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9th High Temperature Solid Looping Cycles Network Meeting

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9th High Temperature Solid Looping Cycles Meeting

14th – 15th March 2023

Palazzo Farnese, Piacenza, Italy

Hosted by

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***Top Left**: 9th HTSLCN Meeting venue: Palazzo Farnese in Piacenza, Top Right: Group photo of the attendees of the 9th HTSLCN Meeting, Bottom Left: Site visit to the CLEANKER pilot plant at Buzzi Unicem's Vernasca cement plant, Bottom Centre: Attendees of the 9th HTSLCN Meeting at the conference dinner, Bottom Right: Attendees of the 9th HTSLCN Meeting following the technical*

Summary

The 9th High Temperature Solid Looping Cycles Network (HTSLCN) Meeting took place from 14th to 15th March 2023 at Palazzo Farnese in Piacenza, Italy, hosted by the CLEANKER consortium. 82 attendees enjoyed a two-day programme with a total of 28 presentations, the official closure of the CLEANKER project with a visit to the pilot plant, a relaxing dinner and a guided tour in the museum of Palazzo Farnese about the millennial history of the city of Piacenza and its territory, from the pre-Roman age to the XX century.

Concluding from the panel discussions and technical sessions, it was noted that calcium looping technology is currently validated, also thanks to the promising results brought by the CLEANKER project, at TRL 7 for applications in the cement industry and in post-combustion applications and needs to move to TRL 8 with the erection of a bigger scale pilot plant. However, being this investment capital intensive, it is mandatory to find an industrial partner that is willing to invest in these advancements, and this represents the major challenge that the community is currently facing in the scale-up of the technology. Negative emissions through solid looping with biomass and flexible operation has been identified as another hot topic of this meeting. It is important that the HTSLCN community has started work on these topics. Next to biomass, sorption enhanced reforming technologies appear as a promising near-term option to party replace conventional H_2 production. Thus, opportunities for solid looping currently seem to be in the industrial sectors, rather than in the primarily targeted power sector.

14th March (HTSLCN Day)

Session 1: Calcium Looping I

Carina Hofmann (Technical University of Darmstadt) opened the first session with a presentation on Pilot-Scale Investigation of the indirectly Heated Carbonate Looping Process for CO_2 capture in Lime Plants. This configuration differs from the conventional calcium looping technology as no combustion takes place directly in the calciner and thus no ASU is necessary, instead the heat to sustain the calcination reaction is indirectly supplied using heat pipes that transfer the heat from an external combustor. Also, with this technology both direct and indirect CO_2 emissions can be captured, as the gases exiting from the combustor are routed to the carbonator. The testing methodology and the results achieved in the 300 kW_{th} pilot plant placed in TU Darmstadt are presented with the combustion of lignite, waste derived fuel, and propane. Sand (combustor bed material) contamination in the purge flow was found as a consequence of some cracks that developed in the refractory wall that separates the combustor from the calciner.

Gabriele Mazzolari (LEAP) presented process modelling and techno-economic analysis results for the integration of the Calcium Looping in Waste to Energy plants. The study was performed in Aspen Plus for two different retrofit configurations, simulating both the WtE and the CaL sections and integrating a previously implemented Matlab model for the carbonator reactor. The implementation of the RDF production process showed that the plants are able to increase the waste disposal capability and the additional steam produced in the CaL section made a power output increase possible. Some technical novelties were introduced in the work as the integration of a reactor for acid gas removal, a reactor for CO_2 polishing and the substitution of the CO_2 recirculation fan with an ejector. The results showed the plants to be able to reach 95% CO_2 capture and to be carbon negative thanks to the biogenic carbon content in the waste. An economic analysis was also presented evaluating the CAPEX, OPEX and revenues of the plant, thus calculating the payback period for the different configurations.

Roberto Garcia (CSIC-INCAR) presented the design of a counter current moving bed reactor pilot to capture CO_2 with calcium containing particles denominated "d-CaL" since it allows the decoupling of the carbonation and calcination reactors. This reactor design is based on a moving bed of either CaO or $Ca(OH)_2$ that is fed from the top of the reactor at ambient temperature and moves downward as the sorbent is progressively reacted and exhausted, being discharged at the bottom of the reactor by a rotary valve. The counter current design allows for lower thermal inefficiencies and to sustain an auto-thermal process allowing the carbonation reaction to take place in its optimum temperature range. CO_2 capture efficiencies of 60-80% were achieved in an inlet CO_2 concentration range of 4-9%. Another experimental campaign is planned in 2023 in the TRL 4 CSIC-INCAR pilot plant to evaluate the effect of different operational variables.

