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IEAGHG 10th High Temperature Solid Looping Cycles Network Meeting & CaLby2030 Project 2nd Dissemination Event

17th – 18th March 2026 - Kulturens Hus, Luleå, Sweden

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IEAGHG

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Leading the way in carbon management with advanced CCS research. IEAGHG are at the forefront of cutting-edge carbon, capture and storage (CCS) research. We advance technology that reduces carbon emissions and accelerates the deployment of CCS projects by improving processes, reducing costs, and overcoming barriers. Our authoritative research is peer-reviewed and widely used by governments and industry worldwide. As CCS technology specialists, we regularly input to organisations such as the IPCC and UNFCCC, contributing to the global net-zero transition.

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JOINT REPORT

Summary

The 10th High Temperature Solid Looping Cycles Network (HTSLCN) Meeting took place on the 17th and 18th of March 2026 at Kulturen Hus in Luleå, Sweden, in partnership with the Horizon Europe Framework Programme funded CaLby2030 project and hosted by Swerim. 32 attendees enjoyed a two-day programme, with a total of 27 presentations, the official opening of CaLby2030's porcupine pilot plant at Swerim with a site visit to Swerim's pilot plant site, and a traditional Sámi dinner in a wooden hut built to resemble a Lappish tent on the banks of a frozen Lake Stora Antnäs.

Concluding from the technical sessions and panel discussion, it is evident that high-temperature solid looping cycles carbon capture technologies have moved from primarily targeting the power sector to harder to abate sectors, such as cement, steelmaking, hydrogen production, as well as negative emission technologies like bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC).

The highlight quote of the meeting: "It is not easy to be a brick." – Carlos Abanades (CSIC-INCAR)

Day 1 - 10th HTSLCN meeting - 17th March 2026

Session 1: Proof of concept

Shareq Mohd Nazir (KTH Royal Institute of Technology) opened the first session with a presentation on utilising high-temperature furnace off-gases in biomass gasification: A pathway for efficient CO_2 utilisation. This concept integrates the electric arc furnace used in steelmaking, biomass gasification, and hydrogen (H_2), synthetic natural gas (SNG), or methanol (MeOH) production. The off-gases account for 20% to 30% of the energy in the electric arc furnace. This concept uses these off-gases with biomass to generate energy. The presented study, which covers 3 to 4 years of research, compared scenarios for the use of off-gases in the production of electricity using a heat recovery system, with biomass

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for the production of H_2/SNG/MeOH . The scenario comparison is done on the basis of both technical and economic key performance indicators (KPIs) including equivalent mass of biomass, net energy production, efficiency, CO_2 avoidance, CO_2 efficiency, net present value, and discounted payback period. This study shows that the electric arc furnace is a dynamic batch process and integrating it with gasification makes the system semi-continuous. When electric arc furnace off-gases are not available, the gasifier can still run auto-thermally using the oxygen (potentially obtained from the electrolyser). The comparison found that the use of off-gases and biomass to produce SNG provides the best compromise between resource conservation and energy conversion performance, but in terms of economic performance, it is very sensitive to electricity price.

Galina Skorikova (TNO) presented the latest on sorption-enhanced reverse water gas shift (SEWGS) technologies: COMAX, a process intensification option for the separation-enhanced reaction used in high-temperature solid looping cyclical carbon capture. The COMAX process operates a single reactor at a temperature of 350 - 400°C and is capable of achieving more than 90% CO_2 conversion in a single pass. The COMAX technology, which is based on a Pt4A bifunctional catalyst, has shown excellent cyclic stability through over 400 cycles of testing carried out over 50 days. The process exhibits an initial pre-breakthrough period in the reactive adsorption step with very high or maximum CO productivity which occurs during the first 40 minutes of operation. After this initial 40 minutes, the reaction proceeds to steady-state, which is accelerated by water breakthrough, i.e., the saturation of the sorbent. TNO have developed a 1-D model to simulate the COMAX technology. The overall trends produced by this model match the experimental results, however, the model can accommodate further improvements to better simulate the COMAX process. These improvements can include incorporating considerations such as the temperature drop caused by the reverse water gas shift reaction, the temperature shift that occurs between adsorption and desorption, and heat losses to the environment. The COMAX technology has potential for use in applications such as the production of MeOH, the production of sustainable aviation fuels, and top gas recycling in steelmaking. TNO are keen on finding a testing site and industrial partners to continue scaling up COMAX.

Dora Andrea Chisăliță (TNO) presented chemical looping for CO_2 purification. CO_2 purity is an important factor for all carbon capture technologies to achieve technical, economic, and safety requirements, as well as ensure the CO_2 fulfils the required criteria for transportation and storage. Purification & Recuperation of Energy Content (PUREC) is a

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process that is conceptualised to increase the purity of CO_2 streams using chemical looping. It is designed to remove reducing agent impurities, such as CO and H_2, from pre-combustion capture. This would minimise secondary contamination and simplify downstream purification. PUREC is a two-step process in which O_2 is transferred using a metal oxide, in this case Fe_2O_3. Experimental results show complete conversion of both CO and H_2 can be achieved at temperatures of 450°C and higher. A techno-economic assessment of the PUREC process showed that it has the highest recovery and lowest energy demand when compared to oxidation and liquefaction CO_2 purification processes.

