Journal of Cleaner Production 358 (2022) 132006

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Mitigation options for decarbonization of the non-metallic minerals industry and their impacts on costs, energy consumption and GHG emissions in the EU - Systematic literature review

Katarzyna Korczak [a,b,*], Maksymilian Kochański [a,b], Tadeusz Skoczkowski [a]

[a] Faculty of Power and Aeronautical Engineering, Warsaw University of Technology, Nowowiejska 24, 00-665, Warsaw, Poland
[b] Research and Innovation Centre Pro-Akademia, Innowacyjna 9/11, 95-050, Konstantynów Łódzki, Poland

ARTICLE INFO

Handling Editor: Prof. Jiri Jaromir Klemeš

Keywords:
Decarbonization
Cement industry
Non-metallic minerals industry
GHG emission mitigation
PRISMA

ABSTRACT

The non-metallic minerals industry is the third-largest industrial energy consumer, and it constitutes around 7% of global CO_2 emissions due to the high energy intensity of production processes. Although the substantial improvement of the energy efficiency of this industry in the EU observed since 1995, the energy intensity of this sector is still relatively high. To reach the goals of the Paris Agreement, it is necessary to implement further steps towards the decarbonization of this sector. Previous works do not provide information about research trends in this field or the current development of technologies. To fill this gap, the following research questions have been asked: (Q1) which decarbonization measures are already applied or under development in the non-metallic minerals sector?; (Q2) which of these measures might bring breakthrough to this sector?; (Q3) what is the impact of these measures on costs, energy consumption and GHG emissions? To this end, this paper performs a systematic literature review of GHG emission mitigation options of the non-metallic minerals industry by screening 2964 articles and performing an in-depth analysis of 48 full-text relevant articles following the PRISMA approach. The results show that the carbon capture, utilization and storage (CCUS) is the most popular research topic and has the highest decarbonization potential for the industry (up to 60%). However, more research is needed for the full-scale implementation. Further lowering the clinker to cement ratio to at least 75% is also of major importance, however, it is a mature technology, and not much research is required in this field. Despite the relatively low representation in scientific literature, heat electrification is an unavoidable direction for the industry in the long term, resulting from the global shift towards sustainable energy from renewables. The article also sets directions for future research, especially in terms of further development of the most promising technologies and on the industry transition pathways that would be legally adopted at the international level.

1. Introduction

The non-metallic minerals industry transforms mined or quarried natural non-fuel minerals (e.g. silica, clays) into products for intermediate or final consumption (e.g. cement, ceramic tiles). Cement and cementitious materials are the most popular construction materials. Their global consumption is over 10 times higher than second the most popular material – wood, and over 40 times higher than iron-based materials. In addition, products of this industry are essential for other sectors, in particular civil engineering (cement, ceramics), and steel industry (lime) (European Commission, 2019). In 2019, the global cement production reached 4.1 billion tonnes, with China being the global leader with a 56% share (CEMBUREAU, 2021). Since 1990, global production has nearly quadrupled (Lim et al., 2020). Processes used by the non-metallic minerals industry, such as grinding, mixing, cutting, shaping, and honing, are energy-intensive and are sources of significant GHG emissions. The non-metallic minerals sector, iron and steel, and chemicals and petrochemicals industries are the primary industrial sources of GHG emissions, responsible for 70% of these emissions (Miró et al., 2018). However, the non-metallic sector in the EU has already significantly reduced its emissions, from 273 in 1990 to 192 million tonnes CO_{2eq} in 2017 (Fig. 1). This was done mainly through increased energy efficiency, the use of alternative fuels, including a wide range of wastes, and clinker substitution (Scrivener et al., 2016). In the

* Corresponding author. Research and Innovation Centre Pro-Akademia, Innowacyjna 9/11, 95-050, Konstantynów Łódzki, Poland.
E-mail address: katarzyna.korczak@proakademia.eu (K. Korczak).

https://doi.org/10.1016/j.jclepro.2022.132006
Received 8 September 2020; Received in revised form 14 March 2022; Accepted 24 April 2022
Available online 28 April 2022

EU, the highest emission reduction was observed in Italy, France, Spain and the UK – between 1990 and 2017, these countries decreased their emissions by 18.9, 11.8, 8.5, and 8.2 million tonnes CO_{2eq}, respectively (United Nations Framework Convention on Climate Change, 2019). On the other hand, countries such as Ireland, Romania and Denmark increased their emissions by 1.4, 0.7, and 0.4 million tonnes CO_{2eq}, respectively (Table 1).

From 1995 to 2016, the energy intensity of the non-metallic minerals sector in the EU has constantly been dropping, reaching the level of 0.4909 koe/€2010 (Fig. 2) (ODYSSEE, 2018). Considering the evolution of the unit energy consumption of cement production, the biggest improvement was made between 1997 and 2006, when the unit energy consumption dropped in the EU by 22%, from 0.0909 to 0.0706 toe/-tonne cement. Then it started growing to reach 0.0814 toe/tonne cement in 2010. Since then, the factor has stayed at a stable level, fluctuating around 0.080–0.082 toe/tonne cement (Fig. 3). Only four countries reached the level of the unit energy consumption better than the EU average, namely Italy, Germany, Austria and Belgium (Table 2). On the other hand, France, Sweden, Spain, Croatia, Poland, Portugal, the UK and Cyprus consumed from 2% (France) to 76% (Cyprus) more energy for the production of one tonne of cement than the EU average (Fig. 4). Still, compared to other world regions, the energy intensity of clinker production in the EU is relatively high – better performance has been reached in regions such as India, the Middle East or Brazil due to using better-performing technologies (Fig. 5). For example, India is getting closer to reaching the highest possible efficiency level of thermal energy consumption due to using the best available technologies (International Energy Agency, 2021). Globally, energy use in some of the most energy-intense segments of the economy increased in 2019, including 5% growth in cement and 7% in steel IEA (International Energy Agency, 2020)

Since clinker production is the most energy-intensive subprocess of cement production, its energy intensity could be decreased by lowering the clinker to cement ratio. Standard types of cement consist of 90–95% of clinkers. Some part of it could be substituted with by-products of other processes such as fly ash or granulated blast furnace slag – to improve cement properties and indirectly reduce CO_2 emissions associated with cement production. In 2017, the clinker to cement ratio varied from 69% in India to 89% in North America. In the EU, with an average share of 77%, there is, therefore, the potential for further improvement (Fig. 6).

The primary source of emissions, including GHG, in the non-metallic minerals sector is cement production, accounting for almost 70% of emissions. It is followed by lime production, responsible for 17% of emissions (European Environment Agency, 2019).