José Fierro (Politecnico di Milano) presented the concept of using CaL retrofitted PCPP for backup electricity generation in scenarios with high penetration of renewables. The plant layout proposed consists of the PCPP connected to the carbonator which are both thought to be operated for around 800 hours per year, while the calciner island is much smaller in scale and designed to operate continuously. The two reactors are decoupled by sorbent buffers. The concept with entrained flow carbonator, instead of CFB, is characterised by lower complexity and CAPEX, however, due to the lower residence times, the use of $Ca(OH)_2$ is more suitable due to the faster reaction kinetics. Sensitivity analyses of different parameters on the SPECCA index are also performed.

Session 2: Calcium Looping II

Juan Carlos Abanades (CSIC-INCAR) started this session with a presentation about the CaLby2030 project that will investigate the integration of Calcium Looping in the cement, Iron&Steel and Waste-to-Energy industries. The speaker highlighted that the extensive experience gained in the last ten years from the operation of "La Pereda" pilot plant will be exploited in this project to complete conceptual designs of four First-of-a-Kind commercial demonstrations of CFB-CaL. The aim of the project is also to demonstrate at TRL 6 the CO_2 -polishing process using the injection of $Ca(OH)_2$. Abanades also reminded of the problem posed by the particle dimensions employed in the calcium looping sections that are usually too large to be successfully employed in cement manufacturing, other than the problems posed by the cruciality of the carbonator cooling system in order to extend CO_2 capture in the reactor which is usually limited by the equilibrium in the lower portions.

Martin Haaf (Sumitomo SFW) presented the application of CFB reactors for calcium looping application in cement plants, presenting the 200 kW_{th} MAGNUS pilot plant in the University of Stuttgart and the results achieved by the work done there. This pilot plant is refractory lined in both carbonator and calciner, with oxy-fired calciner and staged oxygen introduction. The carbonator reactor temperature is moderated by bayonet tube coolers that are inserted from the top and from the bottom. The goal of the experimental campaigns is to test different sorbents with different particle size distributions, parallelly demonstrating CO_2 capture rates exceeding 90%. The cement plant devoted to the scale-up is the Karsdorf plant, that is fired with 65% alternative fuels in the two kiln lines. It currently has no pre-calciner.

Malin Blomqvist (SWERIM) presented the crucial role that decarbonisation of the Iron&Steel sector has in the reaching of the net-zero target by 2050 since, as of today, it is responsible of 11% of total CO_2 emissions. In particular, the traditional steelmaking BF-BOF route, responsible of the 73% in global steel production, emits 1.9 t_{CO2} per tonne of hot-rolled coil. Of those, 1.2 t_{CO2} are produced by the blast furnace, which is the hardest step to decarbonise. As a parallel more sustainable route, electricity-based steelmaking is gaining market shares, based either on scrap or Direct Reduction of the iron ore. In particular, the decarbonisation of the Electric Arc Furnace (EAF) off-gas is proposed to be investigated in the framework of CaLby2030. However, this poses some problems related to the fact that this process is usually discontinuous (batch-wise), dynamic, and releases usually very polluted and dusty gases, which usually get diluted by various false-air infiltrations.

Session 3: Sorption-enhanced reforming

Peter Clough (Cranfield University) opened the session with a presentation of the Hyper project taking place in the UK. In line with the government's target of achieving 10GW of H_2 of which at least 50% is green hydrogen by 2030, a collaboration between Cranfield University, GTI, and Doosan Babcock is set to evaluate the potential of low-carbon hydrogen production by sorbent enhanced steam reforming. The project is constructing a 1.5 MWth pilot plant at Cranfield University based on a compact hydrogen production technology that captures the CO_2 during the H_2 production process and shifts the chemical reactions to favour the production of more hydrogen. Building such large-scale pilot plant highlighted that the development of the components and the interaction between them is the main challenge of this project. A novel entrained flow indirectly heated calciner was designed and constructed to suit the scale of the pilot plant.