Carlos Abanades (CSIC-INCAR) spoke about the use of calcium looping (CaL) in a novel direct air capture (DAC) system. Capturing CO_2 directly from ambient air presents major challenges due to its low concentration, requiring materials and processes that combine high reactivity, scalability, low energy demand, and low specific cost. CaL based on a $Ca(OH)_2/CaCO_3/CaO$ loop exhibits significant potential for large-scale CO_2 removal, owing to its high CO_2 uptake under ambient conditions ($X_{Carb}>0.7$), low cost (potential to reach <150€/tCO_2), moderate energy use (<4GJ$_e$/tCO_2 with hydration-heat recovery) and wide availability when compared to other sorbents (solid or liquid). CSIC-INCAR suggest the use of slow carbonating structures composed of stacked sheets (or other shapes such as bricks, beds of pellets/granulates) that carbonate over weeks and move countercurrently with respect to the air flow, resulting in a modular, scalable and energy-efficient DAC contactor. These carbonating structures are based on CaL chemistry. Under DAC conditions, sorbent conversion is mainly governed by relative humidity and surface area, while reaction kinetics are limited by CO_2 diffusion at the mm–cm scale. These transport limitations require reactor designs specifically tailored for efficient gas–solid contact. CSIC-INCAR have tested two possible contactor designs at TRL3 (technology readiness level) for this novel DAC system: countercurrent and packed-bed carbonators. This design minimises the use of energy for the movement of sorbent and decouples the regeneration process from the capture process.

Session 2: Experimental results

Adam Zaidi (The University of Manchester) kicked off the second session with his presentation on the experimental results of lab-scale chemical lopping CO_2 splitting over Mn-based perovskites and high-entropy perovskites enabled by industrial waste-gas utilisation. Syngas (CO + H_2) is a key intermediate for fuels and chemicals (e.g., MeOH and Fischer–Tropsch fuels). The market is expected to grow by 7% to $731.40 billion by 2032.

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Conventional syngas production relies on fossil-based processes such as steam methane reforming and coal gasification. These routes are energy-intensive and associated with significant CO_2 emissions. CO_2-to-CO conversion offers a pathway for carbon recycling and integration with low-carbon syngas production. High-temperature thermochemical looping enables CO_2 splitting into CO using a redox material compatible with waste gas streams. The experimental campaign found that high-entropy perovskites exhibited more than 99% fuel uptake during CO_2-rich waste gas reduction, more than 99% CO_2-to-CO conversion, and increased stability and reduced sintering. However, further work is needed to understand the unexpected properties from atomic interaction, which is key to material design, improve perovskite oxygen carriers using non-critical elements like lanthanum, samarium, iron and manganese, and explore A-site and B-site substitution to enhance oxygen mobility.

Luis La Calle Canelada (ICB-CSIC) presented sorption-enhanced gasification (SEG) of residual biomass for high-purity hydrogen production with integrated CO_2 capture. Biomass-to-hydrogen routes combined with CCS are among the few options capable of achieving net-negative greenhouse gas emissions. SEG is proposed due to its high hydrogen yield and its inherent CO_2 capture. This study focuses on the evaluation of CaO carbonation and in-situ CO_2 capture during SEG of residual biomass in a TRL5 bubbling fluidized-bed gasifier, and quantifying the impact on the hydrogen-rich product gas: composition (% vol.) and yields (Nm^3/kg), as a function of temperature and steam-to-carbon ratio. The experimental campaign found that both the CaO carbonation extent and the CO_2 capture efficiency decrease as temperature increases; higher temperature increases the H_2 yield (Nm^3/kg) due to higher fixed-carbon conversion, even if the dry-basis H_2 purity becomes slightly lower; increasing the steam-to-carbon ratio enhances WGS and steam reforming, improving both H_2 purity and H_2 yield, but excessive steam dilution reduces the CaO carbonation extent and the CO_2 capture efficiency; and H_2 purities above 80 vol.% (dry basis) are achieved while maintaining high H_2 yields after the fixed-bed cleaning reactors (tar reforming + WGS).

Felix Mangold (The University of Stuttgart) presented on the pilot demonstration of integrated circulating fluidised bed (CFB) calcium looping in cement plants. In the integrated CaL system, raw meal calcination takes place in oxyfuel calciner, only 1/3rd of the CO_2 emissions from cement process must be treated in CaL carbonator, the CaL purge is fed at >900°C directly into the kiln avoiding milling to minimize energy penalty, and the fuel consumption is reduced by about 25%. The experimental campaign that was conducted at

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the MAGNUS pilot facility found that the sorbent make-up must be coarse enough to be easily kept in the loop for CO_2 capture, while the sorbent must be fine enough for the CaL purge. Sorbent fragmentation and attrition of reference sorbent A did not form fine enough particles for the CaL purge; particle size is important for the cyclone solid separation units. The calcination step is most relevant for particle friction and attrition. The CaL sorbent and raw meal are required at significantly different particle size distributions to achieve the required fineness for the CaL purge and to avoid the accumulation of inactive SiO_2 in the loop.

Erik Van Dijk (TNO) presented on the de-risking of sorption enhanced water gas shift (SEWGS). The reactive pressure swing absorption type separation at elevated temperature used in the SEWGS process is an enabling technology that allows for solid sorbent CO_2 removal, combining CO_2 removal with water gas shift conversion, and minimising the energy requirement. Erik reported on a pilot demonstration that showed SEWGS can be a critical enabler for the symbiotic coupling of the iron and steel sector with the NH_3 and urea industry, two large and carbon-intensive industries. Transforming a waste product from the iron and steel industry into a feedstock for NH_3 and urea production, the concept allows an economically attractive business case as well as a 30% decrease in primary energy use, a 40% decrease in raw material demand and up to 90% reduction in direct CO_2 emissions. The pilot also showed SEWGS to be capable of recovering hydrogen from various steel gases via the integration of advanced CO_2 removal technology into various steel production concepts. In both cases, SEWGS combined low energy CO_2 separation with optimum production of H_2 from the steel works arising gasses. Two separate projects, INITIATE and GreenSmith, contribute to the de-risking of the technology for faster roll-out towards a first-of-a-kind TRL8 demonstrator. The INITIATE project demonstrates the SEWGS technology at TRL7 in a multi-column unit using real basic oxygen furnace gas (BOFG) and industrially sourced WGS catalyst and CO_2 sorbent. The GreenSmith project focuses on the industrial design of a SEWGS unit and further enhancing the process efficiency by means of sorbent shaping technologies.

