International Journal of Greenhouse Gas Control 112 (2021) 103524

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Techno-economic assessment of an industrial carbon capture hub sharing a cement rotary kiln as sorbent regenerator

P. Lisbona [a,*], R. Gori [b], L.M. Romeo [a], U. Desideri [b]

[a] EINA. Departamento de Ingeniería Mecánica, Universidad de Zaragoza, Campus Río Ebro, María de Luna 3, Zaragoza 50018, Spain

[b] Facoltà di Ingenieria. Dipartimento di Ingegneria dell'Energia, dei Sistemi, del Territorio e delle Costruzioni. Università di Pisa, Via Carlo Francesco Gabba, 22, Pisa 56122, Italy

ARTICLE INFO

Keywords:
Carbon capture
Cement production
Oxycombustion
Centralized capture system
Economic feasibility

ABSTRACT

The concept of CCS cluster brings together multiple CO_2 industrial emitters using shared capture and/or transportation infrastructure and offers several advantages for network partners compared with point-to-point individual projects. It reduces costs for CCS, and enables CO_2 capture from small volume industrial facilities. The proposed concept connects a cluster of industrial sites with significant heat demands with a cement plant through the implementation of a Ca-looping CCS system. This system treats the flue gas from all the industrial emitters in independent boiler/carbonators while uses the kiln furnace as calciner for the cement and the capture plant. The carbonator reactors located in each one of the industry sites are fed by CaO from the cement plant to capture the CO_2 content of their own flue gas. After carbonation reaction, the exhaust sorbent is transported back to the cement plant for regeneration in the kiln furnace. The aim of this work is to analyse the techno-economic feasibility of the proposed Ca-looping CCS cluster. The economic assessment, assuming 20 €/ton CaO and carbon market 30 €/ton CO_2 points out the feasibility of this kind of centralized carbon capture system to handle the carbon from small emitters. Results show that the operating costs of small companies that use coal or natural gas reduce from 21.3 M€ to 18.8 M€ or from 25.5 to 23.0 M€. For the cement industry this income lessens its operating costs 1.9 M€ lower than a reference situation where CCS is only implemented in cement plant.

1. Introduction

In order to meet the international commitments regarding the reduction of CO_2 emissions and achieve the goal of limiting the global temperature rise this century well below 2 °C above pre-industrial levels, the participation of CCS/CCU technologies is essential (IPCC 2014).

An increase of the share of renewable energy in electricity production will reduce the CO_2 emissions of the power sector (IPCC 2014). This could lead to an important contribution to global emissions reduction since over 40% of CO_2 emissions are caused by power sector (electricity and heat generation) (International Energy Agency IEA 2020). However, the use of renewable energy in the industrial sector has a limited impact given the requirement of very high temperature heat and/or the processing of raw chemicals which releases carbon emissions. Cement and steel industries are the most significant examples of this issue. For this reason, in the last years the contribution of the industrial sector in the CO_2 emission reduction targets is being considered and highlighted. The potential saving of industrial direct emissions is estimated in the range of 4.2–6.6 Gt CO_2 eq/year in 2030 compared to current emissions (Blok et al., 2020). In 2014, 69% of industrial energy use and 74% of direct industrial CO_2 emissions came from five energy-intensive sectors (International Energy Agency IEA 2020): Chemicals and petrochemicals, iron and steel, cement, pulp and paper and aluminium. In 2018, the industry sector accounted for 37% (157 EJ) of total global final energy use. This represents a 0.9% annual increase in energy consumption since 2010, with 0.8% growth in 2018, following stronger growth of 1.6% the previous year (International Energy Agency IEA 2020). The industry sector's energy mix has remained relatively unchanged overall since 2010: the fossil fuel share of the energy mix decreased from 73% to 69%, while electricity rose from 18% to 21%, largely owing to increasing electricity use in non-energy-intensive industry (International Energy Agency IEA. Technology Roadmap. 2017). For these reasons, it is clear that significant efforts have to be done in these sectors to achieve a faster decarbonization. amongst manufacturing industry, cement production presented the second largest share of total direct industrial carbon dioxide CO_2 emissions, at 27% with 2.2 $GtCO_2$/yr in 2014 despite

---

* Corresponding author.
E-mail address: pilarlm@unizar.es (P. Lisbona).

https://doi.org/10.1016/j.ijggc.2021.103524
Received 14 May 2021; Received in revised form 2 November 2021; Accepted 12 November 2021

Nomenclature

ASU	Air Separation Unit
CAPEX	Capital Expenditure (M€)
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CPU	Carbon Processing Unit
OPEX	Operational Expenditure (M€/year)
PC	Pulverized Coal

considerable progress on energy efficiency, the use of alternative fuels and clinker replacements, the cement sector (International Energy Agency IEA. Technology Roadmap. 2017). Cement production involves the decomposition of limestone, which represents about two thirds of the total CO_2 emissions generated in the process, with the remainder of CO_2 emissions coming from the combustion of fuels. The utilization of coal is still the most widely used fuel in clinker production, representing 70% of the global cement thermal energy consumption (although the European share of coal is only 30%) (International Energy Agency IEA 2018). Rising population, urbanization patterns and infrastructure development needs are expected to increase global cement production, which is set to grow by 12–23% above the 2014 level by 2050. Improving energy efficiency, switching to alternative fuels, reducing the clinker to cement ratio and integrating carbon capture into cement production are the main carbon mitigation levers supporting the sustainable transition of the cement sector (International Energy Agency IEA. Technology Roadmap. 2017). However innovative technologies like carbon capture are identified to provide the largest cumulative CO_2 emissions reductions. Several concepts have been proposed for cement industry and CO_2 capture, mainly based on the Ca-looping process (Dean et al., 2013; Martínez et al., 2013; Proaño et al., 2020; De et al., 2018; Martínez et al., 2015; Diego et al., 2016), but also in other post-combustion capture technologies (Kuramochi et al., 2012; Gerbelová et al., 2017; Nwaoha et al., 2018; Cormos and Cormos, 2017; Pérez-Calvo et al., 2020; Laribi et al., 2019) or oxy-fuel concepts (Gerbelová et al., 2017; Carrasco et al., 2019; Laribi et al., 2017). amongst them, Ca-looping presents clear synergies with cement production (Romeo et al., 2011) and the technological readiness level of the process has reached technological demonstration in pilot plants operating under real conditions (TRL 7). Several examples of Ca-looping pilot plants have been built and successfully operated around the world. In 2009, INCAR-CSIC devised the 1.7 MWth pilot-plant located at La Pereda (Spain) in agreement with several partners. The plant was commissioned in 2011, started up in 2012 within the *7thFP CaOling* European project and, by 2017, accumulated more than 3100 h of stable operation (Sanchez-Biezma, 2014). The obtained results proved the feasibility of the process to be further scaled up to 30 MWth if the system is operated with the adequate sorbent inventory and activity (Arias et al., 2013). The TU Darmstadt 1 MWth pilot plant was erected and commissioned in 2011 and, by 2019, accumulated over 3900 h of stable operation under a wide range of conditions (Helbig et al., 2017). The industrial scale feasibility of the CaL process was proven after over 1200 h of stationary capture with efficiencies up to 94%. The experience with this plant served for the scaling of the technology up to 20 MWth (Hilz et al., 2019). In 2013, a 1.9 MWth pilot plant was erected in 2013 at ITRI (Taiwan) for carbon capture from cement plants flue gases (Chang et al., 2014). The pilot plant includes a calciner designed and operated as a rotary kiln. Thus, this configuration is really interesting to assess the potential integration between Ca-looping, power and cement industries. It accumulates more than 300 h of continuous looping operation. The plant represents a milestone for the forthcoming erection of a 30 MWth demo plant (Chang et al., 2014).