Production of cement requires the use of raw materials (mainly limestone), fuels (coal, petroleum coke, natural gas), energy (electricity, heat), air and water (Çankaya and Pekey, 2019). To produce one tonne of cement, it is needed to provide 2.95–5 GJ (0.07–0.12 toe) of thermal energy, 90–150 kWh of electricity, and 1.7 tonnes of limestone. Energy costs account for about 20–25% of total production costs. On average, one tonne of cement production requires 3 times more thermal energy than electricity (Karellas et al., 2012).

Production of one tonne of Portland cement is accompanied by the emission of roughly one tonne of CO_2. The two processes mainly responsible for CO_{2equ} emissions are calcination of limestone (50%) and combustion of fuels (40%). Limestone calcination is also the most energy-intensive and the most expensive process, consuming 80% of energy and 50–60% of costs (Karellas et al., 2012). Depending on the technology, the production of one tonne of clinker can consume from 2.9 to 6.3 GJ (0.07–0.15 toe) of thermal energy (Table 3). In 2017, the average energy intensity of clinker production in the world was 3.4 GJ/tonne (0.08 toe/tonne) (International Energy Agency, 2019).

Considering electricity demand in cement production, grinding is the most energy-intensive process, consuming, on average, 43% of the total electricity use. It is followed by raw material preparation and clinker production – each process accounts for 25% of the total demand (Fig. 7).

In recent decades, increased attention has been paid throughout the economy and society to environmental aspects, climate change and material resource depletion. The Europe 2020 flagship initiative for "Resource Efficient Europe" aims at sustainable growth by identifying and creating new business opportunities, *inter alia*, through new and innovative means of production, business models and product design. It sets out how sustainable growth can be decoupled from the use of resources (European Commission and Union 2014). In another European Commission's policy, the "European Green Deal", decarbonization is considered as one out of the five key pillars of more sustainable models of production, next to energy and material efficiency, circularity, digitalization and reconversion (Sartori, 2019). These objectives result from the IPCC 1.5 °C scenario, which implies that industrial emissions must be reduced at a much larger scale and speed to reach near-zero by 2050 (65–90% reduction from 2010 levels) and to decrease after that, even while industrial production is expected to grow significantly (IPCC, 2018).

These aspects pressure societies and, in turn, the industry to deeply change the manufacturing processes. Moreover, other drivers (e.g. increasing energy and raw material prices, the potential lack of critical resources, necessary investments in environmentally sound technologies, and penalties for lacking compliance with environmental regulations as well as regulative incentives or the widespread of CO_2 emission allowances), are the issues that directly link environmental driven objectives to the business of a company.

Decarbonization of the EU industry is also of primary importance for its global competitiveness. For example, if carbon prices of 30€/tonne CO_2 are passed through to product prices, this would result in significant price increases for cement (27.6%) (Neuhoff et al., 2018). Other drivers of the EU industry decarbonization include the need for a revitalization of the EU industry, particularly energy-intensive sectors, and utilization

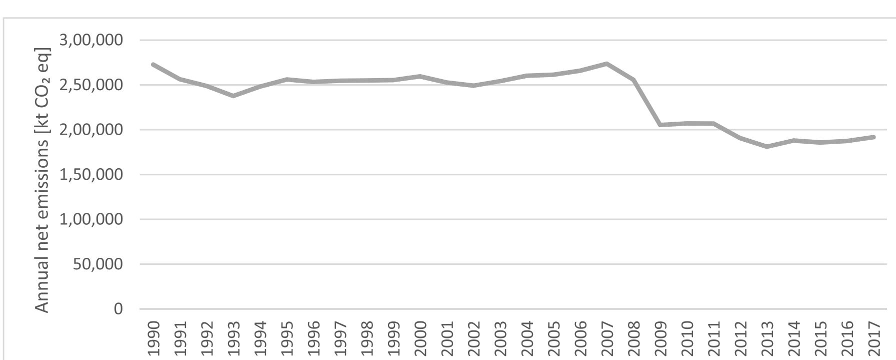


Fig. 1. Annual net emissions of CO_2 equivalent in the non-metallic minerals sector in the EU, 1990–2017, in ktonnes (United Nations Framework Convention on Climate Change, 2019).

Table 1
Annual net emissions CO_2 equivalent in the non-metallic minerals sector in the EU Member States, 1990–2017, in ktonnes (United Nations Framework Convention on Climate Change, 2019).

Country/Year	1990	1995	2000	2005	2010	2015	2017
Austria	4262	3745	3912	4210	3861	4036	4082
Belgium	10,873	11,147	11,108	10,620	8765	7907	7588
Bulgaria	5756	4655	2951	3947	2869	2694	2824
Croatia	1306	748	1433	2015	1526	1374	1520
Cyprus	1099	1276	1379	1620	1145	1379	1448
Czechia	8630	7015	6274	5588	5106	4785	5252
Denmark	2373	3064	3222	3195	1765	2234	2741
Estonia	1571	778	767	784	683	530	802
Finland	2536	1606	1872	2044	1676	1420	1686
France	29,158	25,584	25,134	24,811	22,137	18,282	17,322
Germany	41,949	43,135	40,256	33,331	32,239	32,577	35,409
Greece	12,710	13,619	13,693	14,948	9066	7077	7827
Hungary	5219	3470	3340	3527	2066	1982	2237
Ireland	1939	1589	2629	4472	2219	3013	3326
Italy	42,354	39,420	45,997	48,287	35,893	25,326	23,473
Latvia	1137	400	293	433	770	754	716
Lithuania	5350	1185	752	961	715	1011	881
Luxembourg	1163	1028	1106	958	872	767	832
Malta	1	1	0	0	0	0	0
Netherlands	3168	2789	2785	2389	2186	1769	1948
Poland	18,628	19,735	16,091	13,920	15,920	15,794	18,078
Portugal	6880	7877	8742	9194	7458	6553	5913
Romania	6271	6824	6418	6572	4924	6712	6922
Slovakia	5712	3616	3283	3405	2720	3118	3237
Slovenia	975	787	1121	1222	935	842	927
Spain	31,257	33,912	38,154	42,724	28,124	21,616	22,758
Sweden	3496	3201	3535	3545	3312	3229	3203
United Kingdom	16,946	13,791	13,328	12,731	8080	8976	8721
European Union	272,719	256,000	259,576	261,454	207,035	185,754	191,677