Jochen Ströhle (TU Darmstadt) presented on scaling chemical looping combustion (CLC) for sustainable waste-to-energy (WtE) applications beyond 1 MW_{th}. CLC has the advantages of inherent CO_2 separation, resulting in a low energy penalty, and an absence of problematic substances in the air reactor, resulting in high energy efficiency. The LOUISE project at TU Darmstadt successfully tested the use of waste in CLC, including 24-hour operation at 150 kW and 7 days at 1 MW. The test campaign showed consistency of process

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across scales, high carbon capture rates (›95%), and high residual oxygen demand (›30%). The test campaign also showed reduced operational stability in comparison with earlier biomass tests at 1 MW_{th} scale. The test campaign showed similar operational conditions for biomass and waste. However, switching from biomass to waste exhibits reduced formation of H_2 and enhanced formation of C_xH_y. There is a necessity of targeted strategies for conversion of heavier hydrocarbons. To do this, new oxygen carriers, reactor design, and reforming (calcium looping gasification) need to be further developed.

Borja Arias (CSIC-INCAR) presented operational insights on the fate of HCl in calcium looping systems based on operational insights from the 1.7 MW_{th} La Pereda CFB pilot plant. Borja's presentation reported on the findings from experiments that used a mix of plastic and biomass for WtE combined heat and power (CHP) applications. In general, calcium looping in biomass-based CHP and WtE applications has the potential for co-capture of the acid gases present in the flue gases while simultaneously using residual biomass or residual fuels in the oxy-fired calciner. The biomass used had low Cl content, however, the polyvinyl chloride (PVC) used was 57 wt% Cl. The calcium looping system was tested at a range of different temperatures and limestone to biomass to PVC ratios. The system was also tested under air-fired and oxy-fired combustion conditions. The results showed that operating conditions have a significant effect on chlorine retention; increasing the calciner temperature leads to higher HCl emissions. The analysis from the experimental results assumed that combusting PVC pellets generates HCl, which reacts with the CaO in the limestone to form $CaCl_2$. The $CaCl_2$ decomposes in the calciner due to the high operating temperatures. This means chlorine can leave the system as $CaCl_2$ in the solids exiting the system (in the purge and/or as fines from the cyclones) and as HCl in the flue gas.

Session 3: Modelling

Richard Porter (University College London) kicked off the third session with his presentation on NO_x transformation and reduction kinetics in calcium looping systems. Metallurgical off-gases (e.g. Electric Arc Furnace – EAF) can contain NO_x at several thousand ppm, creating a risk of NO_x transfer through the CaL process into the calciner exhaust and CO_2 product stream, with potential implications for downstream CCUS applications. At the same time, CaL reactors operate under high-temperature and variable redox conditions that may enable in-situ NO_x reduction via interactions with CO, hydrocarbons, char, and solid surfaces. This study aims to understand and predict how NO_x behaves in CaL to enable the control of NO_x effectively and avoid contamination of the CO_2

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product stream. Gas-phase simulations using detailed NO_x mechanisms reproduce methane-assisted NO reduction trends reported in the literature but significantly under-predict NO reduction by CO. A review of historical kinetic data indicates that key homogeneous CO-NO pathways are now assigned very low rates, while experimental evidence points to a dominant contribution from surface-mediated reactions in quartz reactors. To address this, coupled gas-surface kinetic models have been developed to represent NO adsorption, dissociation, and reduction by CO and hydrocarbons. Initial results show that inclusion of surface pathways is essential to reproduce observed NO conversion levels and their sensitivity to oxygen.

Agnese Pedretti (University of Bologna) presented the results of an ex-ante life cycle analysis (LCA) coupled with process modelling of the environmental performance of synthetic CO_2 sorbents for carbonate looping. In CaL systems for post-combustion CO_2 capture, synthetic sorbents are increasingly investigated for improved cyclic stability and reduced regeneration temperatures compared to CaO. Lab-scale studies demonstrate promising performance. However, without a life cycle perspective, upstream production impacts and potential burden shifting across the value chain may be underestimated, limiting informed decision-making for material development and technology scale-up. The case study that was modelled was a 500 MW_e coal-fired power plant with a calcium looping unit that captured 90% of the total CO_2. The sorbents that were explored are CaO, which was used as a benchmark, alkali-doped MgO, and K_2CO_3-doped Li_4SO_4. Results demonstrate that with heat recovery, CaO exhibits the lowest global warming potential, followed by Li_4SiO_4 and MgO. This ranking reflects the influence of two main factors: first, synthetic sorbents lower regeneration temperatures, limit thermal energy recovery potential, offsetting operational energy savings; second, the lower average conversion – in the case of MgO – increases material throughput and production burdens. However, without heat recovery, the ranking reverses: Li_4SO_4 outperforms CaO, demonstrating that, in the adequate context, lower regeneration temperatures combined with superior conversion efficiency can offset production impacts. Resource depletion assessment reveals lithium as a critical vulnerability for Li_4SO_4 and MgO systems, contributing 84.5% and 18.5% of supply risk impacts, respectively. End-of-life material recovery scenarios show negligible environmental benefits, with MgO recovery resulting in net environmental penalties due to energy-intensive processing. All in all, the viability of synthetic sorbent appears dependent on their long-cycle conversion, which has to be suitably higher than benchmark CaO to compensate for the burdens of the synthesis route.

