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ABSALT

Accelerating Basic Solid Adsorbent Looping Technology



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The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.



Zusammenfassung

Das ABSALT-Projekt beabsichtigt, die Integration der Silica-Polyethylenimin-basierten CO₂-Abscheidungstechnologie in ein Zementwerk umfassend zu verstehen. Die Ziele des Projekts sind die Optimierung der Silica-PEI-Zusammensetzung, die Entwicklung von Regenerationsstrategien für Silica-PEI und die Untersuchung der Skalierung der Produktion von Silica-PEI. CEMEX ist direkt an den technoökonomischen und LCA-Studien beteiligt. Bisher zeigen technisch-ökonomische Ergebnisse, dass, obwohl eine Vorbehandlung der Abgase in Betracht gezogen werden sollte, um die Temperatur-, NO_x- und SO_x-Anforderungen zu erfüllen, die Technologie mit dem MEA-System konkurrieren kann, da CO₂ an den Partikeln adsorbiert statt absorbiert wird (wie im MEA-System), was zu einem geringeren Energiebedarf für die Regeneration führt. Die Simulation eines Referenzzementwerks wurde abgeschlossen und die Ergebnisse entsprechen denen eines tatsächlichen Werks (Daten von CEMEX) mit Abweichungen von nicht mehr als 7%. Die potenziellen Vorteile von SALT in Form niedrigerer Betriebskosten im Vergleich zu fortschrittlichen Aminsyste men wurden nachgewiesen, da die Kosten für die CO₂-Entfernung niedriger sind als die für die Aminwäsche. Die Wärmeintegration in einem Zementwerk kann etwa 50% der für den Regenerator in der Feststoff-Adsorptionstechnologie (SALT) benötigten Wärme liefern und dies reduziert die Kosten für die CO₂-Vermeidung auf nahezu das ursprüngliche Ziel von 45€ pro Tonne. Eine Umweltrisikobewertung hat gezeigt, dass SALT mit kieselensäurealkoxyliertem PEI im Vergleich zu den herkömmlichen MEA-basierten Verfahren leistungsfähiger ist. Es wurde eine Endpunkt-Einzelbewertung durchgeführt, die zeigte, dass das SALT-Verfahren im Vergleich zur MEA-Wäsche geringere Auswirkungen auf die menschliche Gesundheit, Ökosysteme und Ressourcen hat (7%, 9% bzw. 26% niedriger). Schliesslich wurde ein High-Level-Design einer Pilotanlage für den Einsatz von SALT in einem Zementwerk fertiggestellt. Obwohl ABSALT sich auf die industrielle Abscheidung am Beispiel von Zement konzentriert hat, eignen sich Silica-APEIs auch für die direkte Abscheidung aus der Luft (Direct Air Capture, DAC), wo externes Interesse besteht.

Résumé

Le projet ABSALT vise à comprendre en profondeur l'intégration de la technologie de capture du CO₂ à base de silice-polyéthylèneimine dans une cimenterie. Les objectifs du projet sont d'optimiser la composition silice-PEI, de concevoir des stratégies de régénération de la silice-PEI et d'étudier la mise à l'échelle de la production de silice-PEI. CEMEX est directement impliqué dans les études technico-économiques et l'évaluation du cycle de vie. Jusqu'à présent, les résultats technico-économiques montrent que, même si un prétraitement des gaz d'échappement doit être envisagé pour répondre aux exigences de température, de NO_x et de SO_x, la technologie peut concurrencer le système MEA, puisque le CO₂ est adsorbé sur les particules au lieu d'être absorbé (comme c'est le cas dans le système MEA), entraînant une baisse de la demande d'énergie pour la régénération. La simulation de la cimenterie de référence a été réalisée avec des résultats proches d'une usine réelle (données de



CEMEX) avec des différences ne dépassant pas 7%. Les avantages potentiels de SALT en termes de coûts d'exploitation inférieurs par rapport aux systèmes avancés aux amines ont été démontrés, le coût de l'élimination du CO₂ étant inférieur à celui du lavage aux amines. L'intégration de chaleur sur une cimenterie peut fournir env. 50 % de la chaleur requise pour le régénérateur dans la technologie d'adsorption par balayage de solides (SALT), ce qui réduit le coût d'évitement du CO₂ proche de l'objectif initial de 45 € par tonne. Une évaluation des risques environnementaux a démontré que le SALT avec du PEI silice-alcoylé présente des performances par rapport aux procédés conventionnels basés sur le MEA. Un score unique a été réalisé, qui a montré que le processus SALT avait un impact plus faible sur la santé humaine, les écosystèmes et les ressources (7%, 9% et 26% de moins, respectivement) par rapport au lavage MEA. Enfin, une conception de haut niveau d'une usine pilote pour le déploiement de SALT dans une cimenterie a été achevée. Bien qu'ABSALT se soit concentré sur le captage industriel, avec le ciment comme exemple, les silice-APEI conviennent également au captage direct de l'air (DAC) qui a suscité l'intérêt de parties externes.

Summary

The ABSALT project intends to deeply understand the integration of the Silica- Polyethylenimine based CO₂ capture technology into a cement plant. The project's objectives are to optimise the silica-PEI composition, to devise regeneration strategies for silica-PEI and to study the scaling up production of silica-PEI. CEMEX is directly involved in the techno-economic and LCA studies. So far, techno-economic results show that, although a pre-treatment of the exhaust gases should be considered to meet temperature, NO_x and SO_x requirements, the technology can compete with MEA system, since CO₂ is adsorbed on the particles instead of absorbed (as is in MEA system), leading to lower energy demand for regeneration. The reference cement plant simulation has been completed with the results being close to an actual plant (data from CEMEX) with differences no more than 7%. The potential benefits of SALT in terms of lower operating costs compared to advanced amine systems have been demonstrated with the cost of CO₂ removal being lower than that for amine scrubbing. Heat integration on a cement plant can provide approx. 50% of the heat required for the regenerator in solids loping adsorption technology (SALT) and this reduces the CO₂ avoidance cost close to the initial target of 45€ per tonne. An environmental risk assessment has demonstrated that SALT with silica-alkoxylated PEI has performance compared to the conventional MEA-based processes. An endpoint single score was conducted which showed that the SALT process had a lower impact on human health, ecosystems, and resources (7 %, 9 %, and 26 % lower, respectively) compared to MEA scrubbing. Finally, a high-level design of a pilot plant for deploying SALT at a cement plant has been completed. Although ABSALT has focused on industrial capture, with cement as the exemplar, silica-APEIs are also suitable for direct air capture (DAC) where there has been interest from external parties.



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Abbreviations

CCGT: Combined Cycle Gas Turbines

Cf.: Concentration Factor

LCA: Life Cycle Analysis

LCI: Life Cycle Inventory

MEA: Monoethanolamine

MW: Molecular Weight

PCC: Post-combustion CO₂ capture

PEI: Polyethylenimine

SALT: Solids Adsorption Looping Technology

SPEI: Silica- Polyethylenimine

TEA: Techno-economic analysis

Base Case Plant – Simulation Plant (all values taken from simulation)

Reference Cement Plant – Cemex Plant (all values taken from data provided by Cemex)



1 Introduction

1.1 Background information and current situation

Of the CO₂ capture technologies currently being developed, amine scrubbing is the most mature having been adapted from natural gas separation. However, it has drawbacks, including high energy demand for regenerating the solvent and reactor corrosion, which are not completely solved by using mixed amines rather than monoethanolamine (MEA). These factors result in relatively high capture costs and this has catalysed the development of alternative or second-generation technologies ^[1]. Although showing considerable promise, solid adsorbents are still at a relatively earlier stage of development and have not been investigated extensively at pilot-scale and demonstration scale.

Silica-PEI has received considerable attention as the leading candidate amongst strong basic adsorbents for both PCC and air capture, with a vast literature covering the impact of silica and PEI properties and composition and additives to improve kinetics and stability. The driving force behind the vast research effort on silica-PEI is the potential to reduce regeneration energies compared to advanced MEA and other amine systems. Regeneration energies have been calculated to be 2.5 GJ/tCO₂ for both coal and natural gas power plant using conservative operating parameters ^[2], including a dynamic adsorption capacity of 5% compared to 3.3 GJ/tCO₂ for advanced MEA systems ^[3], ^[4]. This reduces to 2.2 GJ/tonne CO₂ if the dynamic working capacity can be increased to 7% and this translates into efficiency improvements of over 2%, as was demonstrated in the pilot-scale testing to date by UNOTT^[5].

The key challenges to the successful implementation of silica-PEI in SALT, at demonstration level and then commercially are addressed fully by the project objectives and the targets set. Firstly, maximising the working dynamic CO₂ adsorption capacity at high capture efficiencies and, secondly, keeping the adsorbent replacement costs below ca. 10 € per tonne of CO₂ captured, comparable to those for MEA in amine scrubbing, require the scientific and technical challenges of improving the stability of silica-PEI to be met. This translates in increasing adsorbent lifetimes approaching 12 months, assuming conservative performance parameters. Thirdly, can costs be reduced further by addressing the scientific challenge of recovering the silica from spent adsorbent and converting the spent PEI to chemical feedstocks? This is what comprehensive TEA tried to answer in WP6 and WP7.