Although Ca-looping carbon capture is a technically feasible option for industrial decarbonization, the economic feasibility of industrial CCS/CCU together with regulatory aspects delays its implementation and deployment. There are several limitations for the implementation of industrial CCS/CCU:

- Lack of a clear and global legislation about CO_2 storage based on international agreements.
- Traditionally low emissions market CO_2 price (up to the end of 2020, the maximum historical ETS carbon price was around 30 €/ton) were detrimental for the economic feasibility and reduced the interest in the technology. It must be highlighted the extreme increase experienced by the carbon price in the first quarter of 2021, achieving a current value of 55 €/ton (May 2021).
- Large capital investment needed. Large installations are required to increase the economic feasibility opportunities, but the capital investment for these systems is large enough to discourage the investment.
- Small CCUS systems seems to be economically unfeasible making extremely difficult the deployment of CCUS in the whole industrial sector.

Standalone CCS projects can make commercial sense for large carbon industrial emitters. However, many industrial plants operate at small scales and CCS projects are generally unfeasible for these sizes.

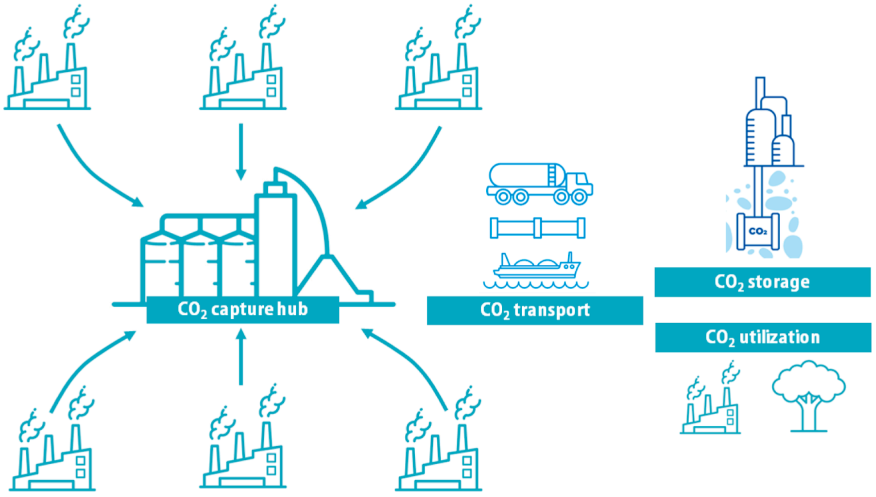

Fig 1. Carbon capture hub implemented in an industrial cluster. Source: modified from Global CCS Institute (Global CCS Institute 2015).

Currently existing CO_2 capture alternatives are economically unfeasible for small-size industries and there is no real motivation for these companies to invest into a whole new process out of their business know-how such as a carbon capture plant. The only carbon reduction alternative for these industries is to minimize emissions through energy saving or efficiency increase measures. Beyond that alternatives, they have to buy carbon emission allowances in the CO_2 market to achieve the legal limit. Clustering of several small or medium industrial sites through the sharing of carbon capture infrastructure as illustrated in Fig. 1 could make the capture process to become economically feasible also for small emitters.

Several reviews of current industrial CCS hubs or future projects have been published by international organizations in the last years (Brownsort, 2019). Existing CCUS hubs in industrial clusters are mainly focused on sharing collection, transport and storage facilities. This implies a shared collection network that would bring CO_2 from each individual source to a collection hub for onward transport to storage or utilization stages. The International Energy Agency Greenhouse Gas Research and Development Program identified the main global CCS clusters and summarized their key technical information (Haines, 2015). This review was focused on a dozen clusters located around the world with varying TRL from early concepts to operating systems, including the largest CO2-EOR clusters in the USA. The Global CCS Institute also published in 2015 a report where the influence of capture clusters and transport networks was assessed as key elements for the deployment of European CCS (Global CCS Institute 2015). The Zero Emissions Platform released a report exploring how the deployment of CCS hubs and clusters contributes to the decarbonization of European economy (Zero Emissons Platform 2016). This research highlighted the lack of available data in some regions where CCS cluster could be advantaged and summarized policy needs to deploy the concept. ECOFYS presented in 2017 a report comparing the readiness level of several potential industrial CCS clusters in the United Kingdom (Stork and Schenkel, 2017). Other study promoted by IEAGHG investigated economic and business issues related to industrial CCS clusters around the world (International Energy Agency IEA 2018). It proposed different business models and suggested the most suitable one for each global region. The Carbon Sequestration Leadership Forum has published a report on CCS clusters, hubs and infrastructure providing updated information of currently active CCS clusters and projects dealing with CCS clusters (Carbon Sequestration Leadership Forum 2018). It provides specific recommendation to policy makers and industrial stakeholders to accelerate the deployment of CCS clusters.

Bronwsort has identified several areas with potential industrial CCS clusters in United Kingdom (Humberside, Teesside, Merseyside, South Wales, Grangemouth and St Fergus), Norway (Grenland) and the Netherlands (Rotterdam) (Brownsort, 2019).

- Humberside, considered CCS cluster for over ten years, has been boosted by the strong interest of the Drax Group (power sector) in cutting carbon emissions. The location is favored by the existence of large and well-characterised storage sites offshore in the Southern North Sea and suitable port facilities. Although there is engagement on industry decarbonisation of the local industrial network, only the large emitter belonging to Drax Group have a clear focus on CCS.
- Teesside has many positive features to establish an industrial CCS cluster such as the presence of several large emitters with high CO_2 concentration, a partial carbon capture facility and a good connection with storage sites through an existing pipeline network. The most significant weakness is the long distance to the nearest storage site.
- The Scottish cluster includes two separate industrial areas linked by an existing natural gas pipeline suitable to transport CO_2 with a low retrofitting cost. It represents a great advantage for potential capture implementation in the Grangemouth refinery and petrochemical complex and St Fergus natural gas processing complex (International Energy Agency IEA 2018). The main strength of this CCS cluster is the existence and availability of three offshore gas pipelines suitable for transporting CO_2 to the identified and available storage sites in the Central North Sea. This infrastructure is positioned to received carbon emissions from St Fergus complex but also from Grangemouth and from other European capture facilities through