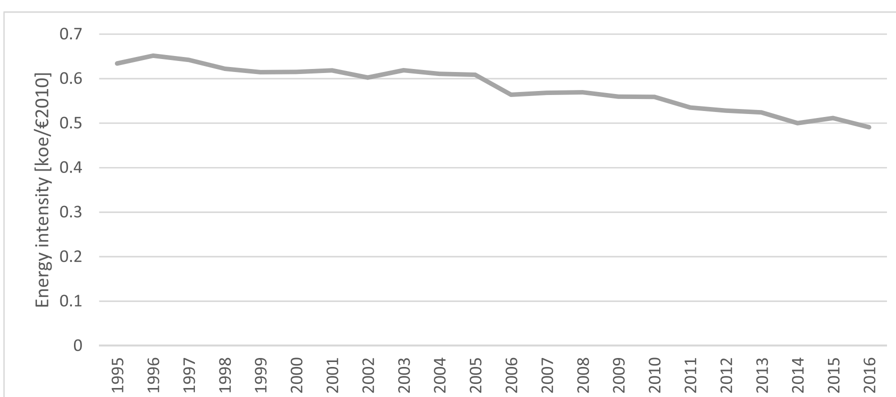


Fig. 2. Average energy intensity of the non-metallic minerals sector (at exchange rate) in the EU, 1995–2016, in koe/€2010 (1 koe = 41.868 MJ, €2010 – EURO values of 2010) (ODYSSEE, 2018).

of opportunities brought by the circular economy, which provides new inducements for more efficient energy and material management (Tagliapietra et al., 2019).

There are several studies on the decarbonization of the energy-intensive industry, including the non-metallic mineral sector in particular. A general overview of selected available technologies supporting the decarbonization of the cement industry, both from the supply and the demand side, was presented by (Rissman et al., 2020). Napp et al. (2014) analyze the decarbonization from a broader view, reviewing interactions between technologies, policies and economic instruments supporting the decarbonization. Similarly Wesseling et al. (2017) characterize the surrounding of the energy-intensive industry, particularly the elements that impact its transition towards a low-carbon future, especially the innovation systems. Koasidis et al. (2020) presented a similar approach, analyzing decarbonization using the Sectoral Innovation Systems and the Systems Failure framework. Jackson et al. (2018) described the current status of the economic growth from the view of GHG emission, but did not propose any technological solutions. Another research group focused on identifying decarbonization pathways, e.g. an optimal decarbonization strategy of the non-metallic minerals sector (Lin and Ouyang, 2014). Correspondingly, Habert et al. (2020) studied how to combine minor improvements to reach up to 50% of GHG emission reduction from the cement and concrete industry. Griffin, Hammond, and Norman (2018) presented a case study to showcase the potential of the cement sector decarbonization. Gerres et al. (2019) presented a review of the decarbonization pathways and roadmaps. Besides the decarbonization, also adaptation strategy of the energy-intensive industry to climate change is discussed in the literature (Ford et al., 2010). Besides general approaches, also country-specific solutions are presented, for example, decarbonization patterns followed by selected countries (J. W. Wang et al., 2017), technological trajectory and policy instruments of the decarbonization of the Swedish energy-intensive industries (Nurdiawati and Urban, 2021), barriers and enablers of low-carbon technologies in the energy-intensive industry in

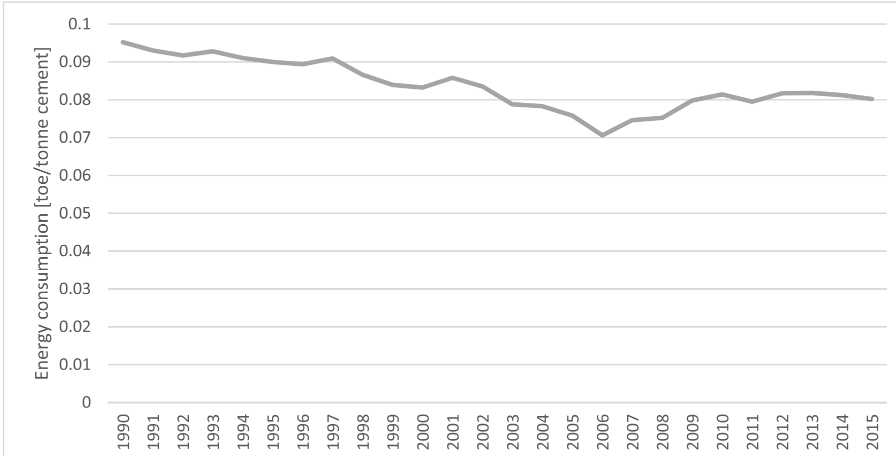


Fig. 3. Evolution of average unit energy consumption of cement production in the EU, 1990–2015, toe/tonne cement; Source: own work based on (ODYSSEE, 2018).

Table 2
Unit energy consumption of cement production in the EU Member States, 1990–2016, in toe/tonne (ODYSSEE, 2018).

Country/year	1990	1995	2000	2005	2010	2015	2016
Austria	n.a.	0	0	0.0712	0.076	0.0737	0.0743
Belgium	0.117	0.0974	0.0938	0	0.0896	0.0757	0
Bulgaria	0	0	0	0	0	0	0
Croatia	0.122	0.1023	0.0982	0.1118	0.0865	0.0873	0.0818
Cyprus	0	0.2061	0.1384	0.1065	0.0992	0.1415	0.0971
Czechia	0	0	0	0	0	0	0
Denmark	0	0	0	0	0	0	0
Estonia	0	0	0	0	0	0	0
Finland	0	0	0	0	0	0	0
France	0.0843	0.0852	0.0865	0.0819	0.0907	0.0817	0.08
Germany	0	0.0885	0.077	0.0636	0.0708	0.0692	0.071
Greece	0.075	0.0648	0.0622	0.0522	0.0504	0	0
Hungary	0	0	0	0	0	0	0
Ireland	0	0	0	0	0	0	0
Italy	0.083	0.0776	0.0746	0.0642	0.0696	0.0661	0
Latvia	0	0	0	0	0	0	0
Lithuania	0	0	0	0	0	0	0
Luxembourg	0	0	0	0	0	0	0
Malta	0	0	0	0	0	0	0
Netherlands	0	0.0552	0.0696	0.0756	0.0729	0	0
Poland	0.1572	0.1459	0.1063	0.1033	0.0947	0.0913	0.0921
Portugal	0.09	0.0783	0.081	0.1204	0.1027	0.1012	0.1197
Romania	0	0	0	0	0	0	0
Slovakia	0	0	0	0	0	0	0
Slovenia	0	0	0	0	0	0	0
Spain	0.0845	0.0772	0.0745	0.0648	0.0745	0.0855	0.0906
Sweden	0.1008	0.0736	0.1034	0.094	0.0975	0.0838	0
United Kingdom	0.1359	0.1138	0.1134	0.1059	0.1461	0.1139	0
European Union (EU 28)	**0.0952**	**0.09**	**0.0832**	**0.0758**	**0.0814**	**0.0802**	**0.0801**

Germany and the UK (Koasidis et al., 2020), or a case study showcasing the potential of GHG emission reduction in the cement industry in the UK (Griffin et al., 2018). Narrower research focused on specific technologies, presenting their selected aspects, i.e. decarbonization potential of different measures applicable for energy-intensive sectors, including cement production (Daehn et al., 2021) and the environmental assessment of CCS/CCUS technologies (Cruz et al., 2021).