1.2 Purpose of the project

Although considerable attention has been given to silica-PEI sorbents for the post-combustion CO₂ capture process, no work has been conducted on its potential application on a commercial scale in the cement industry, even though it could be a solution to decarbonize the cement process. This project provided a detailed insight into the energy penalty reduction, the environmental performance improvement and costs savings by integrating the Silica-PEI based CO₂ capture technology into the cement plant. The work is of interest for cement manufacturers, who can get an idea of the real cost and performances of retrofitting CCS solutions to the cement plant, but also to policy makers, who can find



benchmarking of CO₂ emissions and cost of carbon capture and storage in cement plants and understand the opportunity to eventually support the technical solution.

The key drivers to the successful implementation of silica-PEI in SALT (solids adsorption looping technology) are:

- 1) Maximizing the working dynamic CO₂ adsorption capacity at high capture efficiencies.
- 2) Keeping the adsorbent replacement costs below ca. 10€ per ton of CO₂ captured, which will be comparable to those for MEA in amine scrubbing.

Our goal was to demonstrate that basic silica-PEI in solids adsorption looping technology (SALT) can achieve low capture costs. This involved optimising the silica-PEI composition to minimise the adsorbent replacement cost and regeneration energy, with the extensive pilot-scale testing programme and the techno-economic and life cycle analyses providing the platform for accelerating SALT with silica-PEI to full demonstrations.

1.3 Objectives

The overall aim of the proposed two-year research project was to accelerate the development of SALT by optimising silica-PEI composition, to achieve low costs comparable to other capture technologies. This was accomplished by maximising the dynamic CO₂ adsorption capacity in continuous operation, which reduced the regeneration energy to approach 2.0 GJ/ton CO₂.

dynamic sorption capacity (wt,%) = $100 \times \text{captured CO}_2 \text{ mass flow rate at the sorption reactor (kg/h)} \div \text{solid circulation rate (kg/h)}$

The specific objectives were:

(i) To optimise the performance of silica-PEI in terms of the working dynamic CO₂ adsorption capacity and the physical and chemical stability with respect to flue gases representing PCC from industrial processes, such as cement and lime production. This first involved modifying PEI for optimal stability whilst maintaining high adsorption capacities and investigating a few silicas at a laboratory-scale in work packages (WPs) 1-3. The optimum silica-PEI formulations were evaluated using the SALT pilot-scale facility available at UNOTT.

(ii) To devise regeneration strategies for silica-PEI so that the silica can be recycled and, when PEI degrades, it can be pyrolyzed to yield platform chemicals. This new approach involved a detailed mechanistic study of PEI degradation, optimising the production of amines and other N-containing organics that potentially have high market value (WP5).

(iii) To scale up production of silica-PEI to ca. 100 tons for future demonstrations operating at 10 MWe equivalent, comprehensive techno-economic analysis (TEA) ^[6] and life cycle analysis (LCA) of SALT



were conducted, including the material replacement costs (WP6 and 7, with CEMEX involvement). The information was used to obtain an initial high-level design of a demonstration facility for a cement/lime plant as a platform to accelerate SALT with silica-PEI to TRLs of 7/8.

Achieving the above objectives enabled SALT to be bench marked in relation to amine scrubbing for cement production and provide the platform for taking silica-PEI SALT to full demonstrations.

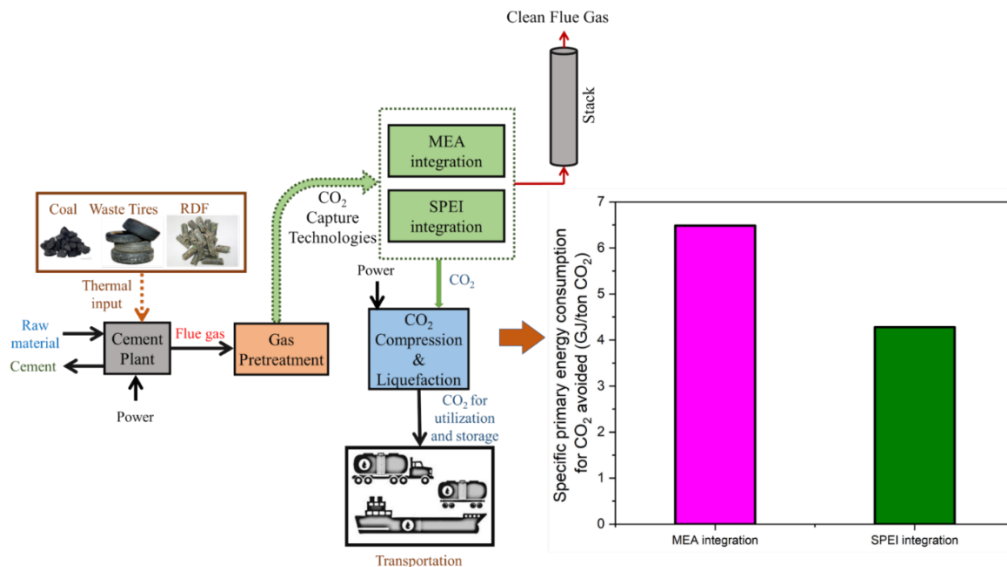


Figure 1. Comparison between the MEA and SPEI integration in Cement Plant^[6]

2 Overall achievements from WP1 to WP5

In this chapter, the main achievements for each WP, from WP1 up to WP5, are summarized.

WP1: Silica selection and properties (PQ Corp.)

- PQ Silicas manufactures mesoporous silicas from sodium silicate and a suite of 11 samples covering a range of pore volumes and particle sizes were evaluated in WP3 using both PEI and APEI. These silicas are vastly cheaper than templated silicas prepared using organic precursors.
- Based on the outcomes of WP3, a sample with a mesopore volume of 1.6 ml/g and a particle size range of 100-300 microns, suitable for moving and fluidized-bed operation, was selected for the large-scale preparations with loadings close to 50% wt.% being achieved for PEIs and APEIs.

WP2: PEI preparation and properties (BASF)

- Forty-eight APEIs were prepared for small-scale testing (WP3) from two commercial PEIs (Lupasol FG and G10 – molecular weight (Mw) of 800 and G100 - Mw of 5000) using propylene oxide and butylene oxide and in some cases, an antioxidant, potassium phosphite.
- Based on the results, four formulations were selected for scale-up to produce 100 kg quantities of APEIs that will find application both for SALT applied to industrial processes as well as DAC.
- Cost performance depends upon stability in SALT but, in terms of material costs, PEI samples Lupasol FG and G10 with propylene oxide are the most favourable combinations for APEIs.



WP3: Silica-PEI screening (small-scale tests, UNOTT)

- In total, over 350 samples were tested and confirmed that alkoxylation not only improves oxidative stability considerably but, compared to normal PEI, enables adsorption and regeneration temperatures to be lowered considerably.
- The composition of the silica-APEI can be tuned to maximise CO₂ uptakes at 50°C (ca. 8-9% w/w adsorbed in first 2-3 minutes) for SALT and other industrial processes while more heavily alkoxyated PEIs give maximum uptakes at ambient temperatures (ca. 7% wt.% adsorbed within 2-3 minutes) suitable for direct air capture (DAC).
- Based on all the results, SALT can be operated between adsorption at 50-60°C and desorption at 120°C or higher in the cement plant being considered (WP5 and 6) with predicted adsorption lifetimes of several months.

WP4: Pilot-scale testing (UNOTT)

- The performance of 5 kg batches of silica-PEI and silica-APEI adsorbents is comparable to the corresponding samples prepared on a laboratory-scale. Minimal degradation of the adsorbent occurred and moisture reduces the extent of degradation at 60°C during CO₂ capture.
- A 100 kg quantity of silica-APEI was successfully tested at the Korea Institute of Energy Research (KIER) where high CO₂ removal efficiencies of over 90% were obtained. Consistently high capture efficiencies were achieved but there was a trade-off with the dynamic adsorption capacity. Minimal degradation of the adsorbent occurred over the 10-day test period.

WP5: Regeneration strategies for PEI (UNIBO, CERTH).

- Conditions have been identified where pyrolysis of spent silica-PEI generates pyrazines, a valuable class of chemicals used for flavoring and other applications.
- Although relatively small reductions in pore volume were observed for the recovered silica from pyrolysis, re-impregnation with PEI and APEI demonstrates minimal loss in CO₂ adsorption capacity. Solvent extraction is much less effective than pyrolysis for removing PEIs from silica.
- Promising applications of the pyrolysis oils were identified as epoxy hardeners co-adjutant, owing to the intrinsic nature of the pyrazines highly mimicking industrial components used as accelerants in epoxy formulations.

3 WP4: Pilot-scale testing (UNOTT and KIER)

3.1 Pilot-tests carried out at the University of Nottingham (5 kg-scale)

The rig at a 5 kg scale has operated for 3 months to investigate the long-term stability of silica-PEI and alkoxyated PEI at 60 °C, the temperature used for adsorption at KIER. This has been supplemented by testing to understand the dynamic adsorption capacity under different regimes for CO₂ desorption and to understand the extent of co-adsorption of water that can occur with CO₂. These results were used to select the test conditions at KIER.

3.1.1 Discussion and conclusions

The 5 kg tests have established that oxidative stability under dry gas condition is low at 50°C, but significant at 60°C over a period of 60 days. However, the test with humidified gas, albeit still at relatively low humidity, significantly reduced the extent of oxidation.

The cyclic tests have established the relation with the dynamic working capacity for CO₂ adsorption with dry gas for the regeneration conditions that were used in the 100 kg test at KIER. Similar conservative



temperatures (95°C in nitrogen; 115°C in 15% CO₂/85% N₂ or pure CO₂) were used to limit any possibility of oxidative degradation.

