Comparative environmental assessment of novel silica pei-based versus mea-based co2 capture technologies in the cement plant

COMPARATIVE ENVIRONMENTAL ASSESSMENT OF NOVEL SILICA-PEI-BASED VERSUS MEA-BASED CO_2 CAPTURE TECHNOLOGIES IN THE CEMENT PLANT

M. Jaffar[a], A. Rolfe[a], C. Brandoni[a], J. Martinez[b], A. Santos[b], C. Snape[c], B. Lysiak [b], N. Hewitt[a] and Y. Huang[a]

[a] Ulster University, Belfast, Northern Ireland, UK

[b] CEMEX Innovation Holding AG, Switzerland

[c] Faculty of Engineering, University of Nottingham, Nottingham, UK

Corresponding author's e-mail address: m.jaffar@ulster.ac.uk

Keywords: Post-combustion capture: adsorption/absorption, silica polyethyleneimine (silica-PEI), Monoethanolamine, environmental assessment, CO_2 removal (CDR)

ABSTRACT

The cement industry is a major contributor to greenhouse gas emissions, responsible for approximately 7% of global CO_2 emissions (Busch et al., 2022, Hannah Ritchie, 2020). With the global demand for cement expected to continue increasing, it is important to find ways to reduce CO_2 emissions from the industry. Several strategies have been proposed, including the use of alternate renewable and sustainable fuels, supplementary cementitious materials (SCMs), and carbon capture and storage (CCS) technologies (Balamuralikrishnan and Saravanan, 2021, Bayraktar et al., 2019a, Bayraktar et al., 2019b, Khan et al., 2020, Nie et al., 2022). However, the supply of alternate renewable and sustainable fuels and SCMs is limited compared to cement production (Gartner and Hirao, 2015). Furthermore, switching to alternate sustainable and renewable fuels can remove only one-third of the carbon dioxide as almost 65 % of CO_2 emissions are linked to the calcination of limestone. Therefore, of these strategies, CCS is considered to have the greatest potential for reducing emissions from cement production.

One approach to CCS is post-combustion carbon capture technology, which involves capturing CO_2 from flue gases after combustion. The technology is already commercially proven, but liquid amine-based sorbents, which are commonly used, have several disadvantages, including high regeneration costs, equipment corrosion, and oxidative degradation (Zhang et al., 2014). Therefore, solid sorbents, such as amine-functionalized mesoporous silica, have been proposed as an alternative for CO_2 capture (Khosravi et al., 2022, Arcenegui Troya et al., 2022, Girimonte et al., 2022, Yan et al., 2022).

In this study, the environmental impact of integrating a novel silica polyethyleneimine based (silica-PEI) carbon capture system into a cement plant for carbon capture is assessed. The

environmental impact of the silica-PEI-based system is compared to a conventional MEA-based carbon capture system, which is widely used in the industry. The assessment is based on real data from an existing cement plant CEMEX in Switzerland and is simulated using experimental and pilot-scale results (Kim et al., 2021, Zhang et al., 2014).

To perform the environmental assessment, three scenarios were established: *i)* a base case cement plant without CO_2 capture, *ii)* cement plant with silica-PEI-based carbon capture technology, and *iii)* cement plant with MEA-based carbon capture technology. The schematic diagrams of silica-PEI-based and MEA based carbon capture technologies are presented in Figure 1. Process models for each scenario were developed using the ECLIPSE modeling software, which provided the technical analysis and provided the basis for life cycle analysis (LCA). To determine the environmental impact, a "cradle to gate" LCA for the CO_2 capture technologies was carried out. The ReCiPE method was used to perform the life cycle impact assessment (LCIA) in the SimaPro software. LCIA transcribes process emissions and material extraction into a limited number of environmental impacts using characterisation factors.