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Markus Secomandi (LUT University) presented steady-state and transient modelling of calcium looping integrated with steelmaking processes. The production of steel in electric arc furnaces (EAF) is a batch process, which means the mas flow, composition and temperature of off-gases vary greatly with time. This temporal variability means it is impractical to design a capture process using steady-state tools. A model for calcium looping applied to steel industry off-gases, capable of simulating both steady-state and transient conditions was developed. The model describes a coupled carbonator–calciner system using a one-dimensional representation of each reactor along its height. Time-dependent conservation equations for mass, energy, and phase fractions are solved for both gas and solid phases across discretised control volumes, thus capturing transient interactions between reactors and circulating solids. Dynamic simulations are carried out by defining variable inputs (e.g., flue gas parameters). Steady-state simulations are carried out by fixing boundary conditions and running the system to convergence. Steady-state simulations establish reference operating points and performance metrics such as CO_2 capture efficiency, temperature profiles, and solid circulation rates under representative steel off-gas conditions. Transient simulations investigate the system's dynamic response to realistic disturbances, like rapid changes in off-gas flow and composition typical of EAF and argon oxygen dacarburisation (AOD) operation. Results reveal the importance of accounting for transient effects on reactor temperatures, reaction extents and capture performance, underscoring limitations of steady-state assumptions for process design and control.

Nestor D. Montiel-Bohórquez (Politecnico di Milano) presented on the integration of CaL and solid oxide electrolysis (SOEC) for e-methanol production in steelmaking. The study considers the production of e-methanol by exploiting: the CO_2 captured from electricity-based steelmaking flue gases as the carbon source, and a high-temperature electrolyser as the H_2 source. The carbon capture step is done via the CaL process, which is well-suited for high-temperature steelmaking due to the fluctuating characteristics of flue gases. On the other hand, the SOEC is the source of hydrogen. The H_2 and CO_2 react in the catalytic Methanol Synthesis and Purification process to form methanol. The CaL system captures 92.67% of the CO_2 entering the system (flue gas, biomass combustion, and fresh limestone), consuming 20 MW_{th} of fuel. About 17 MW_{th} of residual high-temperature heat can be recovered from the CaL flue gases at 600-950 °C and supplied to the SOEC for steam generation, which has a thermal energy demand of 16.5 MW_{th}. Regarding the carbon processing unit (CPU), it recovers 95.3% of the CO_2 from the CaL section, producing 12.6

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tCO_2/hr (purity 99.99 mol.%) and consuming 1.5 MW_e (122 kWh_e/tCO_2). It is important to note that about 50% of the CO_2 from the CPU comes from burning biomass in the CaL calciner, and, therefore, can be accounted as biogenic. Since all the CO_2 is converted to methanol, the SOEC is sized to produce 1.73 tH_2/hr (H_2/CO_2 molar ratio of 3.0), resulting in a power consumption of 64 MW_e (37 kWh_e/kgH_2). The methanol synthesis and purification section is conventional and designed to effectively convert 97.8% of the CO_2 into 8.88 t/hr of methanol with a purity of 99.86 wt.%. Hydrogen production dominates CAPEX (66%), followed by CaL (22%). Hydrogen production accounts for 81% of total OPEX. The levelised costs of methanol (LCOM) is estimated at 1,141 €/tMeOH (clearly driven by electricity consumption), while the average price of natural gas methanol is ~460 €/tMeOH[1].

Jouni Ritvanen (LUT University) presented modelling and model development in novel solid looping projects on behalf of Markku Nikku (LUT University). This presentation covers the modelling-based research and development work carried out for two EU-funded projects, HERCCULES and CORAL. HERCCULES is a Horizon Europe project started in 2023 aimed at accelerating the deployment of CCUS in southern Europe. For the HERCCULES project, the design of a pre-calciner pilot unit that could be integrated with an existing cement plant to produce CO_2-rich flue gas for carbon capture, while at the same time enabling a high calcination degree of the raw meal, is modelled. The CO_2-rich flue gas can be produced using oxy-combustion and recycling of the flue gas. Additionally, biomass fuel is fired in the calciner to further lower the CO_2 emissions. The model reveals that the residence times of the particles are increased due to a vortex which forms in the splashbox. Comparison with 1D and 0D results indicate that there are local differences due to different assumptions and discretisation of the models, but overall agreement is good. This gives confidence to proceed with the pilot building process. On the other hand, the CORAL project investigates the concept of utilising iron powder as an energy storage material. Iron ore is reduced to iron using hydrogen when there is a surplus of renewable energy production, and the iron powder is combusted to produce power in retrofitted CFBs in times of high energy demand. Preliminary results of a sensitivity analysis show that a higher oxygen concentration leads to a faster reaction and an increased temperature in the reactor bed. Also, the conversion of iron is dramatically increased with oxygen enrichment. As iron needs to be circulated between reactors, low conversion is not desired. So even these early results can indicate a

[1] Average value for EU in the period 2020-2025 reported by Methanex.

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need to consider oxygen enrichment or higher temperatures in the further experimental studies.