Moisture uptakes are considerably lower for alkoxyated than for normal PEIs and are no more than 3 Wt.% at 60°C, which will be beneficial for minimising the moisture contribution to the regeneration energy.

3.2 Pilot-tests carried out at the Korea Institute of Energy Research (KIER) (100 kg-scale)

The objective was to evaluate the performance of a silica alkoxyated PEI adsorbent in a 100 kg-scale continuous unit at the Korea Institute of Energy Research (KIER). The adsorbent was successfully prepared using the same mixing procedure as the 5 kg batches of adsorbent prepared earlier (Milestone 6), with the alkoxyated PEI being supplied by BASF. The pilot-scale test at KIER was completed in December over a period of 145 hours. A range of conditions have been tested including the adsorber being operated at 50 and 60°C and the desorber at 95°C in nitrogen, 110-115°C in 15% CO₂ (balance nitrogen) and 115-120°C in 90-95% CO₂. The emphasis was on achieving high capture efficiencies but minimising the desorption temperatures to best protect the adsorbent. The results describe how consistently high capture efficiencies of over 90% were achieved but there was a trade-off with the dynamic adsorption capacity. This was not optimised so as to ensure that minimal degradation of the adsorbent occurred.

3.2.1 Description of the pilot-plant

The 100 kg scale fluidized bed continuous unit was designed to perform post-combustion CO₂ capture using solid adsorbents. Figures 2 and 3 show the schematic diagram and an illustration of the 100 kg scale-unit. It comprises bubbling fluidised-bed type sorption and desorption reactors, a transport system for recycling the solid particles after adsorption, a cyclone for separating the gas and solid, a desorption gas recirculation system to achieve high CO₂ purity in desorption reactor, a rotary valve for adjusting the solid circulation amount, and an infrared (IR) gas analyser (ABB, Advance Optima, Switzerland) for measuring the CO₂ gas concentrations before and after the reaction. For solids handling, a transport system was placed to circulate adsorbents from the sorption reactor to the desorption one and the solid circulation rate was controlled by manipulating revolutions per minute (rpm) of the rotary valve. The desorption gas recirculation system for the CO₂ gas discharged from the desorption reactor has been installed to maintain high CO₂ purity. For heat control, a steam generator supplied energy to the desorption reactor in order to heat adsorbents and supply heat of reaction. An auto chiller (HYUNDAI ENG Co. Ltd., Korea) was used for the cooling adsorbent and removing the heat of reaction in the sorption reactor.

The bubbling fluidised-bed sorption reactor had a width of 0.3 m, a length of 0.3 m and a height of 3.0 m. An air box with a nozzle-type gas distributor was installed at the bottom of the sorption reactor, and an underflow type was manufactured for the circulation of solid particles. The temperature and flow rate of the cooling water were controlled through a heat exchanger installed horizontally inside the sorption reactor to release the heat generated from the sorption and control the adsorption temperature. By injecting steam into a jacket-type heat exchanger installed outside the air box of the sorption reactor to prevent partial cooling of the inside of the reactor (gas inlet), thus minimizing the temperature difference between the injected gas and the inside of the reactor and prevented condensation of moisture flowing into the reactor. In front of the sorption reactor, a bubbler producing water vapor at a specific temperature was installed to control the amount of water vapor in the simulated flue gas. A line heater was installed



in the gas flow line from the rear end of the bubbler to the sorption reactor in order to increase the temperature of the gas stream and prevent water vapor condensation in the gas stream. The simulated flue gas was used for the gas supplied to sorption reactor, the simulated gas with a mixture of Air, CO₂ (99.9%) and H₂O, which was determined based on the experimental conditions.

The bubbling fluidised-bed type desorption reactor had a width of 0.35 m, a length of 0.35 m and a height of 3.0 m. An air box with a nozzle-type gas distributor was installed at the bottom of the desorption reactor, and an underflow type was manufactured for the circulation of solid particles. Steam was injected into a heat exchanger horizontally installed in the reactor in order to supply the endothermic heat of reaction. A partition was installed between the solid inlet and outlet to prevent solids from bypassing the desorption reactor. A bubbler was installed before the desorption reactor to generate vapor, which is required for simulated flue gas conditions. A preheater was installed in front of the desorption reactor to heat the gas, line heaters were installed in the gas inlet and outlet pipes to prevent moisture condensation in the gas. As the fluidising gas in the desorption reactor, a simulated flue gas used comprising mixtures of N₂ (99.999%), CO₂ (99.99%) and water vapor or recirculated gas used that gas stream discharged from the desorption reactor was recirculated by a gas recirculation system.

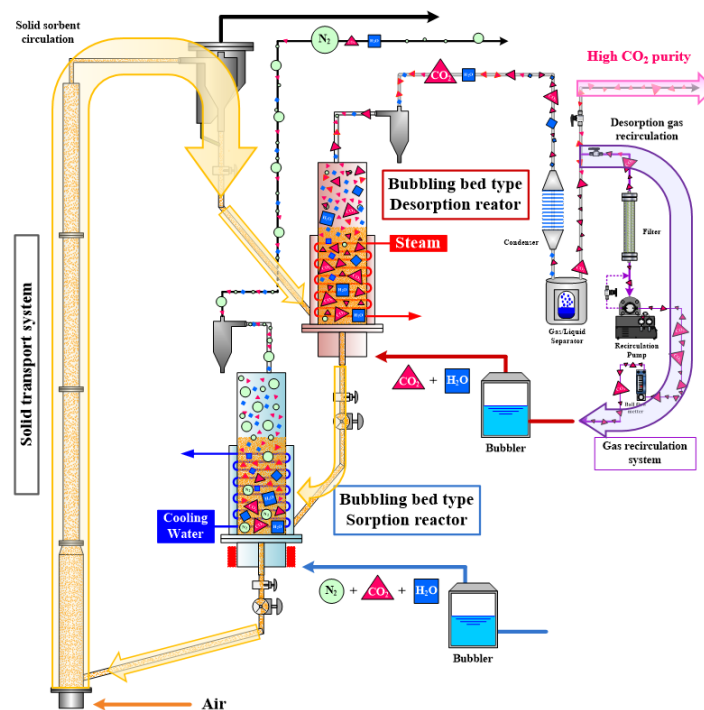


Figure 2. Schematic of the 100 kg scale fluidized bed continuous unit.

The solid transport system consists of a riser with a total height of 8.0 m and a perforated plate-type gas distributor. Air as a fluidizing gas was used to transport the solids to the main cyclone. The gas flowing into the transport tube transfers the solid particles to the main cyclone, the gas and solids were separated in the main cyclone and the separated solids are introduced into the desorption reactor. The solids introduced into the desorption reactor are regenerated and then supplied to the adsorption reactor, and the solids introduced into the sorption reactor adsorb CO₂ and then supplied to the solid transport system.



The solid circulation rate, the amount of solid circulated per time, was controlled by manipulating rotational speed of the rotary valve installed between the desorption and sorption reactor. According to the rotational speed of the rotary valves, this was calculated using the bulk density of the adsorbent and the change of the bed height of the sorption reactor during the given time. The gas flow rate of each component, such as Air, N₂ and CO₂ was controlled using an MFC (mass flow controller, E5850, Brooks instruments). The RTDs (Resistor Temperature Detectors, SENTECH ENG Co., Ltd., SEN-714, Korea) was installed in each reactor and gas and solid flow line so that the temperature of each point was measured. A pressure gauge (SIEMENS, STIRANS P500, France) and a differential pressure gauge (SIEMENS, STIRANS P500, France) were installed to investigate the fluidization state in the reactor and gas flow conditions. The humidity of the gas stream was measured using a thermo-hygrometer (KIMO INSTRUMENTS, C-310 multifunction, France) installed at the front and rear of each reactor. In addition, an IR gas analyser was installed to measure CO₂ concentration before and after the reaction in real time. Measured values from all instruments (thermometer, differential pressure gauge, analyser, etc.), installed in the 100 kg scale fluidized bed continuous unit were collected through PLC (Programmable Logic Controller).



Figure 3. Illustration of the 100 kg scale fluidised bed continuous unit; 1) the sorption reactor, 2) the desorption reactor, 3) the solid transport system (riser), 4) the main cyclone.

3.2.2 Conclusions

The 245-hour continuous test using alkoxyated PEI adsorbent in the 100 kg scale fluidized bed continuous unit demonstrated promising results for CO₂ capture. Under the optimal flow velocity condition of 3.0 cm/s, the alkoxyated PEI adsorbent exhibited excellent performance for CO₂ capture. At a desorption temperature of 110°C and a CO₂ concentration of 15%, the system achieved a



remarkable CO₂ removal efficiency of 96% and a dynamic sorption capacity of 3.3 wt.%. In the desorption phase, under the challenging condition of recovering high CO₂ concentration (95 vol.% of CO₂), a decrease in both CO₂ removal efficiency and dynamic sorption capacity was observed. However, it was observed that at an adsorption temperature of 50 °C and a desorption temperature of 120 °C, the system exhibited nearly 90% CO₂ removal efficiency and achieved a dynamic sorption capacity close to 3.0 wt.%. There is considerable scope to increase the dynamic sorption capacities to over 6.0 wt.%, particularly at 50°C, by operating at slightly higher desorption temperatures. The adsorbent had undergone little degradation during the test with a negligible difference of only 2% in the CO₂ adsorption capacity at the start and finish of the continuous test.