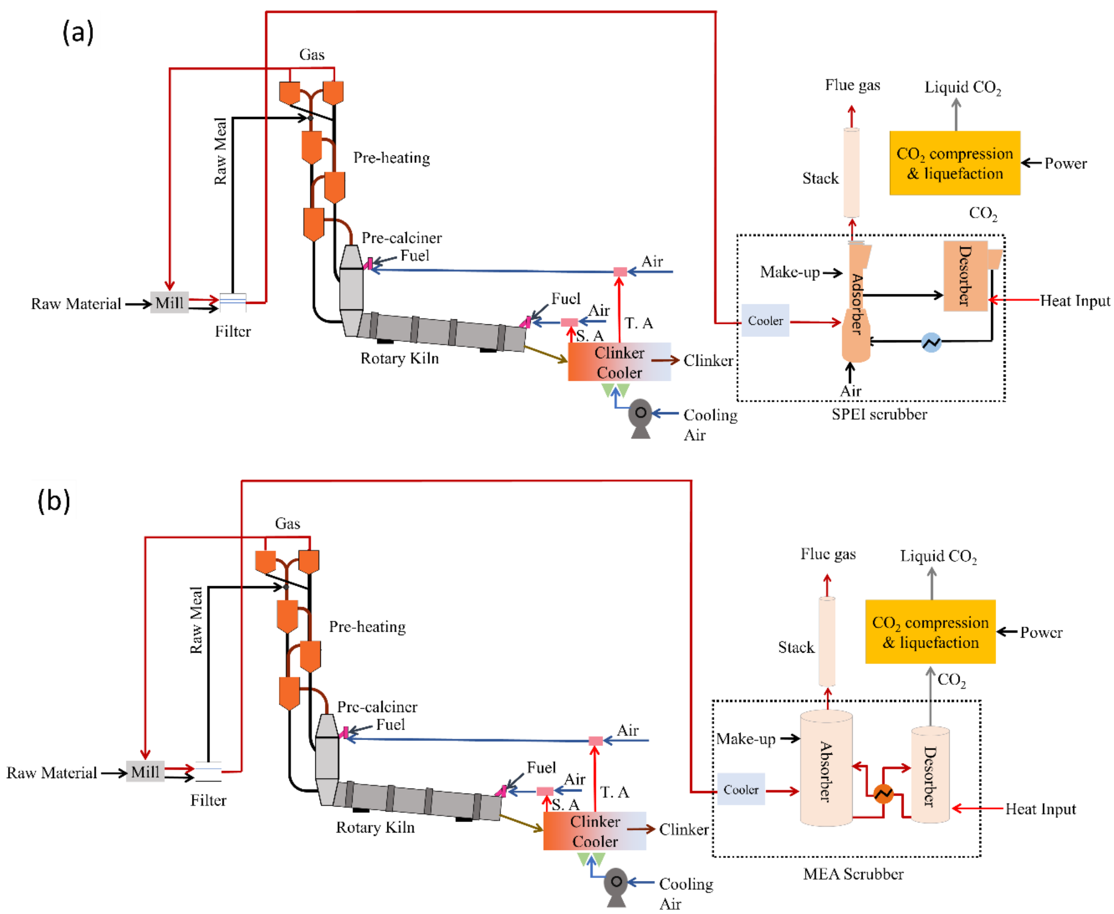
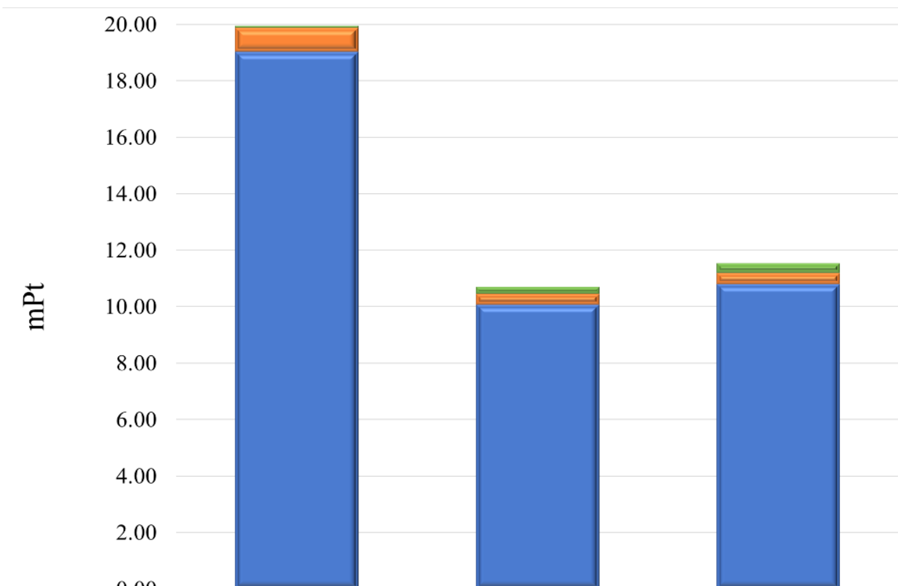