Various technological decarbonization pathways are possible, comprising different mitigation options (Fig. 8). Depending on the industry and technological processes, several decarbonization measures can be applied. Previous works, however, do not show what the research trends in this field are or what technologies are currently under development. Therefore, there is a knowledge gap in identifying the recent progress of the different decarbonization solutions from the point of view of their potential for the non-metallic minerals sector. Furthermore, there is a missing transnational perspective, not narrowing the analysis to selected countries.

This article aims to provide a systematic review of mitigation options for decarbonization of the non-metallic sector, in particular cement production, discussed in the literature in recent years. We discuss the following technologies, solutions and measures: resource, energy and materials efficiency; replacement of energy-intensive construction materials; shift towards hydrogen and clean synthetic methane; carbon capture, utilization, and storage (CCUS); heat eletrcitifaction; utilization of waste heat; energy generation in combined heat and power units (CHP); energy management; and technology replacement. Accordingly, we asked the following research questions:

1) Q1: Which decarbonization measures are already applied or under development in the non-metallic minerals sector?
   - Q2: Which of these measures might bring breakthroughs to this sector?

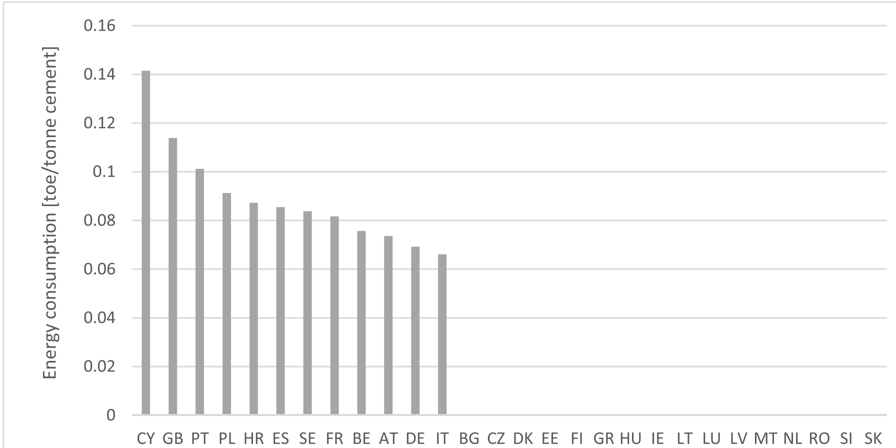


Fig. 4. Unit energy consumption of cement production in selected EU Member States in 2015, toe/tonne cement, 0 – no data; Source: own work based on (ODYSSEE, 2018).

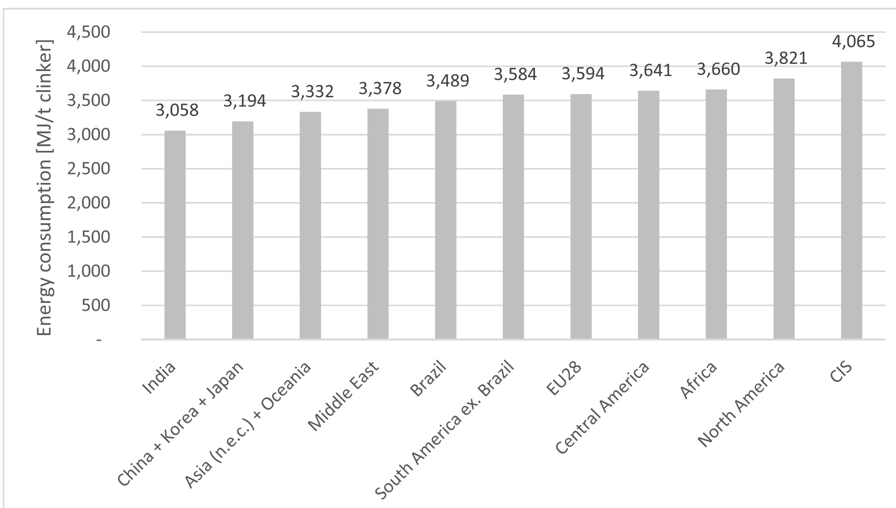


Fig. 5. Comparison of thermal energy consumption of grey clinker production in selected regions, 2017 (Weighted average, excluding drying of fuels), in MJ/tonne clinker; Source: own work based on (GNR Project, 2018).

- Q3: What is the impact of these measures on costs, energy consumption and GHG emissions?

The article is structured as follows. “Introduction” provides an overview of the non-metallic minerals sector in the EU and the driving forces of decarbonization. “Materials and methods” explains the methodology applied in the research. The “Results and discussion” presents findings of the review of 48 full-text research papers, presents the results of our research, and critically analyses and contrasts the findings. Finally, “Conclusions“ highlights the main findings of this research.

2. Material and methods

Our analysis of the potential decarbonization measures of the non-metallic minerals sector is based on the systematic literature review, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses – PRISMA 2009 approach (PRISMA, 2015). PRISMA is a framework supporting researchers in conducting systematic reviews and meta-analyses. It consists of a checklist with 27 topics and a flow diagram presenting 4 stages of identifying relevant studies for analysis (Moher et al., 2009). PRISMA is mostly used in medical science. However, it has also been followed by research in other areas, e.g. in environmental science (Mardani et al., 2019) or agriculture (Song et al., 2018). We selected this approach due to its completeness in reporting systematic reviews and grounded position in the research community.