4 Activities and results for WP6

Within the ABSALT project, CEMEX was engaged in WP6 (Techno-economics/high level plant design) and WP7 (Environmental and project risk assessments), involved in the tasks related to process definition, system integration and operational risk assessment. This chapter is dedicated to the main outcomes of WP6.

Summary of the main achievements in WP6 (Techno-economics and High-level Demonstration Plant Design):

- The reference cement plant simulation has been completed with the results being close to an actual plant (data from CEMEX) with differences no more than 7%.
- The benefits of SALT in terms of lower operating costs compared to advanced amine systems have been demonstrated with the cost of CO₂ removal estimated at 45€ per tonne for a cement plant which can provide ca. 50% of the heat required for the regenerator and so reducing the CO₂ avoidance cost close to the initial target of 45€ per tonne, lower than that for amine scrubbing.
- The high stability of silica-APEI means that the rate of replacement of adsorbent are predicted to be extremely low, ca. 0.01% per hour.

4.1 Process boundary conditions, modelling and comparisons (Task 6.1)

For this task, several activities took place, including:

1. CEMEX providing raw meal chemical composition and raw mix proportions as well process information like fuels composition, fuel consumptions, heat demand, clinker production and raw-meal consumption, flue gases, emissions, etc. related to a **3200 ton per day** clinker plant.
2. The process definition for the full-scale cement integration. The size of the pilot plant corresponds to 5 to 10 MW of electricity. Industrial application would require 4 units, as in the case of the base line pilot plant.
3. Detailed process modelling and simulation with a comparative analysis between ABSALT and the monoethanolamine (MEA) scrubbing system have been carried out (including the calculation of specific CO₂ emissions, specific primary energy consumption for CO₂ avoided - SPECCA, CO₂ avoidance cost, etc.). The base case scenario cement plant is present in Figure 4.

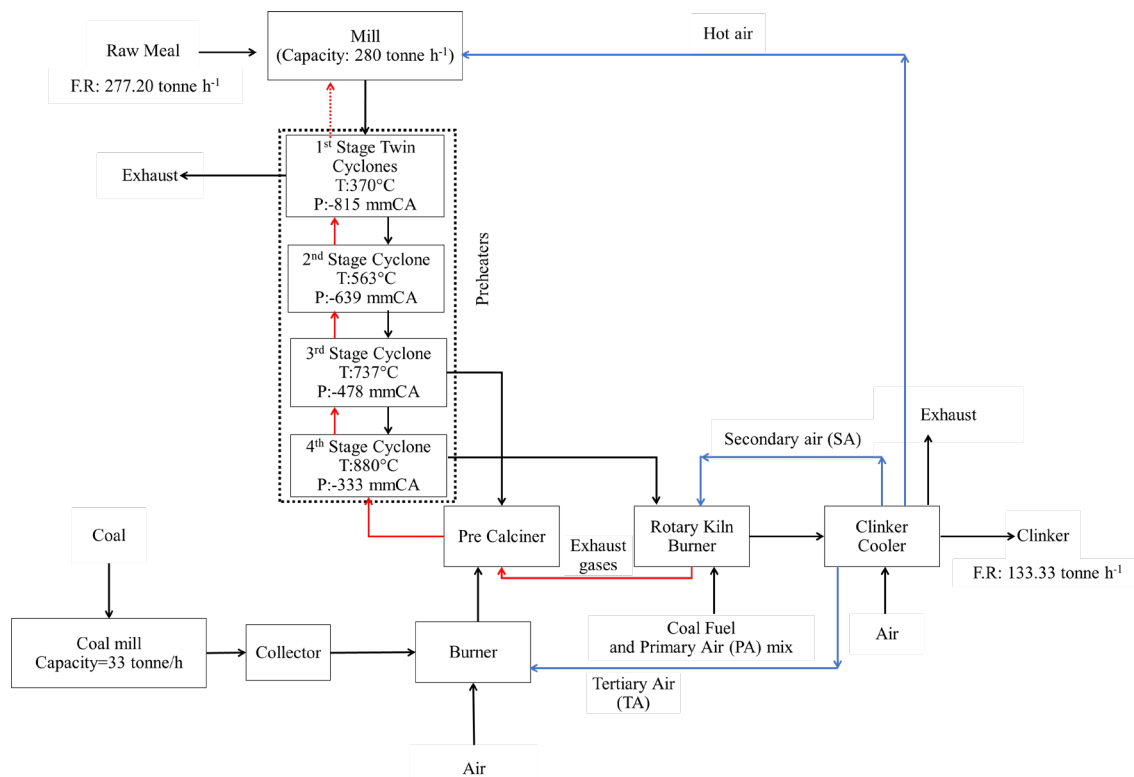


Figure 4. Main operating parameters of the reference cement plant^[6]

4.2 Mathematical modelling of reactors and ASPEN Plus process simulation (Task 6.2)

CERTH has performed simulation, optimization and techno-economic analysis of the overall ABSALT process. A mathematical model has been developed in order to describe the operation of an FCC-type reactor for both adsorption and desorption reactors. The model results of the model are incorporated to the Aspen Plus flow sheet simulation software in order to estimate the detailed mass and energy balances of the process. Based on these results, a techno-economic analysis was carried out in order to estimate: (i) equipment sizing and costing, (ii) fixed capital investment, (iii) annual operating costs, and finally (iv) cost per tonne of CO₂ captured. The following preliminary conclusions can be made for the ABSALT systems based on modelling results and assessment.

The ABSALT process can achieve very successful CO₂ removal. In the product stream, almost pure CO₂ is obtained suitable for further mitigation, while at the same time, 90% of total feed CO₂ is recovered. Also, 99.97% of the solid adsorbing material is recycled from the desorption back to adsorption reactor for reuse.

This results in substantial economic benefit of the proposed process compared to alternative CO₂ removal technologies.



4.3 Techno-economic evaluation of full-scale process integration (Task 6.3)

ULSTER, CERTH and CEMEX performed a techno-economic assessment for the integration of ABSALT into the cement plant. To establish techno-economic models and perform a comparison, three cases were considered. For cement production, a RK-based cement plant was chosen. The main economic results are listed below.

For the reference plant, the total specific direct heat consumption is estimated at 3.60 GJ/tonne clinker produced. In addition, the electricity consumption for process utility usages is calculated at 16.3 MWe, corresponding to 0.43 GJ/tonne of clinker. CO₂ emissions from the reference plant is estimated at 123 tonne CO₂/hr which corresponds to 0.92 tonne CO₂/tonne clinker. If 0.27 tonne CO₂/MWh of CO₂ emission factor for electricity generation is considered, the indirect CO₂ emissions showed the equivalent CO₂ emissions at 0.95 tonne CO₂/tonne clinker.

The following remarks can be drawn from the comparative analysis referring to the silica-PEI carbon capture technology and amine scrubbing integrated with a cement plant:

1. Both the studied processes can potentially remove $\geq 90\%$ of the CO₂ from the flue gas. MEA-based carbon capture process shows the SPECCA at 6.5 GJ/tonne CO₂. While the SPECCA for the SALT SPEI carbon capture process is lower compared to MEA based carbon capture process at 4.3 GJ/tonne CO₂.
2. The CO₂ capture cost of the MEA scrubbing process and SPEI-based processes is estimated at 61.4 and 49.8 €/tonne CO₂, respectively. The CO₂ avoidance cost of the MEA scrubbing process and SPEI-based carbon capture process is estimated at 84.7 and 62.2 €/tonne CO₂, respectively. The capture cost for advanced amine processes is comparable to the SPEI-based process, being lower in comparison to MEA. The reported CO₂ capture cost of advanced amine (MDEA) process is at 54 €/tonne CO₂ and the CO₂ avoidance cost estimated at 68 €/tonne CO₂, still about 9% higher than that of SPEI.
3. The sensitivity study shows that when both adsorber and desorber operating temperatures are increased from 50 to 60°C and from 115 to 125°C, the dynamic sorption capacity has been enhanced slightly from 8.58% to 8.78%. The total impact of temperature increase on CO₂ capture cost and CO₂ avoidance cost is around 4.9%.
4. The sensitivity analysis also shows that the minimum carbon capture cost is observed at 55.4 and 45.7 €/tonne CO₂ for the MEA-based carbon capture process and SPEI-based carbon capture process when the natural gas price is 20 €/MWh.
5. If a carbon tax is implemented, the BEBP of the reference cement plant increases significantly. At a carbon tax above 60 €/tonne CO₂, the cost of clinker produced with the cement plant integrated with the SPEI-based carbon capture process is lower than the reference cement plant. When the carbon tax is approximately 85 €/tonne CO₂, the BEBP of MEA-based carbon capture process is lower than the reference.
6. A maximum of 53 MWth of heat can be recovered from the reference cement plant. If a 100% of the available heat is recovered from the reference cement plant, the total CO₂ emissions reduces to up to 6.5% for the MEA-based carbon capture process. While, for the emissions reduces to up to 6.9% for the SPEI-based carbon capture process.
7. In the case of the 100% heat recovery from the cement plant, the cost of CO₂ capture for the MEAbased and SPEI-based carbon capture processes reduces to 48.0 €/tonne CO₂ and 35.6 €/tonne CO₂ respectively. Furthermore, the CO₂ avoidance cost for the MEA-based and SPEI-based carbon capture processes reduces to 57.5 €/tonne CO₂ and 44.5 €/tonne CO₂ respectively.