Abdelrahman Mostafa (Politecnico di Milano) presented the results of a modelling study to evaluate the role of the reactor thermal Capacity on the Sorption Enhanced Reforming for Blue Hydrogen Production. The results of this study highlighted the need to deliver a sufficient enthalpy input to compensate for the endothermic nature of methane sorption enhanced steam reforming process. Using the thermal energy stored in the fixed bed reactor was evaluated to cover the enthalpy demand of the process. The findings of the work presented showed that increasing the initial solids temperature results in higher CH_4 conversion and H_2 yield indicating the potential to minimize the extent of a cooling step between regeneration and reforming stages with beneficial implications on the overall efficiency of the process. Increasing the bed heat capacity, through the addition of an inert heat carrier, thus the energy stored in the bed was assessed as well.

Navid Khallaghi (University of Manchester) presented the techno-economic evaluation of the blast furnace gas utilization with Ca-Cu looping cycle for hydrogen-enriched syngas production. The study showed the potential of the Calcium Assisted Steel-mill Off-gas Hydrogen (CASOH) production, at 10 bar and 753°C, by combining the Ca-Cu looping with the sorption enhanced water gas shift (SEWGS) technology. The calcination pressure was identified as an important parameter with a major effect on the overall performance of the process. Sensitivity analysis showed that performing the calcination at a pressure of 0.5 bar results in significant reduction of the thermal demand of the process coupled with a slight increase in the electricity demand.

Session 4: Chemical Looping

Christopher de leeuwe (University of Manchester) started this session with a presentation on the results of the GLAMOUR project. The project aims to design, scale up, and validate an integrated process to convert waste bio-based feedstock into aviation and marine fuels. The presentation focused on the lab-scale results achieved for the high-pressure glycerol and methane reforming through the chemical looping processes. Ni catalyst was used for this study and the experiments were performed at high pressure for all the stages of the process (Reforming, Oxidation, and Reduction). Results verified that the process is working close to the thermodynamic limits achieving 100% glycerol conversion and more than 90% methane conversion.

Yongliang Yan (Newcastle University) presented the design of a 3 kW_{th} reactor for the demonstration of the chemical looping water gas shift technology. This technology, using nonstoichiometric LSF as oxygen carrier, was demonstrated in the lab scale for the production of a highly concentrated hydrogen stream and a highly concentrated CO_2 stream alternatively with a CO conversion exceeded 90%. Currently, a new pilot scale reactor is under construction with the aim of increasing the technology readiness from TRL-2 to TRL-4. The single bed reactor will be used to test up to 2kg of state-of-the-art oxygen carrying materials and will be operated at 820°C, up to 10 barg with pure steam and CO/syngas feed.

Adam Ziadi (University of Manchester) presented the use of Iron-Nickel containing perovskites for chemical looping water splitting (CLWS) process. The CLWS is based on the steam iron process with the addition of an additional oxidation step to fully oxides to Fe_2O_3. In this study, the addition of Ni to the perovskites was tested at three loadings to evaluate the effect of the Ni on the stability and surface area of the perovskite ($La_{0.6}Sr_{0.4}FeO_{3-\delta}$). 1.8 g of the material was tested in a lab-scale packed bed reactor for 70 hours with a temperature range of 600-900°C. Results show that addition of Ni leads to greater surface area increasing significantly the H_2 productivity of the material but reduces the cyclic stability of the material with Ni content of 9 wt% showing structure breakdown and carbon deposition.

Ismaeel Ali (University of Manchester) presented a study on the methodology for packed bed chemical looping reactor design. The study aims to design a lab scale test rig capable to collect 2D temperature profile of a packed bed chemical looping reactor. The construction of the lab-scale reactor is coupled with the development of a 2D reactor model which was optimized by developing its own solver. Additionally, CFD model using COMSOL is developed to include the presence of the thermocouples and the heat losses in the lab-scale reactor. The models will be validated against results from the experimental work.

Falko Marx (Technical University of Darmstadt) gave the last presentation of the session about the autothermal operation of a 1MW_{th} chemical looping gasifier for biogenic residues. The presented activities are within the scope of the HORIZON 2020 project CLARA aimed to develop a concept to produce biofuels based on chemical looping gasification of biogenic residues. The experimental activities took place using different bio-based residues in the 1 MWth chemical looping gasification CLG) plant in Darmstadt. Results of over than 150h of operation demonstrated the autothermal operation of the CLG process converting more than 100 tons of various biomasses into syngas suitable for downstream processing.

