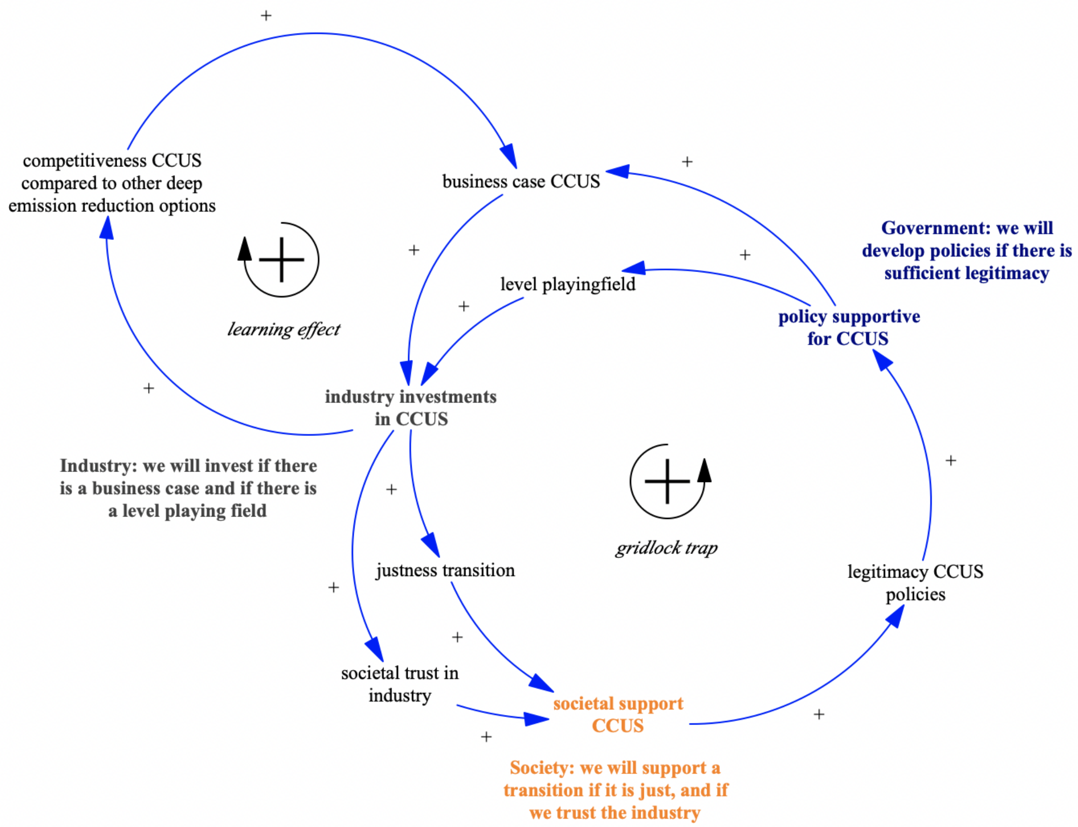

Fig. 17. Interrelation of enablers and barriers to CCUS implementation.

implementation, as shown in Fig. 17, is used as a conversation starter for the interviews and represents a highly simplified starting point to the current hypothesis of enablers and barriers in the transition involving different stakeholders. The interconnected stakeholders place different emphases of importance on relevant factors in the transition. For example, society will only support a transition if it is perceived to be just while government depends on the legitimacy of environmental policy implementation. On the other hand, industry places importance on the business case and creation of a level playing field for industrial developments. The different stakeholders depend on the decisions and the behavior of other stakeholders, and only when all stakeholders act in harmony with the full systems perspective taken, ways to smooth the transition to a more sustainable low-carbon economy can be identified. Building on the expert stakeholder interviews, the next step in this research is a series of focus groups. In these focus groups, group model building exercises are used in order to find enablers and barriers for the sustainability transition of industry. Group model building has facilitated structured discussions between expert stakeholders in order to develop a shared understanding of the sustainability transition of industry and translate this into a more detailed causal loop diagram. There was a prominent role for CCUS societal aspects and stakeholder interaction in these discussions.

These results feed into assessment and strengthening of societal readiness and novel, more engaging narratives for CCUS in industrial clusters. In the process, awareness is created, feedback on technological development and governance is gained and environmental and societal implications are clarified.

6. Business model innovation

The greatest barriers to the development of CCUS in Europe are considered to be commercial, rather than technological issues. Therefore, an important challenge for the development of CCUS clusters is to demonstrate and commercialise the entire value chain and to establish a framework for the long-term business case, requiring governmental and public support. It is only possible to capitalise on such opportunities when stakeholders are firmly on board. As such, stakeholders need to be credibly engaged in decision-making, environmental impacts need to be transparently quantified, and new business models need to be developed and tested. C^{4}U develops novel business models for facilitating CCUS deployment so that the long-term business case can be established through consideration of the concerns of a myriad of stakeholders and identification of optimal scenarios for overcoming financial risks. Business model formulation is conducted in consultation with stakeholders in the North Sea Port CCUS industrial cluster for assessment of risks and barriers to deployment of industrial carbon capture, transport and storage infrastructure, cash-flow, risk management instruments, appropriate funding sources, capital financing and ownership structure.