4.4 Design of demonstration plant facilities (Task 6.4)

The aim of Task 6.4 was to design and construct a small-scale ABSALT pilot plant unit with a flue gas flow rate of 14.5 tonne/hour. The design considered the experimental results provided by Nottingham and the detailed modelling data generated by Ulster University, serving as the foundation for the high-level design of the ABSALT system.

The high-level design of the pilot-scale plant was conducted with a CO₂ capture capacity of 3.6 tonne/hour.

The physical dimensions of the bubbling fluidized bed adsorber, riser, and bubbling fluidized bed desorber reactor were determined. Based on the calculations performed, as fully described in the deliverable report D6.4 for this task, the height and diameter of the bubbling adsorption fluidized bed reactor are 12.0 m and 1.6 m, respectively. For the riser to transfer adsorbent from the adsorber to the desorber, a total height of 32 m is required with a diameter of 0.7 m. Regarding the desorption reactor, a total height of 9.5 m is required with a diameter of 1.7 m. The capital cost required for the demonstration plant can be as high as 1.36 million euros. The capital cost for the proposed demonstration plant is estimated to be up to 3.66 million euros.

5 Activities and results for WP7

Summary of the main achievements in WP7 (Environmental Assessment via Life Cycle Analysis (LCA) and Project Risk Assessment):

- An endpoint single score was conducted which showed that the SALT process with silica-APEI had a lower impact on human health, ecosystems, and resources (7%, 9%, and 26% lower, respectively) compared to MEA scrubbing.

5.1 Environmental assessment via life cycle analysis (Task 7.1)

An LCA study was conducted to evaluate the environmental aspects, potential impact and sustainability associated with ABSALT process integrated with cement plants, using the commercial software SimaPro™ (in compliance with ISO 14040-14044 standards). Initial results demonstrated how clinker production and heat recovery for the reference cement plant can affect CO₂ emissions. In general, integration of both amine scrubbing and SALT with silica-PEI (SPEI) can eliminate the CO₂ from the flue gas to up to 90 %. The equivalent CO₂ emissions avoided were at 742.9 and 749.3 kg CO₂/tonne clinker for the MEA-based carbon capture process and SPEI-based carbon capture process, respectively. However, the requirement for electricity and natural gas increased for both carbon capture technologies, due to the additional energy required to operate CO₂ capture technologies.

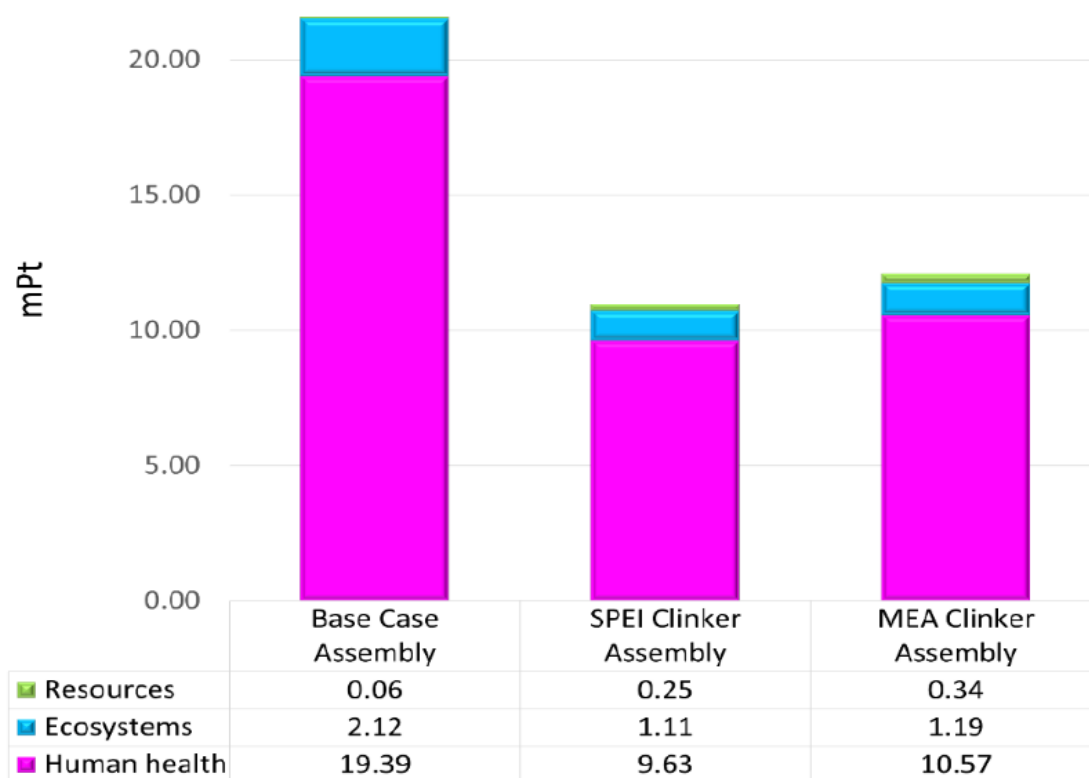


Figure 5. Endpoint single score results of reference cement plant, SALT SPEI-based and MEA-based carbon technology integration. 1 kg clinker.

From an environmental assessment perspective, the SPEI-based SALT carbon capture process integration showed better environmental performance compared to MEA-based integration in all impact categories, including global warming, acidification, and human toxicity. For example, for the global warming indicator, silica-PEI-based carbon capture technology integration has a lower value at 0.295 kg CO₂ eq., while MEA-based carbon capture technology integration exhibits a value at 0.331 kg CO₂ eq. Furthermore, the detailed endpoint analysis was also performed, and the single score endpoint results are shown in Figure 5.

Based on the LCA results the study provides evidence that the integration of silica-PEI-based carbon capture technology into cement plants can provide a viable solution for reducing CO₂ emissions from the cement industry. The result is a promising finding since CCS technologies are essential for mitigating the impact of CO₂ emissions on the environment. In addition, the results of the study suggest that the use of solid sorbents, such as amine-functionalized mesoporous silica, can be a viable alternative to liquid sorbents, such as aminebased solvents, in post-combustion carbon capture technology. The present study provides valuable insights for cement plant operators and policymakers in reducing carbon emissions from the cement industry.



5.2 Project Risk Assessment (Task 7.2)

This task focused on the assessment of possible risks of the applications of the full-scale ABSALT integration in cement plants.

From the perspective of technical risk assessment, no serious risks to human life or health have been found by the participants of the cement side. The highest risk detected on the ABSALT side is the failure in the absorber operation, including flue gas leakages and pretreatment. As well as performing a technical risk and reliability assessment for the ABSALT system integrated with a cement plant, the project also assessed the economic risks associated with technological development of the full-scale plant. Three risks were considered in the study: i) risk on the capital cost estimation; ii) risk on the cash flow coming from the uncertainties in the price/tariff considered (e.g. cement selling price, cost of fuels, electricity tariff, Silica PEI purchasing price); iii) risk related to the equipment failures following a Failure Mode and Effect Analysis.

To carry out the economic risk assessment for the full process, @Risk 8 (Palisade, 2021) was used, based on the Monte Carlo simulation ^[7]. Regarding the capital cost estimation risk, the ABSALT system integrated with the cement plant requires an 8% contingency budget. Assuming 54 M€, the cost for the ABSALT unit means an overall investment of 268 M€ for the ABSALT system integrated with the cement plant.

To avoid overrunning the initial budget, an estimated 23.6 M€ needs to be added to the initial budget.

The detailed findings can be found in the publication ^[8], where the ABSALT system was also compared to a MEA system for CCS. It was concluded that both the MEA investment and the SPEI based CCS processes provide a good investment option, with the SPEI showing better results due to a lower technical and economic risk derived from working at lower temperature (115°C towards 150°C), lower regeneration energy requirement (2.85 GJ/tonne CO₂ versus 4.25 GJ/tonne CO₂) and reduced sorbent losses (0.1% versus 0.3%).

Regarding the emission trading scheme, three Emission Trading Schemes were considered: i) EU ETS, ii) Switzerland ETS and iii) UK ETS. However, all the existing ETS are derived from the EU ETS, and the economic value of the allowances is comparable. They are all cap-and-trade systems. The cap on cement plants is currently the same for all the different schemes and was defined by Phase IV of the EU ETS (running from January 2021 to December 2030). After 2030, the UK could change the benchmark and reduce it to achieve a higher goal. Allowances are traded either in dedicated auctions or in markets. For 2021, the benchmark value was 693 kgCO₂/ton clinker, which was used in the current study. Based on the data shown in Table 1, cement plants need to buy allowances at the market/auction to cover 30% of their emissions. A value of free allowances allocation of 70% and 50% has also been used in the analysis below to understand the impact of the allowance price. In Switzerland, allowances can only be traded in auctions, while in the UK and the EU, allowances can also be traded in markets. For the present study, a price range between 50 to 150 €/tonne of CO₂ was set with the most likely



value of 80 €/tonne of CO₂, considering that the average price for EU and UK allowances in 2022-2026 was predicted to 79.22 and 84.4 €/tonne of CO₂, respectively; and the 2022 average auction price for the Swiss ETS allowances was 82 €/tonne.