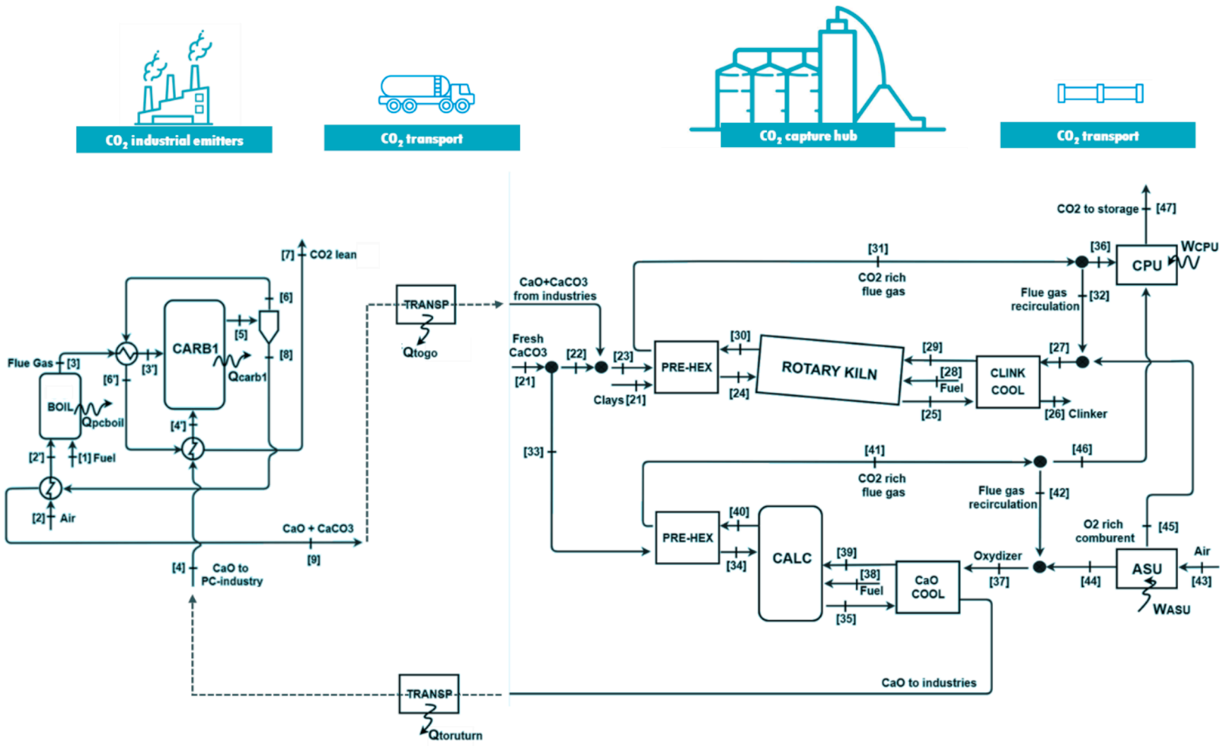

Fig 2. Proposed industrial carbon capture hub: small CO_2 emitters industries and a cement plant to centralize capture process.

Peterhead Port (Alcalde et al., 2019). Despite the clear advantages of this cluster, the engagement of local small size industry is very slow as a result of the difficulty of making a business case for CCS.

- The industry emissions of the Norwegian Grenland cluster are not particularly large and no other emitters are easily added to the cluster. The current proposal for the full-scale CCS project is for just two emitters to capture CO_2, the Norcem cement facility and the Fortum Oslo Varme waste to energy plant. The CO_2 will be transported by ship to a collection hub at Kollsnes, from where it will be piped to a storage site in a saline formation.

All these existing and projected industrial CCS clusters are only focused on large emitters given the critical implementation of carbon capture process in local small-size industrial network. This work presents a new concept of industrial CCS clustering to tackle with these limitations. The double objective of the proposed carbon capture industrial clustering is (1) to increase the economic feasibility of large carbon capture facilities by operating them with higher amounts of CO_2 emissions and (2) to facilitate the CO_2 emission reduction in small size industrial facilities. The new business model proposes the centralization of some elements of the CO_2 capture process in a single key capture facility for several industrial carbon sources. A good example of these key installations is represented by a cement production industry where small industrial CO_2 emitters may transfer their carbon emissions to be captured together with the CO_2 self-generated in the cement plant. The total amount of capture CO_2 is increased while the global investment cost is significantly reduced as the local industrial partners will share one key equipment for the capture process. The low profitability limitation of individual CO_2 capture systems in small size industries may be overcome. Instead, the small industries will incur in a small investment cost and an extra operational cost related to the centralized management of their CO_2 emissions capture. This cost should always be below the CO_2 market price to be a feasible alternative. While, the large-size industry with the shared key equipment for the carbon capture process will receive an economic compensation for the management of the CO_2 from the small local facilities. This income could increase the economic feasibility of the investment. Moreover, governmental subsidies could be provided to these industries since they deal with additional CO_2 emissions (not self-produced) providing the service of capturing CO_2 emissions that, in other case, would be emitted to the atmosphere due to economic reasons.

The originality of this business case for industrial carbon capture hubs relies in the inclusion amongst the shared infrastructure of the cluster key equipment for the capture stage. As presented, existing clusters focus on sharing carbon collection, transport and storage infrastructure but do not overcome the limitations of capture stage for local small-size industry. This work quantifies the techno-economic feasibility of the carbon capture cluster concept using a clinker kiln as key shared infrastructure in the carbon capture stage.

2. Proposed concept of an industrial CCS hub

The concept based on Ca-looping is partially implemented in a cement production facility as centralized infrastructure to capture emissions from several small-size industries, Fig. 1. The integration between the small local industrial emitters and the capture hub is illustrated in Fig. 2. Each industrial site has a boiler (pulverized coal, PC, or natural gas, NG) to cover its thermal energy demand and a carbonator to capture the generated emissions as limestone. Carbonation is an exothermic reaction and the released heat may be recovered and integrated in the industrial process reducing the need of fossil fuels in the original boiler. $CaCO_3$ is sent back to the cement plant where the rotary kiln generates CaO for clinker production and an extra CaO stream for the carbonators of the small emitters in the cluster.

Table 1
Main assumptions of the different equipment of the system.

Cement Plant	**Air-fired**	**Oxy-fired**	
	Size	3150 t clinker/day	3150 t clinker/day
	Clinker to Cement	0.65 t clinker/t cement	0.65 t clinker/t cement
	Fuel	Coal	Coal
	O_2 excess	20%	5%
	Flue gas recirculation ratio	–	55%
	Rotary kiln thermal efficiency	95%	95%
	Auxiliary consumption	97 kWh/t cement	97 kWh/t cement
Boilers	**PC**	**NG**	
	Fuel composition	C 66,20 wt% H 3,75 wt% O 6,76 wt% S 0,60 wt% N 1,54 wt% Ash 13,05 wt% Moisture 8,10 wt %	CH_4 95,39 wt% C_2H_6 3,94 wt% CO_2 0,59 wt% N_2 0,08 wt%
	Boiler efficiency	90%	90%
	LHV	25 MJ/kg	47.7 MJ/kg
Air Separation Unit			
	O_2 purity	95%	
	Electric consumption	220 kWh/tO_2	
	O_2 output		
CPU			
	Electric consumption	100 kWh/tCO_2	

2.1. *CO_2 industrial emitters*

From the industrial sites perspective, one of the goals is the reduction of their CO_2 emissions with the minimum modifications in their initial layout. It is assumed that the industrial cluster includes 10 small-size facilities with 10MWth boilers (pulverized coal or natural gas). The size of the individual industrial boilers could vary, 5–20 MWth, but the results are still valid if the total output is preserved (totalizing 100 MWth). It is necessary to implement a small carbonator (fluidized bed boiler), a gas-solid cyclonic separator at the carbonator outlet and several heat exchangers to recover the energy from hot CO_2 and $CaCO_3$ (around 650 °C). As shown in Fig. 2, this block includes the carbonator reactor, cyclone and heat recovery section composed of three heat exchangers that recover the excess heat from carbonator and reduce the fossil fuel original demand of the small-size industrial emitter. Under the new business case, they have to pay to the cement production facility for the CO_2 captured and its management. The main technical assumptions required for the modelling of the different equipment in the small-size industrial facilities are gathered in Table 1.