Initially, we preliminary identified ten mitigation options relevant to decarbonizing energy-intensive industries. These include the following:

1) Resource efficiency (Moya et al., 2011)
2) Energy-intensive construction materials replacement (Gutowski et al., 2013)
3) H_2 (feedstock and fuel) and clean synthetic methane (ECRA, 2017)
4) Carbon Capture, Utilization, and Storage (CCUS) (Scrivener et al., 2018)
5) Electrification of heat (Schüwer and Schneider, 2018)
6) Strong energy efficiency and material efficiency (Scrivener et al., 2018)
7) Waste heat utilization (Panayiotou et al., 2017)
8) Combined heat and power production (CHP) (Department for Business Energy and Industrial Strategy, 2021)
9) Energy management (strong energy efficiency) (ECRA, 2017) (Talaei et al., 2019)
10) Technology replacement (Hasanbeigi et al., 2013)

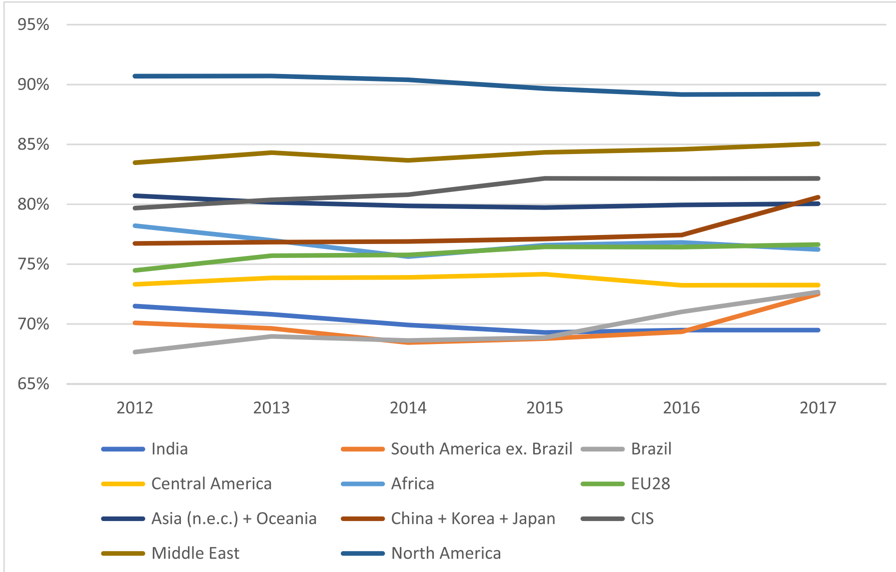


Fig. 6. Evolution of clinker to cement equivalent ratio in world regions, 2012–2017 (Weighted average, grey and white clinker in Portland and blended types of cement), in %; Source: own work based on (GNR Project, 2018).

Table 3
Thermal energy intensity of cement production processes; Source: adapted from (Rahman et al., 2013).

Kiln process	Thermal energy consumption
Wet process with internals	5.86–6.28 GJ/tonne clinker (0.14–0.15 toe/tonne clinker)
Long dry process with internals	4.6 GJ/tonne clinker (0.1099 toe/tonne clinker)
1-stage cyclone pre-heater	4.18 GJ/tonne clinker (0.0998 toe/tonne clinker)
2-stage cyclone pre-heater	3.77 GJ/tonne clinker (0.09 toe/tonne clinker)
4-stage cyclone pre-heater	3.55 GJ/tonne clinker (0.0848 toe/tonne clinker)
4-stage cyclone pre-heater plus calciner	3.14 GJ/tonne clinker (0.075 toe/tonne clinker)
5-stage pre-heater plus calciner plus high-efficiency cooler	3.01 GJ/tonne clinker (0.0719 toe/tonne clinker)
6-stage pre-heater plus calciner plus high-efficiency cooler	<2.93 GJ/tonne clinker (<0.07 toe/ tonne clinker)

Then, we performed an initial search in three databases: Science Direct, Scopus, and Web of Science Core Collection (Table 4). As a result, we received a list of 575,618 records (Table 5).

To narrow down this list of records, we performed a refined search (Table 6). We considered only articles presenting original research published between 2009 and November 2019, written in English.

We received 2964 articles after removing duplicates (Fig. 9). All records have been screened through analysis of title and abstracts. In our further research, we excluded papers that were clearly out of focus, did not focus on the non-metallic mineral sector, did not provide details on the environmental impact of the given decarbonization option or when a full text was not available. As a result, we assessed 270 full-text articles in the field of non-metallic minerals (Table 7). Assessment of an article consisted of answering the following question: does the article provide data on technology impact on GHG emissions, energy consumption, or costs? If yes, the article was found relevant, and findings were included in our review of decarbonization options. Analysis of full-text articles did not reveal any new decarbonization category that was not considered previously.

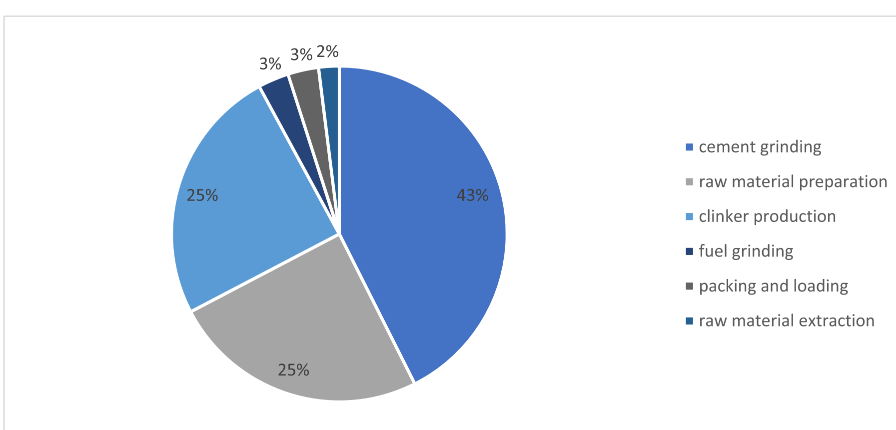


Fig. 7. Electricity consumption of cement production processes (ECRA, 2017).