Session 5: Calcium Looping and Chemical Looping for Energy Storage

Stuart Scott (University of Cambridge) started the session with a presentation about the potential of chemical looping for electricity storage. Using the chemical looping technology provides higher energy storage compared to direct heat storage as the energy is stored both as sensible heat and as chemical energy however lower round-trip efficiencies are expected as a result of the reaction being an added source of entropy. The study revealed a trade-off between the round-trip efficiency and storage capacity. For a simple cycle, a poor efficiency of about 20% was evaluated, limited by the efficiency of the turbo machinery. But on opting for a recuperated cycle efficiency of more than 40% was calculated for a material with ΔH of 185 MJ/kmol. Of the typical metal oxides used for chemical looping, MnO_2/Mn_2O_3 was identified as a suitable candidate for this application given its similar equilibrium curve to the optimal theoretical material.

Carlos Ortiz (Universidad Loyola Andalucía) presented a work based on the employment of the CaL process for thermochemical energy storage integrated with Concentrated Solar Panels. The plant concept presented, based on some remarks from the SOCRATCES H2020 project, was based on a cyclone-shaped calciner placed in the receiving spot of a CSP tower, where the reaction heat is supplied by the primary reflectors that collect and concentrate the sunlight in their focal point corresponding to the calciner itself. Since ambient temperature sorbent and CO_2 storage is reported to be necessary, a heat exchanger network is included in the plant. Heat is then recovered in the carbonator reactor by the carbonation reaction. The main challenge is reported to be the poor absorbance of the white limestone, which can be enhanced by adding iron, chromium or manganese.

Matteo Romano (Politecnico di Milano) presented an analysis on integrating a novel chemical looping combustion reactor into a thermochemical energy storage system. The analysis includes two cases: i) the reactor is fed by a fuel gas (for decarbonization of power production); ii) the reactor is fed by green hydrogen (for renewable energy storage). The novel air reactor concept using indirect gas-solid contact through permeable but nonselective conduit walls guarantees large bypass for unconverted O_2 and prevents the presence of hot spots as the reaction will be controlled by the diffusion of O_2 through the walls. Analysis on coupling the novel reactor with different power cycles shows that high energy densities up to 2200 kWh_{th}/m^3 can be attained using Fe- or Ni-based oxygen carriers with cycle efficiencies up to 43 - 45%.

Open Discussion and Conclusions

Matteo Romano (Politecnico di Milano) started the open discussion showing that several full-scale CCS projects were recently announced. Today, chemical looping (CL) and calcium looping (CaL) processes remain at TRL 6-7. New projects recently started on CL and CaL are addressing new industries and new applications at the same TRL. On discussing the bottlenecks for advancing to higher readiness level, representatives of industries in cement and lime sector highlighted the technical risk driven from the lack of demonstration of these technologies at sufficiently large scale to justify the high investment required for advancing to higher TRL. Additionally, the high capital cost is another limiting factor since, as of today, the construction cost of a full-scale CaL plant is reported to be comparable to that of a new cement plant without any increment in cement production capacity.

of the demonstration of he technology at TRL 8 is seen as necessary before full-scale projects. The match between the cement industry and the CaL technology seems ideal as many components needed for the novel technology are already widely adopted around the world in industrial scale.

15th March (CLEANKER Day)

CLEANKER Project Showcase

Maurizio Spinelli (LEAP) opened the session with an overview of the CLEANKER project, running through the steps since the starting date in October 2017 up to the end of the project in March 2023. The target of the CLEANKER project was the advancement of the Calcium Looping process for CO_2 capture in cement plants, achieved by successfully operating a TRL 7 pilot plant in the Vernasca cement plant, owned by Buzzi Unicem. The pilot plant consisted of two entrained-flow reactors, the carbonator fed with calcined raw-meal and the flue gases coming from the pre-heating tower and the calciner fed with raw meal and operating in oxy-combustion conditions. The results from the 9 experimental campaigns showed good CO_2 capture performances in a wide range of carbonator temperatures (550-700°C) and a linear trend between the increase in the Ca to CO_2 ratio and the CO_2 capture rate. The calciner was stably operated in oxy-combustion conditions and with >70% CO_2 at calciner outlet.