2.2. *CO_2 transport to capture hub*

Transport between the carbon emitting industries and the cement plant is also an issue to be addressed. A continuous provision for incoming CaO and continuous disposal for the outgoing $CaCO_3$ are required; the management of these flowrates with the cement plant is one of the challenges to be tackled if the feasibility of the concept is demonstrated.

Depending on the distance between the industrial site and the cement plant the solid transportation can be done by land transport for significant distances or through a conveying installation for shorter distances. The most common options for land transport of CaO and $CaCO_3$ are the use of dump trucks and tanker truck with self-pumping system. For short distances, conveyor belts, drag chain conveyors or pneumatic conveyors can be implemented. The assessment of the type of transport is beyond the scope of this study since it is strongly influenced

Table 2
Main results of (10 × 10 MWth) Boilers and one Cement plant operating independently. REF case.

BOILERS	PC	NG	CEMENT PLANT	
Energy input (MWth)	111.11	111.11	Energy input (MWth)	117.62
Fuel consumption (kg/s)	4.44	2.33	Fuel consumption (kg/s)	4.71
Direct CO_2 emissions (kg/s)	**10.79**	**6.39**	Direct CO_2 emissions (kg/s)	31.02
Q_PC TOTAL (MWth)	100.00	100.00	Fuel CO_2 emissions (kg/s)	19.59
			Calc CO_2 emissions (kg/s)	11.43
			Total Auxiliaries Power (MWe)	19.59
			Indirect CO_2 emissions (kg/s)	1.43
			Equivalent CO_2 emissions (kg/s)	**32.45**

by the final layout of the industrial sites-cement plant.

The transport stage will generate different heat losses depending on the technique (truck, rail, conveyor belt) and will lead to different final solid temperature. Since both, industries and cement plant, are continuous process, while in general the transport will be discontinuous, storage systems will be required at the entrance and exit of each industry and cement plant.

2.3. CO_2 capture hub – cement production facility

The cement production facility must include a CO_2 capture system if emissions are to be removed in their equipment. Oxyfuel combustion is the chosen technology in the clinker furnace although similar results would be expected with other CO_2 capture alternatives. The modelling and thermodynamic simulations of the concept have been implemented and run in Engineering Equation Solver software to collect, discuss and compare relevant energy data of the reference case and the studied scenarios. To be conservative, it has been neglected potential recovery of low-grade heat from the CO_2 compressing-conditioning process, namely CPU, and from the ASU.

The main benefit of the new concept for the cement plant is related to the incomes received from the capture of extra CO_2 emissions from industrial sites. Of course, the CO_2 capture system in the cement plant has to be redesigned and sized larger than its original dimension when only devoted for the emissions of the cement plant. However, the increment in investment cost is not significant considering the new flowrate of treated carbon emissions. The main technical assumptions of the different equipment in the capture hub are detailed in Table 1.

3. Results and discussion

The system has been modelled and simulated under different configurations for technical and economic comparison: (i) PC/NG fuelled industrial sites and cement plant with air-fired kiln operating independently (REF), (ii) PC/NG fuelled industrial sites and cement plant with oxy-fired kiln operating independently (REFoxy), (iii) PC-fuelled industrial sites and cement plant with oxy-fired kiln operating as industrial CCS hub (Scenario 1) and (iv) NG-fuelled industrial sites and cement plant with oxy-fired kiln operating as industrial CCS hub (Scenario 2).

The carbon emission nomenclature adopted by de Lena et al. has been also applied in this work (De Lena et al., 2019). Emissions from each individual system includes direct carbon emission (fuel combustion or mineral calcination) and indirect carbon emissions from electric consumption. The sum of direct and indirect emissions is referred as CO_2 equivalent emissions for each sub-system. While total CO_2 emissions is used for the addition of direct, indirect and equivalent emissions from the cement plant and the small-size industrial emitters.

Table 3
Energy inputs and CO_2 emissions for Boilers (PC) and Cement plant (air and oxyfuel combustion).

	REF *Cement-air Coal boiler*	**REF-oxy** *Cement-oxy Coal boiler*	**Scenario 1** *Cement-oxy Coal boiler Carbonator*	**Scenario 2** *Cement-oxy NG boiler Carbonator*
ENERGY INPUT (MWth)	**228.73**	**228.73**	**241.34**	**237.17**
ENERGY INPUT (MWe)	**19.59**	**38.60**	**45.29**	**44.04**
Cement fuel CO_2 (kg/s)	19.59	19.59	26.76	24.37
Calcination CO_2 (kg/s)	11.43	11.43	14.89	16.45
Fossil fuel CO_2 (kg/s)	10.79	10.79	7.83	5.22
Indirect cement CO_2 (kg/s)	1.43	2.82	3.31	3.21
CO_2 GENERATED (kg/s)	**43.24**	**44.63**	**52.79**	**49.27**
CO_2 CAPTURED (kg/s)		**29.47**	**46.62**	**43.49**
CO_2 EMISSIONS (kg/s)	**43.24**	**15.16**	**6.17**	**5.78**

Table 4
Main results for Boiler and Cement plant under Scenario 1 (S1).

CEMENT PLANT	S1	BOILERS	S1	TOTAL
Energy input (MWth)	160.66	Energy input (MWth)	80.68	241.34
Fuel consumption (kg/s)	6.43	Fuel consumption (kg/s)	3.22	9.66
CO_2 generated (kg/s)	41.65	CO_2 generated (kg/s)	7.83	49.49
Fuel CO_2 emissions (kg/s)	26.76	Q_PC TOTAL (MWth)	100.00	
Carb CO_2 emissions (kg/s)	14.89	Q_PC BOILER (MWth)	71.81	
Total Auxiliaries Power (MWe)	45.29	Q_PC carb (MWth)	−1.73	
Auxiliaries power (MWe)	19.59	Q_PC CO_2 (MWth)	16.16	
ASU power (MWe)	10.71	Q_PC solid (MWth)	13.76	
CPU power (MWe)	15.00	Q_extra (carb+CO_2+solid)	28.19	
CO_2 indirect emissions (kg/s)	3.31			
Equivalent CO_2 generated (kg/s)	44.96	Equivalent CO_2 generated (kg/s)	7.83	52.79
CO_2 captured (kg/s)	39.57	CO_2 captured (kg/s)	7.05	46.62
CO_2 final emissions (kg/s)	5.39	CO_2 final emissions (kg/s)	0.78	6.17
Mass flow $CaCO_3$ input from boiler (kg/s)	16.03	Mass flow CaO input (kg/s)	14.96	
Mass flow $CaCO_3$ input needed (kg/s)	17.82	Mass flow $CaCO_3$ output (kg/s)	16.03	
Mass flow CaO input from boiler (kg/s)	5.99	Mass flow CaO output (kg/s)	5.99	
Mass flow CaO output (kg/s)	24.94			
Mass flow CO_2 calcination (kg/s)	14.89			
O_2 necessities (kg/s)	13.52			