Session 4: Pilot design and first-of-a-kind

Sergio Celiméndiz (CSIC - Institute of Carbon Chemistry) kicked off the fourth session with his presentation on the evolution of the CO_2 carrying capacity of limestone in CaL systems when exposed to HCl and SO_2 containing gases. This work assesses the impact of exposing CaO to HCl and SO_2 environments in the CaL plant integrated in an WtE plant in Italy. The presence of S and Cl in the solid recovered fuels used in WtE plant will result in the formation of HCl and SO_2 in the calciner environment, which may have a detrimental effect on the performance of CaO as a CO_2 sorbent in the carbonator reactor of the CaL pilot. The utilisation of a thermogravimetric analyser, which has been meticulously designed for the purpose of handling acid gases and cyclic processes, has been deemed the most efficacious to perform the necessary analysis. The impact of CaO chlorination and sulfation reactions has been studied in two stages. Firstly, the two reactions have been studied separately to understand the influence on CO_2 carrying capacity under conditions similar to those found in the calciner of the CaL system. Based on the results obtained, it has been observed that limiting the CaO conversion into $CaSO_4$ or CaClOH below 1 % per cycle (expressed as moles of $CaSO_4$/CaClOH formed per mol of CaO in the fresh sample), the CO_2 carrying capacity of the CaO over cycles is still sufficient for reaching a residual conversion of 5-7%. Secondly, the two reactions have been studied simultaneously to determine the possibility of them coexisting or competing. It was noticed that under carbonation conditions, both chlorination and sulfation reactions may coexist (even in the presence of CaO carbonation) regardless of the SO_2 and HCl contents, whereas at calciner conditions the presence of both reactions depends on the relative content of SO_2 over HCl.

Jochen Ströhle (TU Darmstadt) presented on the design of a mobile carbonate looping pilot plant for on-site CO_2 capture from the flue gases of various industrial plants. The main components of the plant are designed to fit into two standard-sized containers. Since the pilot plant will be coupled with multiple industrial sites (two WtE facilities, a cement plant, a lime plant, and a paper mill), the treated flue gases will have differing compositions. In particular, the CO_2 concentrations, varying from 6 vol % to 20 vol%, pose a significant challenge in designing the pilot plant. As the energy demand in the calciner is directly linked to the CO_2 input into the carbonator, it is not feasible to operate both reactors under identical hydrodynamic conditions across all industrial facilities. If the volumetric flow

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entering the carbonator is kept constant at all sites, the energy demand in the calciner will vary, resulting in different fluidization conditions. Conversely, if the energy input to the calciner is kept constant, the gas flow to the carbonator will need to be adjusted accordingly. Therefore, a compromise in gas flows has been found, and the reactor dimensions, such as height and diameter, have been designed to ensure proper fluidisation and sufficient particle entrainment in both reactors across all flue gas compositions.

Sergio Celiméndiz (CSIC - Institute of Carbon Chemistry) presented on the CO_2 and SO_2 capture in the copper production process. The More4LessCu Project aims to develop a near-zero CO_2 emission copper smelting plant, improving productivity, energy efficiency, and fuel production through CO_2 capture and utilisation. The project uses hydrogen produced using renewable energy to reduce the copper mineral. The resultant flue gas is rich in SO_2 and CO_2. The CaL process uses CaO as a sorbent to capture CO_2 from high-temperature combustion gases. During carbonation, CaO reacts with CO_2 to form $CaCO_3$, and in calcination, $CaCO_3$ decomposes to release CO_2 and regenerate CaO. CaL can also co-capture SO_2 which reacts with CaO and O_2 to form $CaSO_4$, however, it must be purged to avoid accumulation. The captured CO_2 is used in the production of methanol. The configuration that integrates CaS/$CaSO_4$ and CaO/$CaCO_3$ loops requires three reactors: a co-capture reactor where CaO absorbs CO_2 and SO_2 and CaS oxidizes to $CaSO_4$; a calciner/reduction reactor where $CaSO_4$ reacts with H_2 and CO, providing energy to calcine $CaCO_3$ and generating a gas stream rich in CO_2, CO, and H_2; and an oxidation reactor where CaS is converted back to $CaSO_4$ with O_2. At calciner exit a 47/47.5/2.9/2.6 % $CO_2/H_2O/CO/H_2$ gas stream, respectively, is obtained. The study demonstrates that the CaL system is technically feasible for the co-capture of CO_2 and SO_2. Scenarios with high sulphur content require greater purging and consumption of fresh $CaCO_3$. The energy balance indicates that the calciner requires more energy in conditions with higher CO_2 and SO_2 content. Oxy-combustion stands out for its simplicity, lower absolute energy demand and greater operational robustness, it will be viable in scenarios with low amounts of SO_2. The redox cycle, although more complex, offers greater potential for thermal recovery in scenarios with high SO_2 loads.

Martin Haaf (Sumitomo SHI FW Energia Oy) brought the fourth session to a close with his presentation on the engineering and design of a pilot TRL6 CFB based on calcium looping as a CO_2 capture technology for modern steelmaking. The complexity of CO_2 emissions abatement in the iron and steel industry is characterised by the batch-oriented nature of

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modern steelmaking processes. More specifically, both the flue gas flow rate and the CO_2 concentration vary considerably over time, which imposes challenges for a CO_2 capture installation. These flue gases pose the 5Ds challenge: flue gases from AOD and EAFs are Discontinuous, Dynamic, and temporarily Diluted, containing a high concentration of small particles (Dusty), and pollutants such as S- and Cl- components (Dirty). The CFB combustion process has proven its dynamic flexibility in energy production. Hence, CFB-based calcium looping (CFB-CaL) is expected to be well applicable also for the integration with such batch-type steelmaking processes. The new CFB-CaL TRL6 pilot plant, which is currently in the erection phase (at the time of the meeting), has been specifically designed to operate under such challenging conditions. The novel design includes the use of controllable wall seals, a dedicated storage system, and dust feeding to add extra flexibility to the CFB-CaL process. The detailed design of the CFB-CaL pilot plant that was completed in 2025 included 3666 technical documents with 1651 revisions, amounting to 4.9 GB of data.