Juan Carlos Abanades (CSIC-INCAR) presented the studies carried out to evaluate the CO_2 carrying capacity and the kinetics of carbonation, calcination and sulfation of raw meals from different cement plants in Europe. Analyses were performed with thermogravimetric analysers for reactions characterised by a time scale longer than 10 s, and with a drop-tube reactor for reactions characterised by a time scale shorter than 10 s. Belite formation kinetics was also investigated since the bounding of SiO_2 to CaO to form belite makes CaO no longer able to capture and transport CO_2. In the same speech Nico Mader (University of Stuttgart) reported the additional studies devoted to assessing the multi-cycle CO_2 capture capability of the raw meals and the experimental campaign performed in the lab-scale entrained-flow calciner.

Jörg Hammerich (IKN) presented the design, construction and erection phases of the CLEANKER pilot plant in the Buzzi Unicem cement plant in Vernasca. The process of the design and engineering of the plant lasted around 9 months with 15 revisions to the plant diagram. Many of the plant components were custom made for this specific application and the fabrication was carried out across 2019. The final plant, which is 90 m high and weighs 110 tonnes with 40 more tonnes in refractory, was erected between 2019 and 2020, with the opening ceremony in October 2020. Due to the Covid-19 pandemic, test phases started in February 2022.

Francesco Magli (Buzzi Unicem) presented the operating experience and the results from the experimental campaigns of the CLEANKER project. During the 9 experimental campaigns the carbonator reactor totalled 214 h of working with feeding of calcined raw meal. The aim of the first 5 short tests was to identify the most attractive operating conditions for the following 4 long tests. Gas composition was assessed continuously in different points while solid sampling was performed every 1-2 h at the reactor outlets. Among the problems found during the operation of the pilot plant, the most frequent are related to the strong interconnection of the system and to the clogging of the discharge pipes due to their small size. However, this problem is reported to be easily solved by the scaling up of the plant.

Kari Myöhänen (LUT University) presented the work performed on the simulation and validation of reactor models of CLEANKER Vernasca pilot plant. Both the 1D and the 3D reactor modes were developed on LUT in-house code, with the 3D model featuring a fully-coupled simulation of combustor, calciner and carbonator. Boundary conditions were based on measurements and the results from Aspen Plus simulations. Additional Fluent CFD models were developed to model the flow fields in the splash box and in the swirl head. For the measurements from the experimental campaigns that resulted in being either inaccurate or unreliable, Aspen Plus simulations were used to close the mass and energy balances based on the solid samples analysed.

Edoardo De Lena (LEAP) presented the CLEANKER technology process analysis and retrofitting. Three configurations were evaluated: i) Tail end CaL system (including two calciners), ii) integrated CaL technology (including one calciner), iii) Integrated EF CaL system (with two solids recirculation loops). Results of this analysis show that a full oxyfuel process can achieve an equivalent emission reduction of 85% while the CaL technology processes can reach 92% of emissions reduction. Then, Riccardo Cremona (Politecnico di Milano) presented the potential of retrofitting an existing cement plant with the novel carbon capture technologies. The study, performed on ASPEN plus, was applied on Colleferro cement plant. The results of the study show that applying the retrofitting on two steps: firstly, the implementation of the partial oxyfuel concept (leading to a CO_2 emission reduction of 74%) then the implementation of the integrated CaL process (leading to a CO_2 emission reduction of 89%) is a suitable approach for retrofitting of existing plants. For the final part of this presentation, Ancelin Coulon (Quantis) presented the life cycle assessment of the CLEANKER technology. The key messages of this presentation are that the CLEANKER technology allows a reduction of 70% in net CO_2 eq. emissions for cement production but with an increase of the 50% in the energy footprint and 10% of the water footprint. As part of this project, a web-based foot printer is developed to allow users to compare the LCA results of different technologies based on different scenarios.

Jörg Hammerich (IKN) presented the activities performed to evaluate the scale-up and economics for a full-size plant based on the CLEANKER technology. The study showed that scaling up the main equipment is relatively easy where the oxy combustor and calciner are significantly easy to design based on the main technical specifications for large scale application. The shorter carbonator with an effective mixing chamber at the material feed is needed where simulations show acceptable capture rate at 60 m. for the solids transfer, a specific air slide and sorbent cooler would be needed to suit the application. On the topic of the economics of scaling up the technology, Marco Lindeman Lino (VDZ Technology GmbH) showed the results of the assessment based on the CEMCAP methodology. The results show that a CO_2 price higher than 65 €/tCO_2 is required to make this technology interesting. The main contribution to the cost is related to ASU and CPU thus strategies to decrease their sizes is needed.