Table 1. Technical input data for the analysis

Main process data	Baseline	MEA scenario	ABSALT scenario
Raw material input [€/tonnes]	245.77		
RDF input [tonne/hr]	14		
Tyres input [tonne/hr]	1.4		
Coal input [tonne/hr]	7		
Thermal input for the reference plant [MW _{th}]	133.4	133.4	133.4
Energy supply for MEA regeneration [MW _{th}]	/	162.8	/
Energy supply for SPEI regeneration [MW _{th}]	/	/	101.4
Power consumption [MW _e]	16.3	31.03	29.8
Required regeneration energy [GJ/tonne CO ₂]		3.53	2.53
Clinker production [tonne/hr]	133.4		
Natural gas consumption [GJ/hr]	/	162.83	102.38
Specific power consumption [MWh/tonne clinker]	0.12	0.223	0.232
Equivalent specific energy required [GJ/tonne clinker]		9.34	
CO ₂ captured [tonne CO ₂ /hr]		134.5	126.5
CO ₂ emissions on site [tonne CO ₂ /hr]	122.5	14.9	14.1
CO ₂ capture rate [%]		90%	90%
Specific direct CO ₂ emissions [kgCO ₂ /tonne clinker]	919	112.1	108.2
Specific indirect CO ₂ emissions [kgCO ₂ /tonne clinker]	34	63.7	61.02
Equivalent specific CO ₂ emissions (kg CO ₂ /tonne Clinker)	953	175.8	169.4

5.2.1 CASE 1. Baseline case – Cement plant

As previously mentioned, we used 70% and 50% of free carbon allowances for the analysis. In the case of 70% free allowances, there is a risk of 55% having a negative present value (Figure 6) and a risk of 46% (Figure 7), of having an IRR lower than 6% (that is the value of the discount rate = inflation rate plus interest rate on the loan). For 50% free allowances, there is a risk of 77% having a negative present value (Figure 8) and a risk of 58% having an IRR lower than 6% (Figure 9). Therefore, the investment in cement plants is not economically attractive with a carbon tax/mechanism, without a CCS system and using the current fuel.

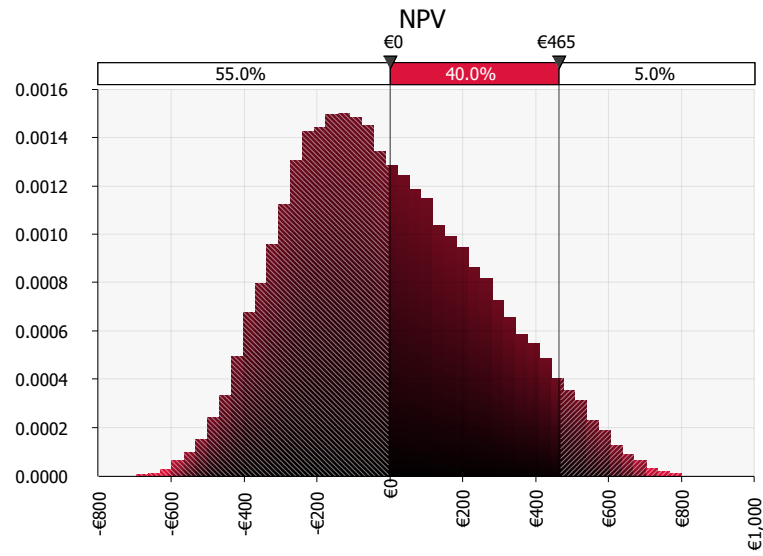


Figure 6. Baseline case with 70% free allocation of CO₂ allowances – NPV probability distribution

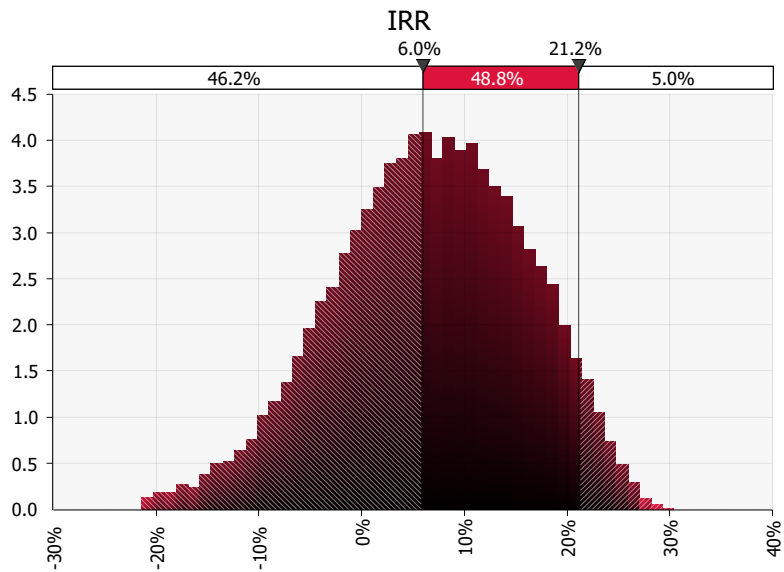


Figure 7. Baseline case with 70% allocation of CO₂ allowances – IRR probability distribution

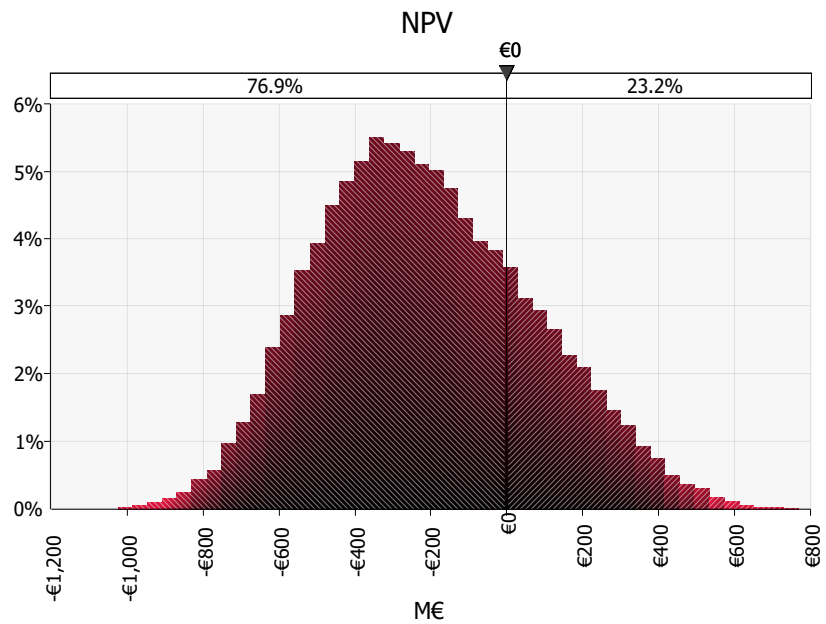


Figure 8. Baseline case with 50% free allocation of CO₂ allowances – NPV probability distribution

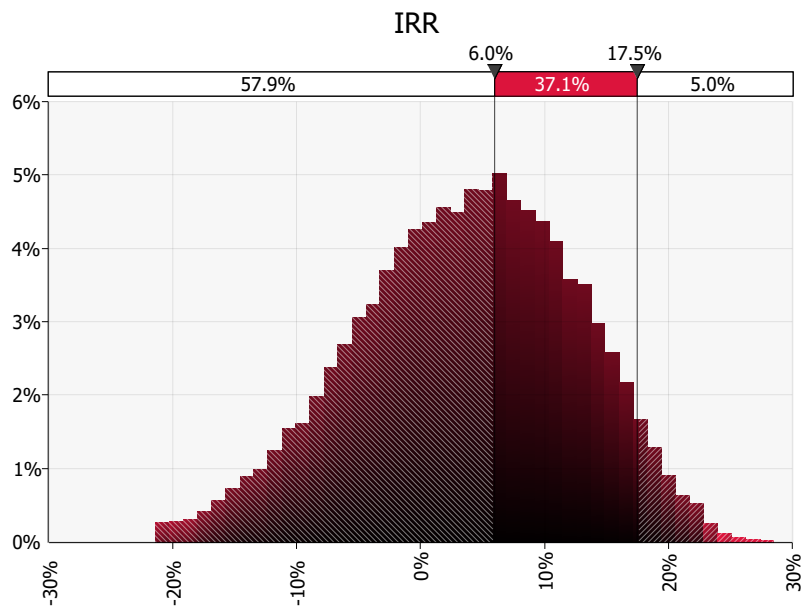


Figure 9. Baseline case with 50% free allocation of CO₂ allowances – IRR probability distribution

It is worth noting that if there is no carbon tax mechanism, there is a risk of 10% of having a negative NPV and IRR; cement plants are, therefore, at risk of relocation. However, following the new Carbon Border Adjustment mechanism adopted in August 2023 to avoid the so-called plant relocation ('carbon leakage'), the cement produced outside the EU must pay a levy to be imported into the EU ^[9].



5.2.2 CASE 2. MEA case

For a cement plant with a MEA CCS, there is a risk of 6.7% having a negative present value (Figure 10) and 6.6% having an IRR below 6% (Figure 11). The investment of a cement plant with MEA CCS is economically viable. If we look at the contribution to variance, the main cost items are the CO₂ tariff (55%), the cement selling price (37%), the electricity price (2.9%) and the NG price (2.5%).