Session 5: Panel discussion and closing remarks

The panel, which was moderated by Paul Cobden (SWERIM), included Carlos Abanades (CSIC-INCAR), Jochen Ströhle (TU Darmstadt) and Martin Haaf (Sumitomo SHI FW Energia Oy). The panel reflected on the ups and downs that CaL has faced over the years but reflected on a noticeable uptake in industries looking to CaL for CO_2 capture. Pilot plants have faced difficulties, however, exciting technology solutions, like electrification and electrolysis, are emerging and the critical mass of knowledge is growing. At its inception, CaL was developed as a solution to decarbonise coal. Now that it is moving to other industries, the energy penalty is not the only concern; a new concern has arisen: where does this energy come from? For example, a cement plant is not an energy producer; there is need to find additional energy sources and/or transport additional fuels and/or locate near a power grid, etc.

Looking to the future, the panel members discussed the main research priorities. These included a full CCUS chain, the use of different fuels (especially practical impacts such as corrosion, impurities and design constraints), the use of CaL in DAC as this would require a very different type of reactor, decoupling the carbonator from the calciner, oxy-calcination, electrocalcination, etc. The panel also reflected on how context changes the perceived economic feasibility of CaL technologies, e.g., electrification is too expensive in the context of O_2 production but is suitable for H_2 production.

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Lessons from global developments, such as the 5 MW_{th} pilot in China and the 3 MW_{th} pilot in South Korea were also discussed. These discussions showed Asia to be moving towards the forefront of CaL technology. Recent developments in Europe were also discussed, including the coming together of cement manufacturers in Germany to share knowledge on the use of oxy-fuel and the 118 projects that applied for (limited) available funding in the EU. These discussions also included reflections on the need for more government support and concentrated efforts.

The panel also reflected on times when they thought “we will not make it.” A poignant note one of the panel members recalled was when they were instructed to not include the phrase “CCUS” on the first page of proposals they were submitting because the organisation they were affiliated with at the time was “not doing that anymore.” The discussion with the audience also included reflections on how capital-intensive the technology is and the associated need for investors to be willing to take the risk. The added complexity that transport and storage introduces to the way projects are defined was also discussed with the meeting attendees. However, the discussion quickly took a positive turn with reflections on life-cycle analyses showing that solid looping is in a much better position to be utilised in the decarbonisation of hard-to-abate sectors than other technologies.

The panel discussion drew to a close on a positive note; with reflections on achievements made in the solid looping technologies space. These included the widespread adoption of more pragmatic approaches (the community has departed from developing “fancy schmancy” materials that will not survive the technology’s boundary conditions) and how the research community is getting more and more diverse with time.

“Knowing chemistry and thermodynamics, how can you possibly think that CO_2 capture is not going to be a thing?” - Paul Cobden (SWERIM)

“These are exciting times; we will see what will happen in the time leading to 2030.” - Martin Haaf (Sumitomo SHI FW Energia Oy)

“R&D in the future will likely see a shift in focus from capture processes to gasification, especially with waste fuels, and utilisation applications.” Jochen Ströhle (TU Darmstadt)

“One of the lessons learnt is that we need to explain, or better explain, to politicians what thermodynamics is, and that it works.” – Carlos Abanades (CSIC-INCAR)

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Day 2 - CaLby2030 project 2nd Dissemination event - 18th March 2026

1. Decarbonisation pathways in iron & steel: an industrial perspective – Paul Cobden (SWERIM)

Decarbonising the steel industry requires combining multiple strategies, as carbon remains inherently necessary in steel production. Even hydrogen-based processes—such as those developed by Stegra—cannot fully eliminate CO_2 emissions, since carbon is essential for material properties, energy input, and process stability.

Two main pathways are considered: electrification with renewable energy (including hydrogen and electric arc furnaces) and the integration of carbon capture, utilisation, and storage (CCUS). While EAF-based production already accounts for about 30% of European steel and significantly reduces emissions through recycling, it still relies on multiple carbon sources, such as alloys, fuels, and electrodes. Therefore, it represents a "low-CO_2" rather than "zero-CO_2" solution.

A key challenge in implementing CCUS is the complex nature of steelmaking gases, characterised by the 5 "D's": dusty, discontinuous, dynamic, dirty and dilute, which complicates capture technologies. Additionally, all decarbonisation routes require substantial energy inputs. For example, carbon capture increases energy demand moderately, while carbon utilisation (e.g., methanol production via hydrogen) can nearly double it.

Overall, effective decarbonisation depends on optimising the balance between electricity use, hydrogen deployment, and carbon management, while prioritising internal utilisation of captured carbon and targeting multiple emission sources across the steel value chain.

2. Conceptual Design for First of a Kind (FOAK) Industrial Demonstration Projects - Martin Haaf (SFW)

The implementation of carbon capture (CC) technologies as a climate mitigation tool is required to reach net-zero emissions by 2050. The accelerated deployment of CC projects by 2030 is essential in reaching that target. The CaL process based on CFB is a cost-competitive option for CC in hard-to-abate industries. The technology relies on the reversible carbonation - calcination reaction of CaO-based sorbents, enabled by the application of commercially proven CFB technology. Sumitomo SHI FW (SFW) - as a technology forerunner - is currently expanding the SFW CaL technology demonstration

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and scale-up based on extensive pilot testing activities, and in-house expertise including dimensioning tools and databases generated from more than 850 commercial FB combustors and gasifiers.

The presentation entitled "Conceptual Design for First-of-a-Kind (FOAK) Industrial Demonstration Projects" provides a status update on the conceptual design and scale-up of full-scale CFB-CaL systems tailored for hard-to-abate industries, such as bioenergy, WtE, cement, and steel production. This covers an overview of the case study sites, site and sector - specific technology features, key steps during the scale-up process and selected results.