3.1. Avoided emissions and fuel consumption

The results obtained for the reference case where the CO_2 emissions from boilers are 10.79 kg/s in PC boilers and 6.39 kg/s in the case of natural gas boilers are presented in Table 2. For the cement plant, the production of clinker demands an energy input of 117.62 MWth; fuel consumption of 4.71 kg/s and direct CO_2 emissions of 31 kg/s. 60% of carbon emissions comes from fuel combustion (19.59 kg/s) and 40% from calcination of limestone (11.43 kg/s). 19.59 MWe are consumed by electrical auxiliaries, representing 1.43 kg/s of indirect CO_2 emissions. Indirect CO_2 emissions are associated to the electric consumption assuming a specific emission of the energy mix of 260 gCO_2/kWh which

Table 5
Main results for Boiler and Cement plant under Scenario 2 (S2).

CEMENT PLANT	S2	BOILER	S2	TOTAL
Energy input (MWth)	146.33	Energy input (MWth)	90.84	237.17
Fuel consumption (kg/s)	5.86	Fuel consumption (kg/s)	1.91	7.76
CO_2 generated (kg/s)	40.83	CO_2 generated (kg/s)	5.22	46.05
Fuel CO_2 emissions (kg/s)	24.37	Q_PC TOTAL (MWth)	100.00	
Carb CO_2 emissions (kg/s)	16.45	Q_PC BOILER (MWth)	81.30	
Total Auxiliaries Power (MWe)	44.04	Q_PC carb (MWth)	−11.88	
Auxiliaries power (MWe)	19.59	Q_PC CO_2 (MWth)	21.44	
ASU power (MWe)	9.75	Q_PC solid (MWth)	9.14	
CPU power (MWe)	14.70	Q_extra (carb+CO_2+solid)	18.70	
CO_2 indirect emissions (kg/s)	3.21			
Equivalent CO_2 generated (kg/s)	44.04	Equivalent CO_2 generated (kg/s)	5.22	49.27
CO_2 captured (kg/s)	38.78	CO_2 captured (kg/s)	4.70	43.49
CO_2 final emissions (kg/s)	5.26	CO_2 final emissions (kg/s)	0.52	5.78
Mass flow $CaCO_3$ input from boiler (kg/s)	10.69	Mass flow CaO input (kg/s)	9.98	
Mass flow $CaCO_3$ input needed (kg/s)	26.71	Mass flow $CaCO_3$ output (kg/s)	10.69	
Mass flow CaO input from boiler (kg/s)	4.00	Mass flow CaO output (kg/s)	4.00	
Mass flow CaO output (kg/s)	24.94			
Mass flow CO_2 calcination (kg/s)	16.45			
O_2 necessities (kg/s)	12.31			

corresponds to the average specific CO_2 emissions per kWh in Europe. The equivalent CO_2 emissions of the cement plant under de reference case are 32.45 kg/s.

Table 3 shows a summary of the four studied configurations: REF, REF-oxy, Scenario 1 and Scenario 2. The energy input of each scenario is obtained from the sum of the cement plant and the industrial boilers needs plus the electrical energy input demanded by the auxiliaries. The CO_2 generated and emitted under the reference case scenario with coal boilers is 43.24 kg/s, mainly related to coal (30.38 kg/s). This carbon generation increases slightly when considering oxy-fuel capture due to the additional requirements of oxy-fuel combustion of 19 MWe (oxygen production and CO_2 compression and purification unit). By capturing 95% of direct emissions, the final total CO_2 emissions are 15.16 kg/s, which represent a reduction of 65% of the total equivalent emissions (cement plant + boilers) and 71% of total direct emissions.

Under Scenario 1, the increase in energy input required in comparison to the reference case is 12.6 MWth and 25.7 MWe. Assuming a thermal-electric conversion factor of 0.35, the increase of global thermal energy input is 86 MWth (73.43 MWth from electric power increase and 12,61 MWth from thermal input increase). Under Scenario 2, the increase in global input of thermal energy is 78.3 MWth, slightly lower than Scenario 1 due to the specific emissions of natural gas compared to coal.

Table 4 details the results obtained for Scenario 1 where carbon industrial emissions are reduced by 27% given the lower requirement of fossil fuel derived from the integration of carbonation heat released during carbon capture (capture efficiency of 90%) and heat from solid and CO_2 streams cooling. As a consequence, CO_2 emissions from the industrial boiler to the atmosphere are 0.78 kg/s which represent a reduction of 93% compared to the reference case. To achieve this value, it is necessary to continuously supply 54 t/h of CaO to the industries and dispose 79.3 t/h of a $CaCO_3$—CaO mixture. This material reaches the cement plant where it is added for the production of clinker together with additional fresh $CaCO_3$. Due to the extra calcination requirements, fuel consumption in the cement plant increases by 36.6% as well as the final CO_2 emissions from fuel combustion. Emissions from calcination increase with the inclusion of CO_2 from industries and amount to 14.89 kg/s, 30% higher than the reference base case. The total CO_2 generation in Scenario 1 is 52.79 kg/s, which is 22% higher than the base case. However, after capture stage the total emissions amount up to 6.17 kg/s. 86% of the total emissions from the cement plant plus small industries (including emissions related to electricity consumption of the proposed concept) are captured while 93% of direct carbon emissions generated in situ are avoided. They represent 9.0 kg/s of CO_2 less than in the REF-oxy case and achieve almost total decarbonization of the small-size local industry (95% decarbonization).

Table 6
Main assumptions for CAPEX and OPEX calculations.