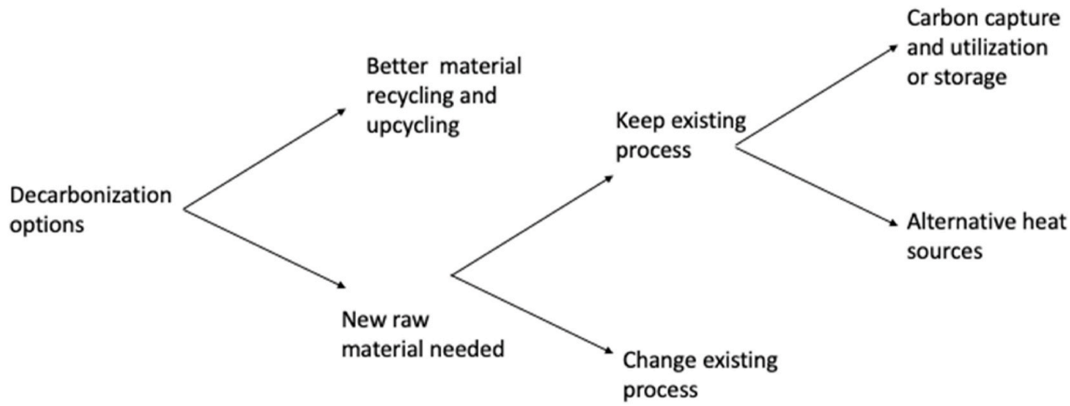


Fig. 8. Generalized energy-intensive industry decarbonization options, Source: adapted from (Bataille, 2018).

Table 4
Initial search terms for non-metallic minerals sector decarbonization options.

Ref. No.	Search Term
1a.	"resource efficiency" AND ("Non-metallic minerals" OR cement OR glass OR ceramics OR lime)
2a.	("materials replacement" OR "replacement of materials") AND ("Non-metallic minerals" OR cement OR glass OR ceramics OR lime)
3a.	"hydrogen" AND ("Non-metallic minerals" OR (cement OR glass OR ceramics OR lime)
4a.	"synthetic methane" AND ("Non-metallic minerals" OR cement OR glass OR ceramics OR lime)
5a.	("carbon capture and storage" OR "carbon capture and sequestration" OR "carbon capture, utilization and storage") AND ("Non-metallic minerals" OR cement OR glass OR ceramics OR lime)
6a.	("electrification of heat" OR "heat electrification") AND ("Non-metallic minerals" OR cement OR glass OR ceramics OR lime)
7a.	"energy efficiency" AND ("Non-metallic minerals" OR cement OR glass OR ceramics OR lime)
8a.	"waste heat" AND ("Non-metallic minerals" OR cement OR glass OR ceramics OR lime)
9a.	("combined heat and power" OR "CHP") AND ("Non-metallic minerals" OR cement OR glass OR ceramics OR lime)
10a.	"energy management" AND ("Non-metallic minerals" OR cement OR glass OR ceramics OR lime)
11a.	("technology replacement" OR "novel technology") AND ("Non-metallic minerals" OR cement OR glass OR ceramics OR lime)

Table 5
Results returned from initial search terms (records identified through database searching) – non-metallic minerals.

Ref. No.	Science Direct	Scopus	Web of Science Core Collection
1a.	1756	100	57
2a.	984	51	7
3a.	457,006	29,434	15,672
4a.	115	0	0
5a.	4064	276	163
6a.	26	0	0
7a.	30,560	4248	1392
8a.	10,426	1215	391
9a.	7897	245	99
10a.	4398	678	92
11a.	3841	312	113
Total	521,073	36,559	17,986

Table 6
Refined search terms – non-metallic minerals.

Ref. No.	Search Term
1b.	resource efficiency AND (cement OR glass OR ceramics OR lime) AND (cost OR emission OR CO2) AND ("consumption of materials" OR "materials consumption")
2bi.	(("cement replacement" OR "replacement of cement") AND cost AND emission AND sustainability AND construction AND "impact assessment" NOT ("bioactivity assessment" OR "dental application"))
2bii.	("glass replacement" OR "replacement of glass") AND sustainable NOT ("glass fiber")
2biii.	("ceramics replacement" OR "replacement of ceramics") AND emission
2biv.	("lime replacement" OR "replacement of lime") AND (emissions OR energy)
3bi.	hydrogen AND ("cement production" OR "cement manufacturing" OR "cement plant") AND co2 NOT "co2 capture"
3bii.	hydrogen AND ("glass production" OR "glass manufacturing" OR "glass plant") AND co2 NOT "co2 capture"
3biii.	hydrogen AND ("ceramics production" OR "ceramics manufacturing" OR "ceramics plant") AND co2 NOT "co2 capture"
3biv.	hydrogen AND ("lime production" OR "lime manufacturing" OR "lime plant") AND co2 NOT "co2 capture"
4b.	"synthetic methane" AND (cement OR glass OR ceramics OR lime) AND (cost OR emission OR co2)
5bi.	("carbon capture" OR ccs) AND ("cement production" OR "cement manufacturing" OR "cement plant") AND cost AND energy NOT (electricity OR policy)
5bii.	("carbon capture" OR ccs) AND ("glass production" OR "glass manufacturing" OR "glass plant") AND cost AND energy NOT (electricity OR policy)
5biii.	("carbon capture" OR ccs) AND ("ceramics production" OR "ceramics manufacturing" OR "ceramic plant") AND cost AND energy NOT (electricity OR policy)
5biv.	("carbon capture" OR ccs) AND ("lime production" OR "lime manufacturing" OR "lime plant") AND cost AND energy NOT (electricity OR policy)
6b.	("electrification of heat" OR "heat electrification") AND ("Non-metallic minerals" OR cement OR glass OR ceramics OR lime)
7b.	energy efficiency AND (cement OR glass OR ceramics OR lime) AND (production OR plant) AND "co2 emission" NOT (potential OR policy)
8b.	waste heat utilization AND (cement OR glass OR ceramics OR lime) AND industry AND emission
9b.	("combined heat and power" OR CHP) AND (cement OR glass OR ceramics OR lime) AND industry AND emission NOT biogas
10b.	energy management AND (cement OR glass OR ceramics OR lime) AND co2 AND implementation
11b.	("technology replacement" OR "novel technology") AND (cement OR glass OR ceramics OR lime) AND production

3. Results and discussion

Industry accounts for about 25% of EU final energy demand, and its dominant energy carriers are fossil fuels, mostly gas, coal, and oil. This means that this sector is critical for achieving European climate goals. Non-metallic minerals, besides iron and steel, and chemicals and petrochemicals, is the top-emitting industry. This means that to achieve the EU climate goals, the EU industry must inevitably transform to a low carbon economy (European Commission, 2017). The EU "Roadmap for moving to a competitive low-carbon economy in 2050" (European Commission, 2011) has set a target of reducing emissions in the industry by 83–87% by 2050. The articles analyzed within this paper show that it