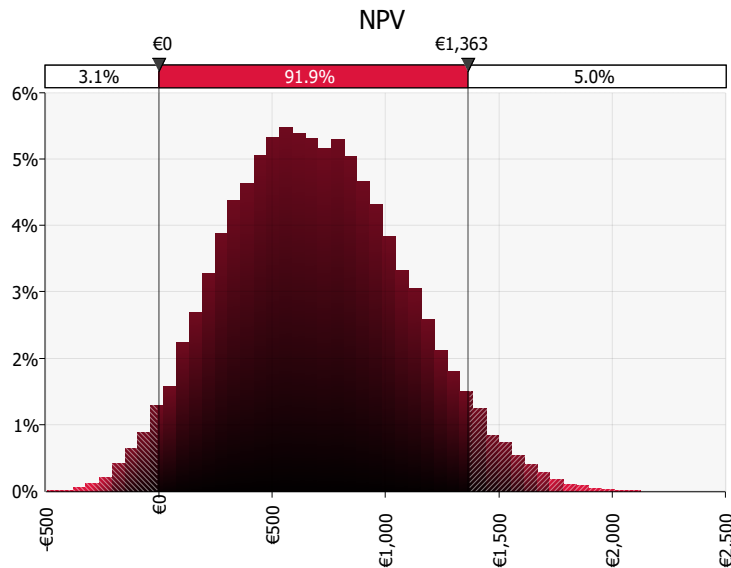


Figure 10. MEA scenario – NPV probability distribution

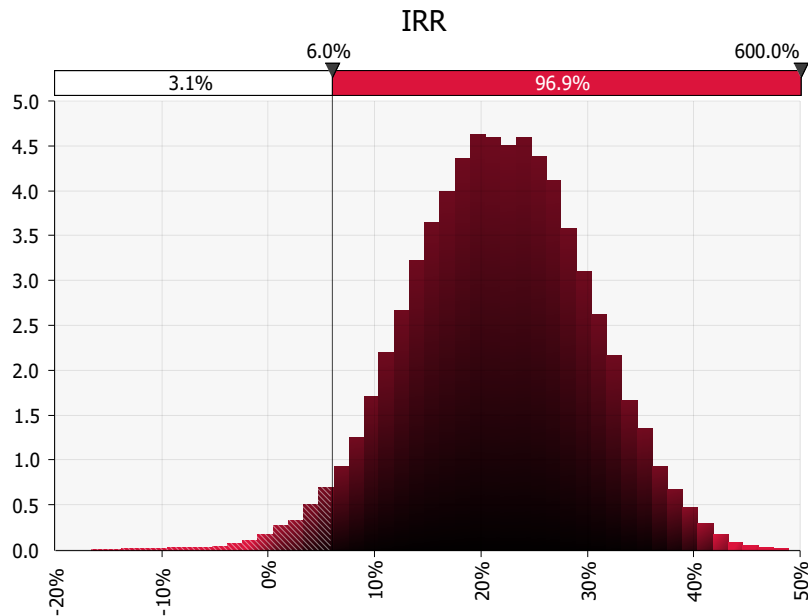


Figure 11. MEA scenario – IRR probability distribution



5.2.3 CASE 3. Case ABSALT

In the case of the ABSALT CCS, there is a risk of less than 1% having a negative present value (Figure 12) and an IRR below 6% (Figure 13). Compared to the MEA solution, the better result derives from a lower capital cost and reduced exposure to the cost of natural gas and electricity prices since the electricity and NG consumption is lower than the MEA solution. If we look at the contribution to the variance of the different parameters, the main parameters are the cement selling tariff (53%) and the CO2 tariff (42.6%), followed by the electricity purchasing price (2.9%) and the NG tariff (1%).

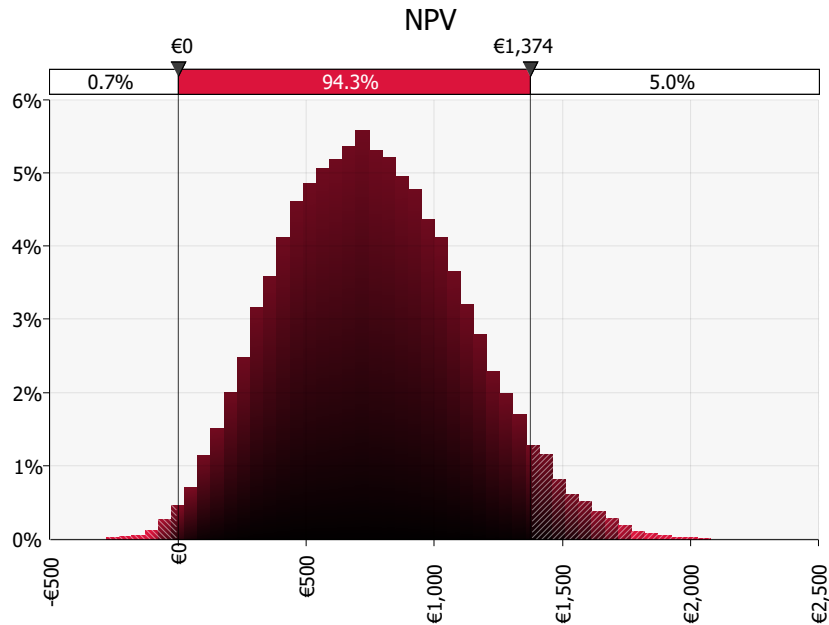


Figure 12. ABSALT scenario – NPV probability distribution

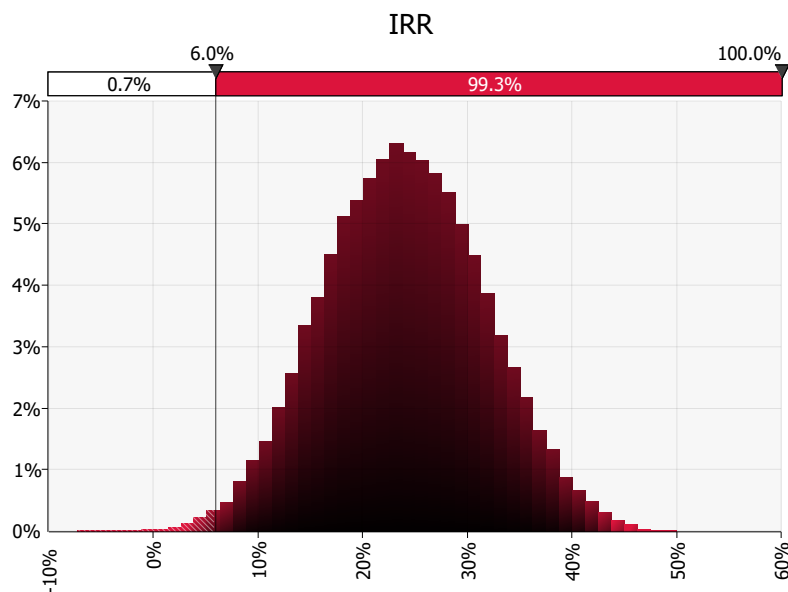


Figure 13. ABSALT scenario – IRR probability distribution



5.2.4 Public Availability and Transferability to Switzerland

The results of the techno-economic study (TEA) and life cycle analysis (LCA) conducted as part of the ABSALT project are publicly available and have been designed to be transferable to Switzerland's conditions. The studies are congruent with existing research on CO₂ capture technologies and provide a comprehensive understanding of the integration of Silica-Polyethylenimine (PEI) based CO₂ capture technology into cement plants.

The quantitative results from the ABSALT project are largely transferable to Swiss applications. However, some adaptations may be necessary to account for specific local conditions. Swiss cement facilities operate under distinct regulatory, operational, and environmental conditions compared to other European plants. Factors such as stricter emissions regulations, varying feedstock compositions, and differences in production processes may influence the technology's performance and efficiency in real-world scenarios.

The LCA was conducted using software that is also utilized by Swiss authorities, ensuring compatibility and alignment with local standards. This compatibility facilitates the transferability of the results to Swiss applications and enhances the reliability of the findings.

It is important to note that the Silica-PEI based CO₂ capture technology has not yet been tested under real cement flue gas conditions. A thorough assessment is necessary to understand how the technology can be adapted to meet Switzerland's specific requirements, including any potential modifications to optimize its effectiveness in capturing CO₂ from actual flue gas emissions. Additional pilot testing in a real Swiss cement plant environment will be essential to validate the technology's transferability and ensure its success in contributing to Switzerland's sustainability goals. Therefore, it is recommended to conduct pilot testing in any type of facility to ensure the technology's effectiveness before making any investment and scale-up decisions. This step is crucial to validate the technology's performance and address any potential uncertainties.

Detailed reports on the LCA and TEA are provided as appendices to this report. These reports include comprehensive data and analysis on the environmental and economic performance of the Silica-PEI based CO₂ capture technology. For further details, please refer to the appendices or visit the following link: [Publications – ABSALT](#)

6 Comments & conclusions

- The proposed technology results very attractive according to the results presented, especially the development of the alkoxyated PEI which has been proven to improve stability vs conventional PEI. It would be interesting to observe how this technology evolves in the field of carbon capture.
- With further research and development of this technology, it is possible that in the next years it could achieve even better performance and be comparable absorbents already in operation that should be used as a benchmark.
- The reference plant information was a combination of online information and Cemex data, therefore we recommend (in case of a next step in the cement plant application) using real data from a specific cement plant.