CAPEX		OPEX	
PC-Boiler	250 €/kW	Natural Gas (Eurostat 2020)	6 €/GJ
NG-Boiler	200 €/kW	Raw meal	5 €/tClink
Rotary kiln (Gardarsdottir et al., 2019).	190 €/(tClink/yr)	Coal (Eurostat 2020)	3 €/GJ
Extra rotary kiln	57 €/(tCaO/yr)	Electricity	50 €/MWh
ASU	280 €/(tO_2/yr)	O&M	2,5 * CAPEX%
CPU	80 €/(tCO_2/yr)	Natural Gas (Eurostat 2020)	6 €/GJ
Capacity	85%		
Fixed charge factor	0,1 yr		

As detailed in Table 5, under Scenario 2 industrial emissions are reduced by 19% in comparison with the reference case, which represents final CO_2 emissions of 0.52 kg/s (reduction of 92%). In this case, it is necessary to supply 36 tCaO/h to the industries and dispose 52.8 t/h of a $CaCO_3$—CaO mixture. These values are clearly lower than those required when boilers are fed by coal. Again, fuel consumption for clinker production increases by 24.4% as well as emissions related to fuel usage. Emissions from calcination are 16.45 kg/s, 43% higher than the base case. The total CO_2 generation in Scenario 2 is 49.3 kg/s which is 14% higher than the base case. Given the CO_2 capture process, the total final emissions to the atmosphere are limited to 5.78 kg/s due mostly to indirect emissions. When indirect emissions associated to ASU and CPU are considered, carbon emissions represent a 125% of the reference plant values. To be conservative, these emissions have been included in this study although there exist different alternatives to reduce electricity carbon intensity in the process. An 87% of total emissions from the cement plant plus small-size industries (including indirect emissions) is captured while 94% of direct carbon emissions generated in the cement plant and small industries are avoided. They represent 9.4 kg/s of CO_2 less than the emissions under REF-oxy configuration and, total decarbonization of the small-size local industry can be achieved.

3.2. Economic assessment of the carbon capture cluster

Regarding costs, the CAPEX associated to the boilers has been assumed to be proportional to their primary energy consumptions and the CAPEX associated to the rotary kiln proportional to its yearly clinker production. A substantial increase of the oxy-fuel cement kiln capital cost is caused by the additional plant components, ASU and CPU. The assumption is in agreement with previous literature where the oxy-fuel cement kiln CAPEX includes 43% for the rotary kiln, and the remaining 57% shared with a 29% to the ASU and 28% to the CPU (Gardarsdottir et al., 2019). Calciner CAPEX has been estimated as percentage of rotary kiln capital cost, in particular a 30%. In order to carry out a comparison with the oxyfuel combustion clinker, a capacity factor of 7500 h/y has been considered and, from the financial point of view, a fixed charge factor equal to 0.1 per year was assumed. Table 6 shows the main assumption in CAPEX and OPEX for all the simulated scenarios. Fuel

Table 7
Capital Expenditure (CAPEX) for Boiler and Cement plant in different scenarios [M€].

	REF COAL	REF NG	REF-oxy COAL	REF-oxy NG	Scenario 1	Scenario 2
PC Industry	**27.78**		**27.78**		**27.78**	
PC-Boiler	27.78		27.78		20.17	
Carbonator	0		0		7.61	
NG Industry		**22.22**		**22.22**		**22.22**
NG-Boiler		22.22		22.22		18.17
Carbonator		0		0		4.05
Cement plant	**218.46**	**218.46**	**384.14**	**384.14**	**471.33**	**442.26**
Rotary kiln	218.46	218.46	218.46	218.46	218.46	218.46
Extra rotary kiln	0	0	0	0	26.89	17.94
CPU	0	0	78.26	78.26	106.59	97.16
ASU	0	0	87.42	87.42	119.38	108.7
TOTAL	**246.24**	**240.68**	**411.92**	**406.36**	**499.11**	**464.48**

costs have been assumed to be proportional to their primary energy and raw meal to the amount of clinker product. It is assumed that for an industrial customer the cost of electricity depends on the amount of energy required in a year. After estimating the yearly electric consumption of cement kiln, this cost has been assumed to be 50 €/MWh, average EU electricity cost for large industry consumption (Eurostat 2020).

Table 7 further details the CAPEX information summarized in Table 6. The costs of boilers and carbonators are dependant on thermal energy (278 k €/kW for coal and 222 k€/kW for gas); thus, for Scenario 1 and 2, the boiler costs will be lower than in the base case given the boiler size reduction after carbonation integration. However, it is assumed that the reduction of the investment cost related to the size of the boiler is offset by the investment cost of the new carbonators required in these two scenarios. The cost of the clinker kiln is assumed to be the same under air or oxy-fuel conditions, the difference is only related to the extra size of the equipment (included in the calciner heading) plus the ASU and CPU which increases the cost of the cement plant by 76% when oxy-fuel is installed in the cement plant, 115% in Scenario 1 and 102% in Scenario 2 since in the last two cases it is also necessary to increase the size of the clinker. As shown in Table 7 for the case of PC boilers, the total cost would be 246 M€ under the reference case, 412 M€, which is an increase of 76% in the case of oxy-fuel in the cement plant (REF-oxy) and 499 M€ in Scenario 1 where CO_2 is also captured from small industry. In the case of gas, the reference is € 240.7 M€ and the increases are 69% and 89% respectively.

Regarding operating costs (OPEX), Table 8 shows the comparison between values for different configurations. In the base case, operating costs mainly associated to fuel consumption are slightly lower than 37 M€/year. They increase by 30.5% in the case of oxy-fuel combustion and 46% in Scenario 1. In the latter case, the operation costs of the industry are lower as they need 27% less fuel, which implies considerable savings. In the case of natural gas, its higher price leads to more significant operating costs. In the base case, they amount up to 45.8 M€/year and increase a 25% in the case of oxy-fuel combustion and 60% in Scenario 2.

These operating costs dramatically change when including a cost of 30 €/ton CO_2 emitted, Table 9. For the industries, Scenario 1 clearly lead to very large savings since they do not emit CO_2 and cost reduces from 21.3 to 8.1 M€/year in the case of coal boilers and from 25.5 to 15.8 M€/year in the case of natural gas. However, the cement plant increases its costs under these scenarios the carbon emissions of the small industries are also treated. The base case presents the highest operating costs with € 60.8 M and a strong influence of the cost of CO_2. The lowest cost is related to the situation of CO_2 capture only in the cement industry with € 40.2 M€/year and a reduction of 34%. In scenarios 1 and 2 they have higher costs than the oxyfuel cement option (REF-oxy) also due to the greater reduction of CO_2 in these situations. The increase with respect to the capture in the cement plant is 8.9 M€ in Scenario 1 for coal boilers and 5.9 M€ in Scenario 2 for gas boilers.

This costs increment has to be transferred by the cement company to small industries to achieve a win-win situation for all parties. The small industries have a very large reduction in costs associated with emissions without making large investments in their facilities and the cement plant could obtain an income, thereby financing its large investment, by avoiding emissions from small industries. Globally, it would be possible to eliminate emissions from small industries that today are considered diffuse and very difficult to avoid.

Finally, Table 10 shows the economic analysis associating a cost-income to the ton of CaO diverted to small industries. A value of 20 €/ton CaO has been assumed, which would be equivalent to 25.5 €/tonCO_2 leading to a profitable option for small industries as the carbon allowance obtained is below the assumed cost of 30 €/ton CO_2. For the cement plant, it represents an extra income with which to compensate and improve their financial results. The overall consequence is the reduction of the costs for all agents and the reduction of CO_2 emissions to the environment. With these assumptions, the operating costs of small companies that use coal lessen from 21.3 M€ to 18.8 M€, reduce their emissions by more than 90% without making investments to achieve this. In the case of natural gas boilers, they lessen from 25.5 to 23.0 M€. For the cement industry, this income offsets its operating cost of 49.1 M€ in Scenario 1 and reduces it to 38.3 M€, which is less than that obtained for a situation where there is only CO_2 capture in the cement plant (40.2 M€). The same happens in Scenario 2 where the costs are reduced to 38.9 M€. In the case of considering a higher base price of CO_2, i.e. 50 €/ton CO_2 instead of 30 €/ton CO_2, the savings will be greater than these results for both, the industries and the cement

Table 9
PC-Industry, NG-Industry and Cement plant operating Costs [M€/year].