Figure 1 Schematic diagram of a) Silica-PEI-based carbon capture process integration b) MEA-based carbon capture process integration.

The analysis showed that the silica-PEI-based carbon capture unit has a lower environmental impact compared to the MEA-based carbon capture technology. This is primarily due to the lower CO_2 emissions resulting from the requirement for less heat from the natural gas boiler for sorbent regeneration. The CO_2 emissions rate from the natural gas boiler is at 56.1 kg CO_2/GJ NG (Voldsund et al., 2019). The lower regeneration heat requirement of the silica-PEI-based process is due to the lower heat capacities of solid sorbents compared to aqueous solvents, resulting in less heat needed for regeneration. In addition, the solid silica-PEI-based carbon capture process avoids solvent and water evaporation, which further contributes to its lower environmental impact (Bos et al., 2018). The CO_2 produced from the reboiler is also captured; therefore, the electricity requirement for compressing and liquefying the captured CO_2 is lower for the silica-PEI-based process due to the production of less CO_2. It is assumed that the electricity is obtained from the national grid with a CO_2 emission rate of 274 kg CO_2/MWh (bp, 2022). The results of the LCA showed that the environmental impact of the silica-PEI-based system was lower than that of the MEA-based system in all the midpoint categories. For example, for the global warming indicator, silica-PEI-based carbon capture technology integration has a lower value at 0.338 kg CO_2 eq., while, MEA-based carbon capture technology integration exhibits a value at 0.363 kg CO_2 eq. Furthermore, the detailed endpoint analysis was also performed and the single score endpoint results are shown in the Figure 2.



	Reference cement plant	SPEI Integration	MEA Integration
Resources	0.06	0.26	0.35
Ecosystems	0.85	0.37	0.40
Human health	19.02	10.07	10.79

Figure 2 Endpoint single score results of reference cement plant, SPEI-based and MEA-based carbon technology integration. 1 kg clinker.

In conclusion, the study provides evidence that the integration of silica-PEI-based carbon capture technology into cement plants can provide a viable solution for reducing CO_2 emissions from the cement industry. The result is a promising finding since CCS technologies are essential for mitigating the impact of CO_2 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 amine-based 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.

REFERENCES:

ARCENEGUI TROYA, J. J., MORENO, V., SANCHEZ-JIMÉNEZ, P. E., PEREJÓN, A., VALVERDE, J. M. & PÉREZ-MAQUEDA, L. A. 2022. Effect of Steam Injection during Carbonation on the Multicyclic Performance of Limestone (CaCO3) under Different Calcium Looping Conditions: A Comparative Study. *ACS Sustainable Chemistry & Engineering,* 10**,** 850-859.

BALAMURALIKRISHNAN, R. & SARAVANAN, J. 2021. Effect of addition of alccofine on the compressive strength of cement mortar cubes. *Emerging Science Journal,* 5**,** 155-170.

BAYRAKTAR, O. Y., SAGLAM-CITOGLU, G., BELGIN, C. M. & CETIN, M. 2019a. Investigation of the mechanical properties of marble dust and silica fume substituted portland cement samples under high temperature effect. *Fresenius Environmental Bulletin,* 28**,** 3865-3875.