3. Pilot demonstration of CFB-CaL integrated in Steel industries - Malin Blomqvist (SWERIM)

The iron and steel industry accounts for approximately 7% of global CO_2 emissions, making it a key target for decarbonisation efforts. In this context, Circulating Fluidised Bed - Calcium Looping (CFB-CaL) stands out as a promising solution, as it is well suited to the demanding conditions of steel production, including high temperatures and dust-laden gas streams. The process utilises calcium oxide—already widely applied in steelmaking—as a sorbent for CO_2 capture. Another important advantage of this technology is its ability to store CO_2 in solid form, thus avoiding the need of gas storage.

SWERIM's new TRL6 pilot plant demonstrates the integration of CaL within a realistic industrial environment. It employs circulating fluidised bed reactors and an advanced solids flow control system based on fluid dynamics developed by SFW, eliminating the need for mechanical valves. The system is designed for flexibility, operating with multiple heat sources such as liquefied petroleum gas (LPG) and electricity, and uses limestone as the primary sorbent.

By spring 2026, the pilot plant is expected to be fully operational, with the first experimental campaign commencing shortly thereafter. These campaigns will focus on optimizing operating conditions while generating key data to support process modelling and the future scale-up of the technology.

4. Carbon Transport & Storage: Optimisation tools for Multimodal Transport - Richard Porter (UCL)

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The presentation addressed the optimisation of CO_2 transport systems for onward geological storage, with a focus on identifying efficient, safe, and flexible multimodal solutions. A range of transport options—including pipelines, trucks, ships, and rail—can be combined to enhance flexibility, particularly for small-scale or early-stage deployment scenarios.

The analysis is structured around three key criteria: techno-economic performance, environmental impact, and safety. Cost evaluation considers factors such as CO_2 conditioning requirements (compression or liquefaction), transport mode (or combinations thereof), and key operational parameters including distance, speed, and loading/unloading constraints.

Environmental performance is assessed based on lifecycle CO_2 emissions associated with fuel use, infrastructure development, conditioning processes, and, in the case of shipping, boil-off losses. Safety is evaluated using a quantitative risk assessment framework that accounts for both accident likelihood and potential consequences, including population exposure.

Within CaLby2030, UCL has developed a mixed-integer linear programming (MILP) framework for optimising transport mode selection and multimodal configurations. Techno-economic, environmental, and safety criteria are also evaluated, providing a basis for exploring trade-offs and supporting decision-making in CO_2 transport system design.

5. Dynamic modelling of CFB-CaL systems - Markus Secomandi (LUT)

One-dimensional (1D) and pseudo-two-dimensional (1.5D) models are widely used tools for the simulation of CFBs. These models provide reasonably accurate predictions of complex gas–solid processes while remaining computationally efficient compared with more detailed approaches such as computational fluid dynamics. As a result, 1.5D models are valuable for pilot unit design, process analysis, experimental planning, and scale-up studies.

At LUT University, a 1.5D model has been developed specifically to enable dynamic simulation of the CFB-CaL process. The model is implemented in Simulink using C-based S-function blocks. The reactor is discretised into 40 axial elements with a core–annulus radial structure. It includes hydrodynamic submodels for solids behaviour, kinetic expressions for relevant reactions, heat transfer correlations, and mass and energy

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balances for each element. The resulting system of ordinary differential equations is solved using MATLAB solvers to obtain a time-dependent description of reactor behaviour.

Recent developments supporting the CaLby2030 project include multiple particle size fractions, new component models for separators and loop seals, support for $Ca(OH)_2$ sorbents, and a population balance model to simulate sorbent aging. Example simulations demonstrate the model's capability to capture strongly time-dependent process dynamics that cannot be represented using steady-state approaches.

6. EMPHATICAL project presentation - Galina Skorikova (TNO)

The EMPHATICaL project (Efficient Methanol from Pumped Heat and Calcium Looping) is a 4.5-year Horizon Europe initiative developing an integrated, energy-efficient pathway for producing e-methanol from industrial residual gases. The project combines innovative oxy-blown CaL CO_2 capture with advanced CO_2 purification, renewable hydrogen supply, methanol synthesis and innovative heat pump assisted distillation. EMPHATICaL targets the metallurgical sector, specifically electric arc furnace and ferrochrome alloy off-gases, enabling continuous carbon capture and utilization under highly variable operating conditions.

At its core, EMPHATICaL will demonstrate a TRL7 pilot achieving continuous production of up to 1 tonne per day of fuel-grade e-methanol. The project aims to reduce specific energy consumption by at least 25% and methanol production costs by at least 15%, while reaching net-zero CO_2 emissions. Key innovations include flexible CaL for high-purity CO_2 supply, heat-pump-assisted distillation delivering over 60% energy savings, and AI-based process control to manage fluctuating feedstocks and renewable power.

Beyond demonstration, EMPHATICaL will deliver a bankable pre-FEED (front end engineering design) for a modular first-of-a-kind plant producing 100 kt/y of e-methanol, supported by techno-economic, life-cycle, and market assessments.

7. INITIATE project presentation - Eric Van Dijk (TNO)

The H2020 INITIATE project (grant no. 958318) focusses on the industrial symbiosis between the iron and steel sector and the ammonia and urea sector. Using the steel arising gasses as feedstock for NH_3 and urea, this industrial symbiosis approach directly contributes to reduce emission, energy and raw material use. It shows that carbon capture,

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re-use and storage are sustained by generating added value products such as NH_3 and urea.

The INITIATE project takes all necessary steps to provide the basis for the roll-out of a 1st commercial size demonstrator at 50 kt/y urea on the basis of basic oxygen furnace gas (BOFG). The operational reliability of the technological innovations is demonstrated in a pilot plant at TRL-7. Positive energy, economic and environmental advantages are shown via the verification of the key-performance indicators of the concept and comparing them with a base case without CO_2 removal and reference cases that use amine-based CO_2 removal technology. A bankable design of the First-Of-A-Kind (FOAK) commercial plant is made to convert BOFG to AdBlue® and/or another NH_3-based product. The development of a long-term implementation plan ensures the successful implementation beyond the FOAK plant.