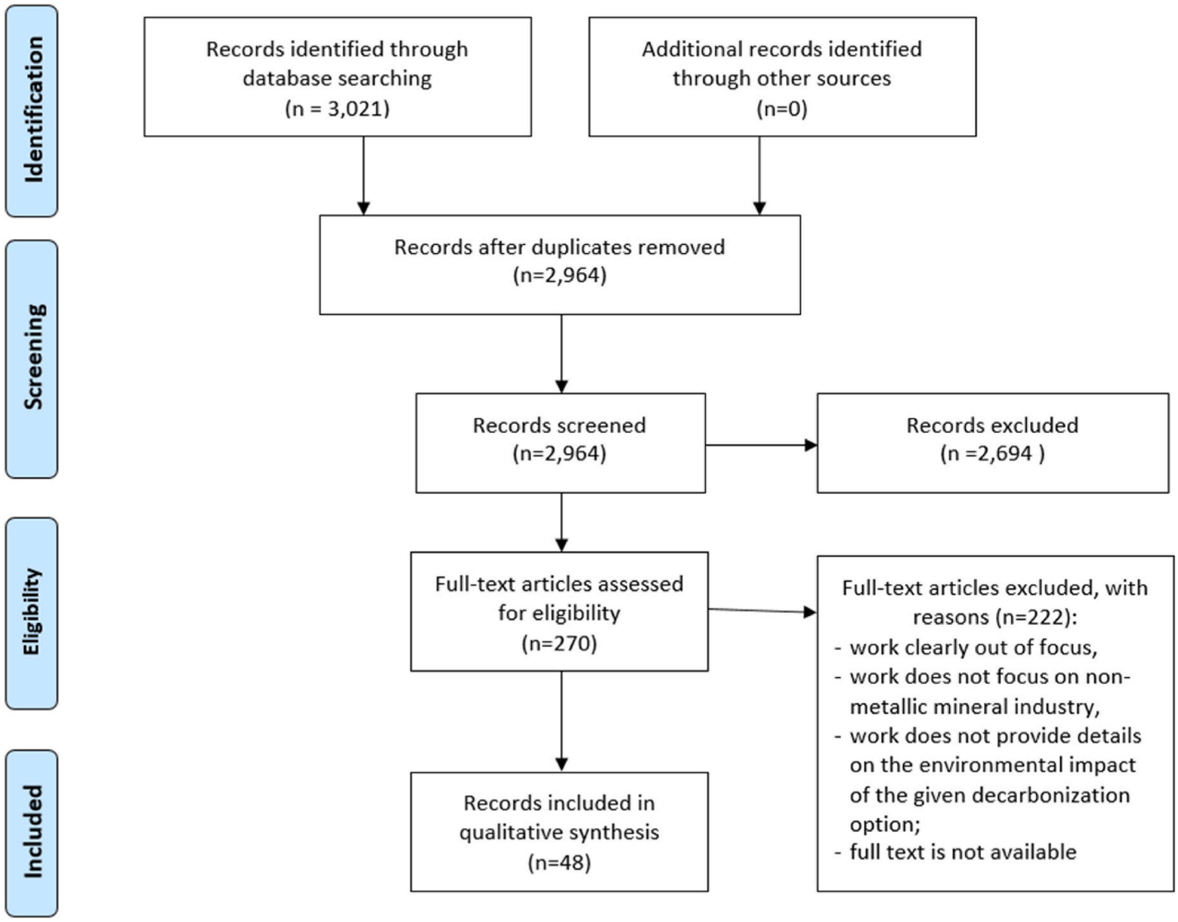


Fig. 9. PRISMA 2009 Flow diagram as applied in our research.

Table 7
Records screened, and full-text articles assessed – non-metallic minerals.

Ref. No.	Number of records screened	Number of full-text articles assessed	Number of full-text articles found relevant
1b.	50	10	4
2b.	93	14	4
3b.	244	17	1
4b.	21	1	0
5b.	140	40	18
6b.	20	3	1
7b.	206	44	9
8b.	14	9	6
9b.	863	16	1
10b.	207	18	1
11b.	1106	98	3
Total	2964	270	48

is technically feasible to significantly reduce emissions from the non-metallic minerals sector and reach the target set.

3.1. CCS/CCUS

Among the analyzed papers, carbon capture, (utilization) and storage (CCS/CCUS) is the most discussed mitigation option in the non-metallic minerals sector, presented in 18 identified relevant papers (Table 9, Fig. 11), mainly due to the challenge of high process-related CO_2 emissions for clinker burning. Presented technologies include post-combustion capture, oxyfuel combustion with CO_2 capture, pre-combustion and carbon looping. Post-combustion seems to be an option that could be implemented in the near future – pilot and demonstration plants already exist in Scotland (Barker et al., 2009) and Norway (Dubois et al., 2017). The technical risk of this option is comparatively low, but it requires large amounts of heat. Oxyfuel combustion is another option that could be used to retrofit existing kilns, but it requires significant structural changes to the core units in the cement plant (Kuramochi et al. 2012). Options like oxyfuel combustion and carbon looping technologies are not mature and require more research and development. In the frame of the EU H2020 project LEILAC, another CCS technology developed for the lime industry, based on direct separation, has the advantage of not requiring large amounts of additional energy for the CO_2 capture since a pure stream of process-related emissions from calcination is generated by separating it from fuel combustion (Herbst et al., 2018). Reports and roadmaps developed by independent organizations agree that the most perspective technology with the highest mitigation impact is the CCS. According to OECD and IEA, CCU/CCUS is virtually the only technology solution for

Table 8
Alternative fuel options for the cement industry (Rahman et al., 2015).

Alternative fuel type	Materials
Liquid waste fuels	Industrial chemical wastes, waste solvents, used oils, paint waste, oil sludge, distillation residues, wax suspensions, tar, petrochemical waste, asphalt slurry
Solid waste fuels	Used tire, paper waste, plastic residues, spent cell liner (SPL), meat and bone meal (MBM), sewage sludge, municipal solid waste (MSW), agricultural biomass (green waste, wood waste, nutshells, rice husk, etc.), refuse-derived fuel (RDF), rubber residues, pulp sludge, battery cases, oil-bearing soils
Gaseous waste	Landfill gas, pyrolysis gas

Table 9
Decarbonization case studies of the non-metallic minerals sector (ND – no data available).