BAYRAKTAR, O. Y., SAGLAM-CITOGLU, G., BELGIN, C. M., CETIN, S. & CETIN, M. 2019b. Investigation of effect of brick dust and silica fume on the properties of portland cement mortar. *Fresenius Environmental Bulletin,* 28**,** 7823-7832.

BOS, M. J., KROEZE, V., SUTANTO, S. & BRILMAN, D. W. F. 2018. Evaluating Regeneration Options of Solid Amine Sorbent for CO2 Removal. *Industrial & Engineering Chemistry Research,* 57**,** 11141-11153.

BP 2022. bp Statistical Review of World Energy.

BUSCH, P., KENDALL, A., MURPHY, C. W. & MILLER, S. A. 2022. Literature review on policies to mitigate GHG emissions for cement and concrete. *Resources, Conservation and Recycling,* 182**,** 106278.

GARTNER, E. & HIRAO, H. 2015. A review of alternative approaches to the reduction of CO2 emissions associated with the manufacture of the binder phase in concrete. *Cement and Concrete research,* 78**,** 126-142.

GIRIMONTE, R., TESTA, F., TURANO, M., LEONE, G., GALLO, M. & GOLEMME, G. 2022. Amine-Functionalized Mesoporous Silica Adsorbent for CO2 Capture in Confined-Fluidized Bed: Study of the Breakthrough Adsorption Curves as a Function of Several Operating Variables. *Processes,* 10**,** 422.

HANNAH RITCHIE, M. R. A. P. R. 2020. CO_2 and Greenhouse Gas Emissions. *OurWorldInData.org*.

KHAN, F. A., SHAHZADA, K., ULLAH, Q. S., FAHIM, M., KHAN, S. W. & BADRASHI, Y. I. 2020. Development of environment-friendly concrete through partial addition of waste glass powder (WGP) as cement replacement. *Civil Engineering Journal,* 6**,** 2332-2343.

KHOSRAVI, S., HOSSAINPOUR, S., FARAJOLLAHI, H. & ABOLZADEH, N. 2022. Integration of a coal fired power plant with calcium looping CO2 capture and concentrated solar power generation: Energy, exergy and economic analysis. *Energy,* 240**,** 122466.

KIM, J.-Y., WOO, J.-M., JO, S.-H., KIM, H., LEE, S.-Y., YI, C.-K., MOON, J.-H., NAM, H., WON, Y., STEVENS, L. A., SUN, C., LIU, H., LIU, J., SNAPE, C. E. & PARK, Y. C. 2021. Performance of a silica-polyethyleneimine adsorbent for post-combustion CO2 capture on a 100 kg scale in a fluidized bed continuous unit. *Chemical Engineering Journal,* 407**,** 127209.

NIE, S., ZHOU, J., YANG, F., LAN, M., LI, J., ZHANG, Z., CHEN, Z., XU, M., LI, H. & SANJAYAN, J. G. 2022. Analysis of theoretical carbon dioxide emissions from cement production: Methodology and application. *Journal of Cleaner Production,* 334**,** 130270.

VOLDSUND, M., GARDARSDOTTIR, S. O., DE LENA, E., PÉREZ-CALVO, J.-F., JAMALI, A., BERSTAD, D., FU, C., ROMANO, M., ROUSSANALY, S. & ANANTHARAMAN, R. J. E. 2019. Comparison of technologies for CO2 capture from cement production—Part 1: Technical evaluation. 12**,** 559.

YAN, H., ZHANG, G., XU, Y., ZHANG, Q., LIU, J., LI, G., ZHAO, Y., WANG, Y. & ZHANG, Y. 2022. High CO2 adsorption on amine-functionalized improved macro-/mesoporous multimodal pore silica. *Fuel,* 315**,** 123195.

ZHANG, W., LIU, H., SUN, C., DRAGE, T. C. & SNAPE, C. E. 2014. Performance of polyethyleneimine–silica adsorbent for post-combustion CO2 capture in a bubbling fluidized bed. *Chemical Engineering Journal,* 251**,** 293-303.