8. Site visit

After one-and-a-half days of presentations on cutting-edge solid looping CCUS research, meeting delegates went to SWERIM premises for the grand opening of the new CFB-CaL pilot plant, owned by SWERIM and designed by SFW.

The site visit began with an insightful presentation from Dr Elsayed Mousa, Senior Researcher at SWERIM, on the roadmap for transitioning from fossil-based to green ironmaking, highlighting the critical role of CCUS in this transformation. Following Dr Mousa's presentation, that laid bare the impossibility of fully decarbonising the iron and steel industry without CCUS, the group made their way on a red carpet and through a balloon arch to the new CFB-CaL pilot plant, nicknamed "The Porcupine" because of the many test-points built into the pilot. This cutting-edge facility was designed to demonstrate the performance of CFB-CaL for future steelmaking applications and is one of three TRL6 demonstration pilots within the CaLby2030 project. The pilot uses flue gas from the nearby SSAB steel mill to test under real-world conditions.

Participants were divided into two groups for guided tours of the site, offering a unique opportunity to witness pilot-scale implementation of carbon capture technology tailored for the steel industry. The visit underscored the immense potential for scaling up these technologies and reinforced the pivotal role of CaLby2030 in driving innovation, experimentation, and collaboration within the CCUS field.

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As part of the site visit, attendees were also given exclusive access to SWERIM's brand new Hydrogen autoclave, a unique facility designed to test materials in hydrogen environments. The tour also showcased a range of advanced pilot installations, including reheating furnaces such as a 3-ton walking beam furnace, an EPGH (electric process gas heater), Prothal by Kanthal, an AC/DC electric arc furnace, a converter, an electrolyser, and SEWGS (sorption-enhanced water-gas shift) reactors, collectively offering a comprehensive and engaging insight into cutting-edge research and innovation.

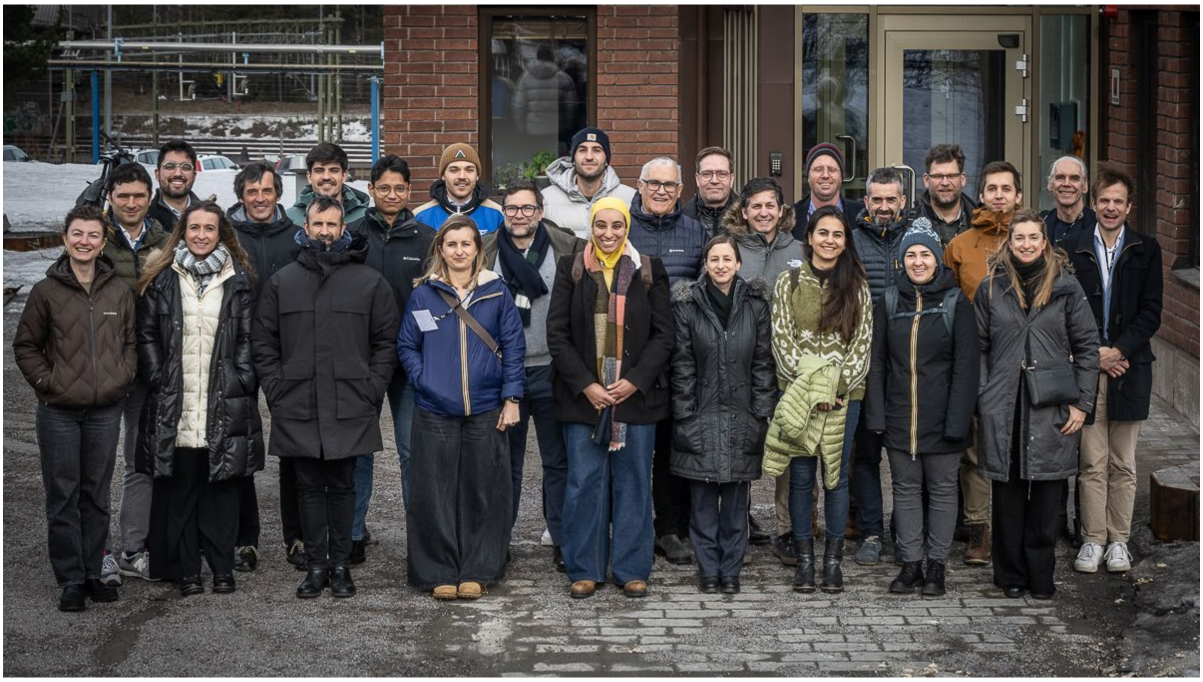

Figure 1: Meeting delegates at the entrance to SWERIM's pilot testing facilities

Conclusions and Recommendations

Concluding from the technical presentations, the panel discussions, and the site visit, it was noted that CCUS calcium looping is a versatile technology that has successfully pivoted from coal-powered applications to vital hard-to-abate sectors, such as the production of iron and steel, as well as newer applications, like direct air capture. The discussions noted that calcium looping benefits from integration with other decarbonisation strategies, like electrification and H_2 production. The funding and construction of pilot plants in Europe, like "The Porcupine" that meeting attendees got to see, and in China and South Korea are a testament to governmental recognition of the

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potential CCUS calcium looping has to decarbonise hard-to-abate sectors and a willingness to fund, construct and test this promising technology.

The main recommendation from the meeting is a wish to see more industrial stakeholders and participation from more diverse attendees, with hopes for the participation of representatives of more countries at future High-Temperature Solid Looping Cycles Network Meetings. This recommendation will begin to be implemented in the next meeting in 2027, which is planned to be held at TU Darmstadt in Germany.

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