Part of the initial study performed on business model innovation in C^{4}U has summarised the work conducted and key findings from a series of literature reviews related to: sustainable business model innovation; CCUS risks and challenges; and planned and operational CCUS projects [37]. An understanding of these topics is considered highly important for the successful development and subsequent assessment of business models for CCUS in industrial clusters. This research provided the foundation for understanding the needs and opportunities associated with CCUS business models, providing an overview of CCUS cluster developments in the UK and the operational support packages that are being developed by the UK government as part of plans to establish four CCUS clusters by 2030 [38]. Transferable learnings from the UK CCUS experience for potential use in other parts of Europe including in the North Sea Port area were also elucidated. The UK has six large industrial clusters each with emissions totalling between 3 to 10 Mt_{CO2} per year, which have been developing roadmaps for their decarbonisation. The UK has outlined the ambition to have two CCUS clusters operational by the mid-2020s and a further two by the 2030s. The characteristics of these potential CCUS clusters are briefly summarised in Tables 6 and 7. Based on these projects, features for successful cluster design include, being comprised of a portfolio of emitters with an anchor project, having access to a storage site, either via pipeline or ship, the ability to reuse legacy infrastructure and the ability to repurpose an existing skilled labour force.

Business models to support CCUS Early CCS competitions in the UK emphasised the importance of ensuring capture projects are commercially viable, with the likely need for ongoing government operational subsidies or alternative support mechanisms to allow capture sites to be competitive in current markets. Here, the latest proposed business models take the form of, Regulated asset (a regulated asset base type model for CO_2 transport and storage, with a user pays revenue model), ICC (Industrial Carbon Capture) Contract (A contract for difference style support mechanism for industrial carbon capture based on a strike price of the quantity of CO_2 captured), and dispatchable Power Agreement (A contract for difference style support mechanism for carbon capture on power stations based on a strike price of electricity generated) [39].

Further developments are ongoing in the UK to determine appropriate business models for applications such as Greenhouse Gas Removals (GGR), blue hydrogen, CO_2 utilisation and CO_2 shipping. The work highlighted similarities and differences for CCUS cluster and business model development when comparing the UK and Netherlands experience. Similarities in the emitter profile in the North Sea Port region is comparable to the broad range of industrial emitters in the Humber cluster and there are similar interests in blue hydrogen as a decarbonisation

Table 6. Capture project profiles for industrial clusters in the UK: Existing emitters in dark blue, with planned new build projects (with CCS) indicated by light blue. Local emissions (estimated for 2017/2018).

Cluster location	Local emissions ($MtCO_2$/yr)	Industry	Power	Blue hydrogen	GGR	Anchor Project
Scotland	6-7	✓	✓	✓ (light blue)	✓ (light blue)	Natural gas processing
Humber	10	✓	✓ (light blue)	✓ (light blue)	✓	Hydrogen
Teesside	4	✓	✓ (light blue)		✓	Power
Merseyside	5	✓		✓ (light blue)		Hydrogen
South Wales	9-19	✓	✓			Industry

Table 7. CO_2 transport and storage plans for industrial clusters in the UK. Green indicates sufficient availability of CO_2 storage capacity and red indicates limited storage capacity in the region.

Cluster location	Local emissions	Onshore CO_2 pipeline	Offshore CO_2 transport	CO_2 storage site	Shipping imports
Scotland	**Offshore** (Central NS)	**Existing** Feeder 10	**Existing pipeline** Atlantic / Goldeneye / Miller	**Gas fields** North sea	**Yes**
Humber	**Offshore** (South NS)	**New network**	**New pipelines** NEP (*or existing – Viking*)	**Saline aquifer** North Sea (*or Viking fields*)	**Possible** (*unknown*)
Teesside	**Offshore** (South NS)	**New network**	**New pipelines** NEP	**Saline aquifer** North Sea	**Possible**
Merseyside	**Offshore** (Irish Sea)	**New & existing**	**Existing pipelines**	**Oil & gas fields** Irish sea	**Possible**
South Wales	**Limited**	**Unknown**	**Shipping**	**Flexible**	**No**

strategy. There are however aspects of the policy environment, funding strategies and ambition that may have influenced UK cluster developments that may not yet be applicable to the North Sea Port region such as the inclusion of GGRs in UK cluster proposals. The Dutch government has a contract for difference style support mechanism known as SDE++ which has similarities with the mechanisms proposed in the UK, with contract for difference style mechanisms for capture sites and an expectation that CO_2 T&S is charged as a fee to capture sites. However, there are differences in the implementation of the support mechanisms. The UK has specific funding for CCUS infrastructure and is coordinating funding timelines based around cluster CO_2 T&S proposals while the Netherlands instead has adopted a competitive approach between multiple emission reduction technologies aimed at prioritising the most cost efficient routes.