- For this technology to become viable in real-world applications, it would need to demonstrate effectiveness and efficiency in capturing CO₂ in actual cement plant operations beyond synthetic flue gas conditions.

Several conditions need to be met for successful implementation:

- **Scalability and Adaptability:** The technology must integrate seamlessly into existing cement plant infrastructures without significant operational disruptions or prohibitively high retrofitting costs.
 - **Energy and Cost Efficiency:** To be attractive, the CO₂ capture process should minimize energy demand and operational costs to stay competitive within the cement industry's thin margins.
- Unfortunately, Cemex was not able to see any pilot operating on site (neither 5 kg, nor 100kg) which would be good to enhance further partnership and potential future pilot in one of the Cemex sites.
 - Switzerland's cement industry is a relatively small yet essential part of its industrial sector, contributing notably to national emissions. Given the country's ambitious carbon neutrality targets, this technology could significantly impact the cement industry's ability to meet these goals. Switzerland has a strong focus on sustainable practices and innovation, and the adoption of efficient CO₂ capture technologies aligns well with its environmental goals. The current synthetic test results, while promising, indicate that continued development and real-plant trials are necessary to validate the technology's effectiveness and cost-efficiency in a Swiss context.
 - Suggested Path Forward for Swiss Industry:
 - **Conduct a Swiss-Specific TEA and LCA:** To quantify the technology's feasibility, economic impact, and environmental benefits under Swiss market conditions.
 - **Identify Pilot Testing Partners:** Partner with local cement plants interested in hosting pilot trials, which will provide real-world data and potential early adopter benefits.
 - **Collaborate with Policy Makers:** Work closely with Swiss environmental regulators to ensure the technology aligns with evolving policies, such as the CO₂ tax and potential subsidies for carbon capture.



7 Dissemination activities including list of publications

7.1 Patent applications

1. Application No. EP22207176.3 Process for preparing compositions containing alkoxyated polyalkyleneimines, said compositions and their uses. Filed 14 November 2022. Proceeded to secondary filing, application no. PCT/EP2023/08671.
2. Application No. 22215665.5 Sorbents for carbon dioxide capture. Filed 21 December 2022. Proceeded to secondary filing, application no. PCT/EP 2023/086718.

7.2 Published peer-reviewed journal papers and linked conference presentations

1. I. Coralli, D Fabbri, A Facchin, C Torri, LA Stevens and CE Snape, Analytical pyrolysis of branched polyethyleneimines, J. Analytical & Applied Pyrolysis, 2023, 169, 105838. *Presented at PYRO 2022: 23rd International Conference on Analytical and Applied Pyrolysis Ghent (BE). Almost 250 scientists participated at this Conference; the oral contribution was presented at the opening event with a large participation; some of the attendees expressed their appreciation for the novelty and interest on the pyrolysis of PEI.*
2. I. Coralli, D Giuri, L Spada, J Ortolani, L Mazzocchetti, C.Tomasini, L.A Stevens, C.E Snape and D.Fabbri, Valorization Strategies in CO₂ Capture: A new life for exhausted silica-polyethylenimine, International J. of Molecular Sciences, 2023, 24, 14115.
3. I. Coralli and D Fabbri, Pyrolysis acetylation: a novel on-line Py-GC-MS derivatisation for the characterisation of nitrogen-containing polymers J. of Analytical and Applied Pyrolysis, 2023, 175, 106178.
4. I. Coralli, D. Giuri, L. Spada, J. Ortolani, L. Mazzocchetti, C. Tomasini, L.A. Stevens, C.E. Snape and D. Fabbri, Valorization strategies in CO₂ capture: A new life for exhausted silica-polyethylenimine, Int. J. of MolecularSciences, 2023, 24(19), 14415, doi: org/10.3390/ijms241914415.
5. I. Coralli, L. Spada, D. Fabbri, Seyedeh Rojin Sahriati Pour, J. Fiori, I. Vassura, S. Stefanidis, A. Lappas, L.A. Stevens and C.E. Snape, GC-MS analysis of alkylpyrazines in the pyrolysis oils of silica-polyethylenimine CO₂ sorbents, J. of Chromatography Open, 2024, 5, 100108, doi: org/10.1016/j.jcoa.2023.100108.
6. M.M. Jaffar, C. Brandoni, J. Martinez, C. Snape, S. Kaldis, A. Rolfe, A. Santos, B. Lysiak, A. Lappas, N. Hewitt and Y. Huang, Comparative techno-economic analysis of the integration of MEA-based scrubbing and silica PEI adsorbent-based CO₂ capture processes into cement plants, J. of Cleaner Production, 2023, 414, 137666, doi.org/10.1016/j.jclepro.2023.137666. *Based on this manuscript, a conference paper was presented at the TCCS 12th conference in Trondheim. About ninety people from universities, businesses, and environmental agencies attended the oral presentation, generating a great deal of interest in the research topic and encouraging dialogue. Following the talk, a few attendees expressed gratitude and asked for more details. Especially, the Korea Institute of Energy Research and Technical University of*



Darmstadt offered potential for future collaboration. IIT Bombay promised avenues for future research partnerships.

7. M.M. Jaffar, A. Rolfe, C. Brandoni, J. Martinez, C.E. Snape, S. Kaldis, A. Santos, B Lysiak, A. Lappas, N. Hewitt and Y Huang, A technical and environmental comparison of novel silica PEI adsorbent-based and conventional MEA-based CO₂ capture technologies in the selected cement plant, Carbon Capture Science & Technology, 2024, 10,100179, doi: org/10.1016/j.ccst.2023.100179.

7.3 Other conference presentations

1. S.D. Stefanidis et al., Recycling of spent solid CO₂ adsorbents via catalytic pyrolysis for the recovery of mesoporous silica and valuable heteroaromatic chemicals, PYROLIQ II – 2023: Pyrolysis and Liquefaction of Biomass and Wastes, Schloss Hernstein, Austria, May 7-12, 2023. *The oral presentation engaged an audience of approximately 100 attendees, sparking significant interest and interactive discussions around the research topic. Following the presentation, several participants expressed their appreciation and requested additional information, particularly concerning the reuse of the recovered mesoporous silica as a substrate for producing new Si-PEI adsorbents.*
2. S.D Stefanidis et al., Catalytic pyrolysis of spent solid CO₂ adsorbents for the recovery of raw materials and valuable heteroaromatic chemicals, EUBCE 2023 - 31st European Biomass Conference and Exhibition, Bologna, Italy, June 5-8, 2023. *The work was presented as a poster to about 1500 attendees of the conference from 79 countries. The poster presentation was supplemented by a concise 2-minute talk to a group of about 20 attendees. The presentation successfully engaged the audience, eliciting follow-up questions about the composition of the pyrolysis oils and the pore volume of the silica recovered. Additionally, numerous attendees noted the ABSALT project's website for further exploration.*
3. I. Coralli, D. Giuri, L. Spada, J. Ortolani, L. Mazzocchetti, C. Tomasini and D. Fabbri,
(i) 2022. XXIX Congresso Nazionale della Divisione di Chimica Analitica Milazzo (IT). *The most important Conference in Italy for Analytical Chemistry; the poster was presented at the separation science session attracting the interest of attendees in the analytical application in the field of CCS.*
(ii) 2023. XXX Congresso Nazionale della Divisione di Chimica Analitica Milazzo (IT). *The most important Conference in Italy for Analytical Chemistry; the poster was presented at the separation science session, the new analytical method developed within ABSALT raised the interest of attendees.*
2023. Giornata della Ricerca CIRI-FRAME Ravenna (IT)
The talk was presented at a local meeting of stakeholders from academy and industry in Ravenna; the area of the Adriatic coast will be involved in of one of the largest hub for CCS in Europe.
4. M.M. Jaffar, A. Rolfe, C. Brandoni, tw N. Hewitt and Y Huang, Post-combustion CO₂ capture: A comparative techno-economic assessment of solid adsorbent looping technologies in cement plants, IACC-CSCST-SCI workshop on carbon capture, Queen's University of Belfast, 05 December 2023 (*This workshop was originally supported by EU and Global Partnership*). *About 40 people from UK and Chinese universities and businesses, attended the oral presentation,*



creating a great deal of interest in the research topic. After the presentation, we were approached by several participants asking for more detail.

7.4 Peer-reviewed publications in preparation

Now that the two patent applications have proceeded to secondary filing, publications from WP1-4 are now being drafted. This will cover applications to both industrial and direct air capture. Further, a non-specialist publication on ABSALT to the World Cement Organisation is being prepared with CEMEX.

7.5 Remaining conference presentations

8. M.M. Jaffar, A. Rolfe, C. Brandoni, J. Martinez, C.E. Snape, S. Kaldis, A. Santos, B Lysiak, A. Lappas, N. Hewitt and Y Huang, Technical and economic risk of post-combustion carbon capture and storage systems integrated into cement plants. 6th International Conference on Energy and Environment: bringing together Engineering and Economics, Guimarães, Portugal, 6-7 June 2024.
9. S.D. Stefanidis et al., Confirmed oral presentation at the 24th International Symposium on Analytical and Applied Pyrolysis (Pyro2024) that was held on 19–23 May, 2024, in Beijing, China (<https://pyro2024.csp.org.cn/>)
10. S.D. Stefanidis et al., Confirmed oral presentation at the 14th Panhellenic Scientific Chemical Engineering Conference that was held on 29-31 May, 2024, in Thessaloniki, Greece (<https://pesxm14.gr/>)

8 References

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