	REF	REF-oxy	Scenario1	Scenario2
Coal	9.00	9.00	6.54	9.00
O&M	0.69	0.69	0.69	0.69
Carbon tax	11.65	11.65	0.84	11.65
PC-Industry	**21.34**	**21.34**	**8.07**	**21.34**
Natural gas	18.00	18.00	18.00	14.72
O&M	0.56	0.56	0.56	0.56
Carbon tax	6.91	6.91	6.91	0.56
NG-Industry	**25.47**	**25.47**	**25.47**	**15.84**
Coal	9.53	9.53	13.01	11.85
Raw	4.92	4.92	4.92	4.92
Electricity	7.35	14.47	17.07	16.20
O&M	5.46	9.60	11.78	11.06
Carbon tax	33.51	1.68	2.29	2.08
Cement plant	**60.77**	**40.20**	**49.07**	**46.11**

Table 8
Operational Expenditures (OPEX) for Boiler and Cement plant in different scenarios [M€/year].

	REF COAL	REF NG	REF-oxy COAL	REF-oxy NG	Scenario 1	Scenario 2
PC Industry	9.69		9.69		7.23	
NG Industry		18.56		18.56		15.27
Cement plant	27.26	27.26	38.52	38.52	46.79	44.03
TOTAL	**36.95**	**45.82**	**48.21**	**57.08**	**54.02**	**59.3**

Table 10
Main economic results for Boiler and Cement plant with 20€/ton CaO [M€].

	REF COAL	REF NG	REF-oxy COAL	REF-oxy NG	Scenario 1	Scenario 2
PC-Industry	21.34		21.34		8.07	
CaO cost					10.77	
PC-Industry	**21.34**		**21.34**		**18.84**	
NG-Industry		25.47		25.47		15.84
CaO cost						7.19
NG-Industry		**25.47**		**25.47**		**23.03**
Cement plant	60.77	60.77	40.20	40.20	49.07	46.11
CaO sale					10.77	7.19
Cement plant	**60.77**	**60.77**	**40.20**	**40.20**	**38.31**	**38.92**

plant or centralized capture facility.

These values show that a detailed and particular analysis of this concept makes sense with which the advantage of decarbonise small-size industry. This decarbonizing objective would not be economically feasible unless a concept similar to that presented in this work is implemented. The results represent an approximation that allow concluding that there are room for finding synergies between small industries and large facilities in which CO_2 is captured centrally. Another assumption in this example is that the transport of CO_2 in the form of carbonate is simple and has a low environmental impact. In this regard, 10 kg/s (table 4) of CaO represents 36 tn/h, approximately one truck per hour is necessary to transport CaO from cement plant to the boilers. As 10×10 MW_{th} boilers has been considered for calculations, that means 2.4 trucks for boiler and day (aprox 1 truck per shift). The other way round, the quantity of $CaCO_3$ is bigger than CaO due to carbonation is not complete and a mix stream of $CaCO_3$ (10.7 kg/s) and CaO (4.0 kg/s) is sent from boilers to cement industry. In this case, it is necessary 1.5 trucks/shift/boiler to transport this material and it does not represent a physical or economic limitation to the presented concept. Due to the high apparent density of both, CaCO and $CaCO_3$, in the range of 1500–2000 kg/m^3 (two times the density of liquefied CO_2) there is not volume limitations for the transportation of these solids in trucks.

4. Conclusions

There is an urgent necessity of deploy CCS system in the industrial sector. The complexity of the industry and their relative lower carbon emissions would difficult the economic feasibility and implementation of CO_2 capture systems. The concept of CCS cluster, that brings together multiple carbon dioxide industrial emitters using shared capture and/or transportation infrastructures, offers advantages for network partners compared with point-to-point individual projects. The cluster approach reduces costs for CCS projects, and enables CO_2 capture from small industrial facilities.

This work has presented a new concept that connects a cluster of industrial sites with significant heat demands with a cement plant through the implementation of a Ca-looping carbon capture system. This carbon capture system uses the kiln furnace as calciner for both the cement and the capture plants at the industrial emitters site. Different scenarios with different level of integration have been studied. The economic assessment points out the feasibility of this kind of centralized carbon capture system to handle the carbon from small emitters

It has been assumed a value of 20 €/ton CaO, that is equivalent to 25.5 €/tonCO_2 and below the assumed cost of carbon market 30 €/ton CO_2. With this data, the cement plant has an important an extra income that compensate and improve their financial results, and small industries have a very large reduction in costs associated with emissions without making large investments in their facilities. As a results there is a clear cost reduction for all agents and CO_2 emissions to the environment are cut down. In the case of higher CO_2 market prices there will be more room profitability of the concept and higher benefits for both, the industries and the cement plant or centralized capture facility.

These calculations represent a first approximation to the possible feasibility of the concept and there are many (and very uncertain) variables that influence the economic result. In this work, the bases are laid and the concept have been presented, with an illustrative example, but the final calculations will depend, among others: on the market price of CO_2 emissions, the price of fossil fuels and the price that is agreed between industries for CaO.

CRediT authorship contribution statement

P. Lisbona: Methodology, Software, Writing – original draft. **R. Gori:** Methodology, Software. **L.M. Romeo:** Conceptualization, Methodology, Writing – original draft. **U. Desideri:** Writing – review & editing.

Declaration of Competing Interest

None.