The work also highlighted that driving CCUS cluster developments in the UK requires a clear government narrative on the role of CCUS in achieving national decarbonisation targets, encouragement of innovation and a diversified set of projects, and clear recognition of the need for ongoing operational support for industry. Further research specific to the North Sea Port is conducted primarily using stakeholder analysis integrated with the above research into policy instruments and on integration into cluster infrastructure. Semi-structured stakeholder interviews with local North Sea Port stakeholders highlighted business models for CO_2 shipping, allowing access to a range of North Sea storage sites as an important consideration requiring further exploration. The wider results of the interviews are interpreted using thematic analysis guided by operationalisation of the adoption theory and business model aspects. This is being triangulated with a document analysis of decarbonisation roadmaps, assessment reports, policy documents, and public statements. This analysis will guide decisions on the core business model ‘elements’ to be included in the next stages of the project.

7. Conclusions

This paper has provided an overview of the work and preliminary results of the C^4U project. Based on the comprehensive multi-scale experimental test program complemented with state-of-the-art mathematical modelling, C^4U is tackling the scale-up of CO_2 capture technologies from TRL5 to TRL7, while trialling innovative functional materials under different operating conditions and developing novel reactor processes for steel mill off-gases. C^4U is expected to significantly improve the performance of these CO_2 capture technologies in accordance to key performance indicators, through validation of the reliability of C^4U capture demonstrators via 4000 hrs of operational time. The activities thus far for the two CO_2 capture pilots, CASOH and DISPLACE have involved the engineering design and construction phases. Both plants have completed the Basis of Design, which defined the scope for all activities that are being performed over the project. This includes determining where equipment will be built, unit sizes and partner responsibilities for operations and material delivery. The pilot plants use industrial process gases from steel mills. Both pilots completed the Detailed Engineering design, which included developing piping and instrumentation diagrams, HAZOP studies and equipment procurement. These defined all instruments and elements of the pilots, operating modes and control strategies. The construction phases of both pilots are well underway. Functional materials for the CASOH pilot have been successfully screened at lab-scale.

Process simulation and design for integration of C^4U technology into steel plant while considering a range of different gas sources and determining fixed and operating costs is being performed according to plant operating conditions and results from TRL7 pilots. This involves detailed integration and performance assessment of reference and DISPLACE and CASOH technologies using advanced mathematical modelling tools. Amine based adsorption was selected as the reference technology and the calculation of its performance were finalised.

Industrial CCUS cluster operation and logistics is studied in C^4U, involving evaluating performance metrics (economics, energy, safety and environment) by developing and using mathematical models for CCUS cluster optimisation. C^4U assesses new technologies through analysis of scale-up using LCA with methods developed and applied to determine industrial cluster level environmental impact of capture technologies and integration opportunities with other industries. This is enabling the evaluation of C^4U capture technology potential to contribute to cost reduction of decarbonising an industrial cluster under scenarios defined for 2030 and 2050 emission reduction targets in the North Sea Port industrial cluster. This will ensure the economic demonstration of an integrated CCUS chain, while accelerating learning to facilitate fast CCUS deployment.

C^4U is elucidating a framework on how societal readiness for CCUS can be described and assessed. This is helping to gain insight into the social and political dynamics for CCUS in the North Sea Port cluster by developing an engaging narrative in consultation with end-users and stakeholders. A literature review was undertaken which compares impacts of different steel production decarbonisation technology on society and a series of interviews with North Sea Port stakeholders followed by a detailed analysis of the results has been carried out, yielding key socio-technical insights for smoothing the transition to a low carbon economy in this reason. Furthermore, novel business models are being formulated in consultation with the stakeholders in the North Sea Port industrial cluster while assessing risks and barriers to deployment of infrastructure, cash-flow, risk management instruments, funding sources, capital financing and ownership structure. Reviews on risks and challenges for CCUS and conditions that enable business models success have been carried out. An overview of UK's CCUS cluster developments and associated support packages was provided for identifying transferable learnings. Future work in this area will identify and evaluate policy instruments for implementation of CCUS in steel plants in industrial clusters as well as governance arrangements.

In conclusion, C^4U accords with the strong consensus to intensify R&D work on the development of promising breakthrough CO_2 capture technologies leading to needed step-change impacts on reducing CO_2 emissions in the iron & steel industry. C^4U is contributing to de-risking of new technologies, while recognising the needs of sequential and stepwise approaches for decreasing the cost of capturing CO_2 from diverse streams in an integrated steel mill, together with further needs of a common shared infrastructure (i.e. a CCUS cluster). C^4U is expected to ultimately contribute to securing jobs in the iron & steel and ancillary industries in Europe, thereby reducing the potential for carbon leakage. For assessment of public and political acceptance and societal readiness, C^4U has involved an exploration of framing CCUS in a just transition, for preserving employment and economic possibilities while addressing the energy transition. Through direct industrial stakeholder involvement, the work of C^4U is expected to enhance innovation capacity, market opportunities, competitiveness and growth at the European level.

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