Daniela Gastaldi (Buzzi Unicem) presented a study on the CO_2 utilization, transport, and storage within the cement industry. Several analyses were presented in this study where at first results of a technoeconomic analysis of the Baltic CCUS onshore scenario shows the possibility to avoid 6.8 Mt CO_2 annually including 0.42 Mt of CO_2 avoided using mineral carbonation of the oil shale ash. Then a technoeconomic analysis for the CCS scenario for the Northern Italy cement industry was presented and the results indicate the possibility to avoid 23 Mt CO_2 during 20 years by capturing the emissions produced from the two largest cement plants in the region. Finally, with the aim of demonstrating the possibility of the mineral carbonation of CaO-rich waste ash, the presenter showed the latest results performed in lab-scale successfully showing that burnt oil shale ash (BOS) can be used as mineralizers for CO_2 storage. During the in-situ test performed in Vernasca, 20-25g of CO_2 per kg of BOS were stored.

Matteo Romano (Politecnico di Milano) presented the final technical presentation of the meeting providing the CLEANKER project strategic conclusions. The CLEANKER project has demonstrated the usability of the raw meal as a CO_2 sorbent suitable for the CaL process. Even though the limitations of the pilot plant prevented the achievement of long periods of stable testing, results of the tests performed showed 80-90% total equivalent CO_2 capture efficiency. The CLEANKER project confirmed that CaL technology has significant advantages over other technologies for the cement industry where: materials and components are already familiar in this industry, the process has no impact on the rotary kiln and the clinker cooler, and the process provides self-production of baseload low-carbon power with a possible achievement of overall negative emissions with biogenic fuel. These advantages are the driving force behind developing the novel, patent pending, dual-calciner CaL process.

CLEANKER Pilot Plant Visit

After the technical sessions of the second day, the attendees enjoyed a site visit to the Vernasca cement plant where the CLEANKER pilot plant is hosted. Francesco Magli (Buzzi Unicem) led the pilot plant tour showing the equipment of the CLEANKER technology and the connection points with the cement production plant. The CLEANKER pilot plant tour was followed by a tour of the rest of the Vernasca cement plant showing the attendees all the steps of the cement production. Finally, detailed virtual tour was presented showing all the details of the equipment installed for the CLEANKER pilot plant.

Conclusions and recommendations of the 9th HTSLCN Meeting

Concluding from the panel discussions and technical sessions, it was noted that calcium looping technology is technically ready for an advancement to TRL 8. The discussions identified the high capital cost and the competition with other technologies that are easier to apply as the reasons for the slow progress towards higher TRL. Calcium looping will be the protagonist technology in two Horizon projects started in the past six months and will be applied for the first time in the Iron & Steel and in the Waste-to-Energy sectors with the erection of pilot plants in industrially relevant environment

Annex

International Scientific Steering Committee

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List of acronyms

Acronym	Explanation
BOS	Burnt Oil Shale
CaL	Calcium looping
CASOH	Calcium Assisted Steel-mill Off-gas Hydrogen
CFB	Circulating fluidised bed
CLC	Chemical looping combustion
CLG	Chemical looping gasification
CLR	Chemical looping reforming
CLWS	Chemical looping water splitting
COE	Cost of electricity
CSCM	Combined sorbent catalytic material
HTSLCN	High Temperature Solid Looping Cycles Network
IEAGHG	IEA Greenhouse Gas R&D Programme
LHV	Lower heating value
OC	Oxygen carrier
OTM	Oxygen transfer membrane

PCC	Post-combustion capture
PCLC	Pressurised chemical looping combustion
PCPP	Pulverised Coal Power Plant
SADG	Steam assisted gravity drainage
SCPC	Supercritical pulverised coal
SECLSR	Sorption enhanced chemical looping steam reforming
SEM	Scanning electron microscopy
SEM-EDX	Scanning electron microscopy with energy dispersive X-ray spectroscopy
SER	Sorption enhanced reforming
SEWGS	Sorption enhanced water gas shift
TGA	Thermogravimetric analysis/analyser
TRL	Technology readiness level
USC	Ultra supercritical

IEA Greenhouse Gas R&D Programme

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