References

IPCC. Climate change 2014: mitigation of climate change. 2014. 10.1017/CBO9781107415416.
International Energy Agency IEA. Tracking Industry 2020. 2020.
Blok, K., Afanador, A., Van Der Hoorn, I., Berg, T., Edelenbosch, O.Y., Van Vuuren, D.P., 2020. Assessment of sectoral greenhouse gas emission reduction potentials for 2030. Energies 13, 1–24. https://doi.org/10.3390/en13040943.
International Energy Agency IEA. Technology Roadmap. Low-Carbon Transition in the Cement Industry. 2017.
International Energy Agency IEA. Global CO2 emissions by sector, 2018 2018.
Dean, C., Hills, T., Florin, N., Dugwell, D., Fennell, P.S., 2013. Integrating calcium looping CO2 capture with the manufacture of cement. Energy Procedia 37, 7078–7090. https://doi.org/10.1016/j.egypro.2013.06.644.
Martínez, A., Lara, Y., Lisbona, P., Romeo, L.M., 2013. Operation of a cyclonic preheater in the ca-looping for CO2 capture. Environ. Sci. Technol. 47 https://doi.org/10.1021/es401601k.
Proaño, L., Sarmiento, A.T., Figueredo, M., Cobo, M., 2020. Techno-economic evaluation of indirect carbonation for CO2 emissions capture in cement industry: a system dynamics approach. J. Clean. Prod. 263, 121457 https://doi.org/10.1016/j.jclepro.2020.121457.
De, Lena E, M, Spinelli, Romano, M.C, 2018. CO2 capture in cement plants by "Tail-End" Calcium Looping process. Energy Procedia 148, 186–193. https://doi.org/10.1016/j.egypro.2018.08.049.
Martínez, A., Lisbona, P., Lara, Y., Romeo, L.M., 2015. Energy intensity reduction of Ca-Looping CO2 capture by applying mixing loop seals and cyclonic systems. Int. J. Chem. React. Eng. 13 https://doi.org/10.1515/ijcre-2014-0155.
Diego, M.E., Arias, B., Abanades, J.C., 2016. Analysis of a double calcium loop process configuration for CO2 capture in cement plants. J. Clean. Prod. 117, 110–121. https://doi.org/10.1016/j.jclepro.2016.01.027.
Kuramochi, T., Ramírez, A., Turkenburg, W., Faaij, A., 2012. Comparative assessment of CO2 capture technologies for carbon-intensive industrial processes. Prog. Energy Combust. Sci. https://doi.org/10.1016/j.pecs.2011.05.001.
Gerbelová, H., van der Spek, M., Schakel, W., 2017. Feasibility Assessment of CO2 capture retrofitted to an existing cement plant: post-combustion vs. Oxy-fuel combustion technology. Energy Procedia 114, 6141–6149. https://doi.org/10.1016/j.egypro.2017.03.1751.
Nwaoha, C., Beaulieu, M., Tontiwachwuthikul, P., Gibson, M.D., 2018. Techno-economic analysis of CO2 capture from a 1.2 million MTPA cement plant using AMP-PZ-MEA blend. Int J Greenh Gas Control 78, 400–412. https://doi.org/10.1016/j.ijggc.2018.07.015.
Cormos, A.-.M., Cormos, C.-.C., 2017. Reducing the carbon footprint of cement industry by post-combustion CO2 capture: techno-economic and environmental assessment of a CCS project in Romania. Chem. Eng. Res. Des. 123, 230–239. https://doi.org/10.1016/j.cherd.2017.05.013.

Pérez-Calvo, J.-.F., Sutter, D., Gazzani, M., Mazzotti, M., 2020. A methodology for the heuristic optimization of solvent-based CO2 capture processes when applied to new flue gas compositions: a case study of the Chilled Ammonia Process for capture in cement plants. Chem. Eng. Sci. X 8, 100074. https://doi.org/10.1016/j.cesx.2020.100074.

Laribi, S., Dubois, L., De Weireld, G., Thomas, D., 2019. Study of the post-combustion CO2 capture process by absorption-regeneration using amine solvents applied to cement plant flue gases with high CO2 contents. Int. J. Greenh. Gas Control. 90, 102799 https://doi.org/10.1016/j.ijggc.2019.102799.

Carrasco, F., Grathwohl, S., Maier, J., Ruppert, J., Scheffknecht, G., 2019. Experimental investigations of oxyfuel burner for cement production application. Fuel 236, 608–614. https://doi.org/10.1016/j.fuel.2018.08.135.

Laribi, S., Dubois, L., De Weireld, G., Thomas, D., 2017. Optimization of the sour compression Unit (SCU) process for CO2 purification applied to flue gases coming from oxy-combustion cement industries. Energy Procedia 114, 458–470. https://doi.org/10.1016/j.egypro.2017.03.1188.

Romeo, L.M., Catalina, D., Lisbona, P., Lara, Y., Martínez, A., 2011. Reduction of greenhouse gas emissions by integration of cement plants, power plants, and CO2 capture systems. Greenh. Gases. Sci. Technol. 1 https://doi.org/10.1002/ghg3.5.

Sanchez-Biezma A. Final Report Summary - Development of postcombustion CO2 capture with CaO in a large testing facility (CaOling Project). 2014.

Arias, B., Diego, M.E., Abanades, J.C., Lorenzo, M., Diaz, L., Martínez, D., et al., 2013. Demonstration of steady state CO2 capture in a 1.7 MW th calcium looping pilot. Int. J. Greenh. Gas Control 18, 237–245. https://doi.org/10.1016/j.ijggc.2013.07.014.

Helbig, M., Hilz, J., Haaf, M., Daikeler, A., Ströhle, J., Epple, B., 2017. Long-term Carbonate Looping Testing in a 1 MWth Pilot Plant with Hard Coal and Lignite. Energy Procedia 114, 179–190. https://doi.org/10.1016/j.egypro.2017.03.1160.

Hilz, J., Haaf, M., Helbig, M., Lindqvist, N., Ströhle, J., Epple, B., 2019. Scale-up of the carbonate looping process to a 20 MWth pilot plant based on long-term pilot tests. Int. J. Greenh. Gas Control 88, 332–341. https://doi.org/10.1016/j.ijggc.2019.04.026.

Chang, M.-.H., Chen, W.-.C., Huang, C.-.M., Liu, W.-.H., Chou, Y.-.C., Chang, W.-.C., et al., 2014. Design and Experimental Testing of a 1.9MWth Calcium Looping Pilot Plant. Energy Procedia 63, 2100–2108. https://doi.org/10.1016/j.egypro.2014.11.226.

Global CCS Institute. The Global Status of CCS: 2015. Special Report: The Role of CCS Hubs and Clusters in Europe. Melbourne, Australia.: 2015.

Brownsort P. Methodologies for cluster development and best practices for data collection in the promising regions. Part 1 -Industrial CCUS Clusters and CO2 transport systems: methodologies for characterisation and definition. 2019.

Haines, M., 2015. Carbon capture and storage cluster projects: review and future opportunities. IEAGHG.

Zero Emissons Platform. Identifying and developing European CCS Hubs. 2016.

Stork M., Schenkel M. ICCUS Readiness of UK industrialclusters ECOFYS. 2017.

International Energy Agency IEA. Enabling the deployment of industrial CCS clusters. IEAGHG Tech. Rep. 2018.

Carbon Sequestration Leadership Forum. Task force on clusters, Hubs and infrastructure and CCS. Result. Recommendat. from"Phase0." 2018.

Alcalde, J., Heinemann, N., Mabon, L., Worden, R.H., Coninck, Hde, Robertson, H., 2019. Acorn: developing full-chain industrial carbon capture and storage in a resource- and infrastructure-rich hydrocarbon province. J. Clean. Prod. 233, 963–971.

De Lena, E., Spinelli, M., Gatti, M., Scaccabarozzi, R., Campanari, S., Consonni, S., et al., 2019. Techno-economic analysis of calcium looping processes for low CO2 emission cement plants. Int. J. Greenh. Gas Control 82, 244–260. https://doi.org/10.1016/j.ijggc.2019.01.005.

Gardarsdottir, S., De Lena, E., Romano, M., Roussanaly, S., Voldsund, M., Pérez-Calvo, J.-.F., et al., 2019. Comparison of Technologies for CO2 Capture from Cement Production—Part 2: cost Analysis. Energies 12, 542. https://doi.org/10.3390/en12030542.

Eurostat. Electricity prices components for industrial consumers - annual data 2020.