Topic	Source	Technology	Impact on costs	Impact on energy consumption	Impact on GHG emissions	Remarks
CCUS	Barker et al. (2009)	CCS - Oxy-combustion	€40/tonne CO_2	ND	61% CO_2 emissions reduction (at cement plant); 52% reduction including import)	–
CCUS	Barker et al. (2009)	CCS - Post-combustion capture	€107/tonne CO_2	ND	74% CO_2 emissions reduction (at cement plant); 77% reduction including electricity exports	–
CCUS	Chang et al. (2013)	Calcium Looping technology	ND	ND	CO_2 capture efficiency: 80–95% in both Carbonator (bubbling fluidized bed) and calciner (directly fired rotary kiln) for 3-kW_{th} installation	Results of the 3-kW_{th} bench-scale installation in Taiwan
CCUS	(Cormos and Cormos 2014)	Calcium Looping technology	specific capital investment costs: 458.57 EUR/t; O&M costs: 57.48 EUR/y; cement production costs 106.73 EUR/t; CO_2 avoided cost 57.76 EUR/t	ND	Carbon capture rate: 90%; CO_2 captured: 962.19 kg/t	–
CCUS	Nelson et al. (2014)	RTI's technology (solid sorbent-based process which selectively removes CO_2 from flue gases)	cost of CO_2 avoided: 38 ÷ 46 €/t- CO_2	Electric energy consumption: 135 kWh/t-CO_2avoided; Thermal energy consumption: 2.4 MJ/kgCO_2avoided	CO_2 capture efficiency: >85%	Results of the technical and economic assessment for the cement plant in Norway
CCUS	Ozcan et al. (2014)	carbon capture - amine process	89 €/tonne CO_2	Incremental energy consumption: 8.1 GJ_{th}/ton CO_2 avoided	CO_2 capture rate: 90%	Results of a numerical simulation
CCUS	Ozcan et al. (2014)	Carbon capture - Hybrid System	55 €/tonne CO_2	Incremental energy consumption: 3.2 GJ_{th}/ton CO_2 avoided	CO_2 capture rate: 90%	Results of a numerical simulation
CCUS	Ozcan et al. (2014)	Carbon capture - Calcium Looping process	42 €/tonne CO_2	Incremental energy consumption: 2.5 GJ_{th}/ton CO_2 avoided	CO_2 capture rate: 90%	Results of a numerical simulation
CCUS	Ozcan et al. (2014)	Carbon capture - Ca–Cu Looping process	ND	Incremental energy consumption: 1.7 GJ_{th}/ton CO_2 avoided	CO_2 capture rate: 90%	Results of a numerical simulation
CCUS	Ozcan et al. (2014)	Carbon capture - indirect calcination process	34 €/tonne CO_2	Incremental energy consumption: 1 GJ_{th}/ ton CO_2 avoided	CO_2 capture rate: 56%	Results of a numerical simulation
CCUS	Dubois et al. (2017)	Post-combustion CO_2 capture technology using amine-based chemical absorption + partial oxyfuel combustion applied to cement kilns	ND	ND	CO_2 absorption rate: 90%	–
CCUS	Kemache et al. (2017)	Aqueous mineral carbonation for CO_2 sequestration:	ND	ND	CO_2 capture rate: 8.5–10.8%	Results of an experiment performed in a cement plant in Canada
CCUS	Liu and Yu (2017)	Thermal-Electrochemical Co-drive System	ND	Energy demand of the process: 2 GJ/ tonne CO_2	CO_2 capture efficiency: > 90%	–
CCUS	Calvo, Sutter, Gazzani, & Mazzotti, 2017)	Application of a Chilled Ammonia-based Process (CAP) for CO_2 Capture	ND	ND	CO_2 capture efficiency: 85.2%	Results of a numerical simulation
CCUS	Vega et al. (2017)	CO_2 capture process sing MEA 5M as a solvent	ND	Specific energy consumption for CO_2 capture: 7.9 GJ/t CO_2	CO_2 capture efficiency: 94%	Results from a lab-scale plant in Spain
CCUS	Ma et al. (2018)	Calcium-based synthetic sorbent with hollow core-shell	ND	ND	CO_2 capture efficiency: 90%	–

(continued on next page)

Table 9 (*continued*)

Topic	Source	Technology	Impact on costs	Impact on energy consumption	Impact on GHG emissions	Remarks
		structure under calcium looping conditions				
CCUS	Spinelli et al. (2018)	Calcium looping process for cement plants	ND	ND	CO_2 capture efficiency: 90%	Results of a numerical simulation of 1D model
CCUS	Andersson et al. (2019)	CO_2 uptake in cement products during use stage and end-of-life stage	ND	ND	23% of corresponding annual total emissions (fuel + calcination) from production of cement	–
CCUS	(César de Carvalho Pinto et al., 2019)	Calcium Looping technology	ND	ND	Absorption rate: 50%wt (i.e. absorption of 0.5 gCO_2/g of absorbent material)	–
CCUS	Dai et al. (2019)	Hollow fiber membrane module with a PVA/ProK hybrid membrane containing up to 40 wt % amino acid salt	ND	ND	CO_2 capture efficiency: 90%	Results of a pilot installation in a cement plant in Italy
CCUS	Saponelli et al. (2019)	CCS in based on carbon reduction and methane formation (ceramic production)	Methane formation of 13% of the total natural gas consumption of the considered kiln	ND	Avoided emissions: 640 tonne/y	Results of Computer Flud Dynamics simulation
Strong energy efficiency and material efficiency	Kabir et al. (2010)	Application of energy audit suggestions in a cement plant	Cost savings: 2318.18 USD/y	Energy savings: 42.88 MWh/y	GHG emission reduction of 14.10%	Results of waste heat recovery steam generator (WHRSG) and Secondary kiln shell application in a cement plant in Nigeria (dry cement process line of a total annual capacity of 800,000 metric tonnes)
Strong energy efficiency and material efficiency	Rahman et al. (2013)	Use of alternative fuel (e.g. industrial and households, waste, wood chips, tires, agricultural waste)	ND	Increase of thermal energy consumption from 10.9% to 13% has brought 2.7% reduction of CO_2 emission	ND	–
Strong energy efficiency and material efficiency	Kaddatz et al. (2013)	Coal fuel replacement by used tires	ND	ND	CO_2 emission reduction: 9%	Results of a numeric simulation
Strong energy efficiency and material efficiency	Kwon et al. (2015)	Use of cementitious powder as the main ingredient of recycled cement	ND	ND	CO_2 emission reduction of 54% (from 90 g-CO_2/g cement to 48.19 g-CO_2/g cement)	–
Strong energy efficiency and material efficiency	Monkman and MacDonald (2016)	Carbon dioxide upcycling into industrially produced concrete blocks	ND	ND	CO_2 utilization: 1.4% of the initial carbon footprint of cement	–
Strong energy efficiency and material efficiency	Kaliyavaradhan and Ling (2017)	Active carbonation techniques adopted for crushed concrete aggregate and waste cement derived from the construction and demolition waste	cost per 1 t of $CaCO_3$ extraction from waste cement: USD 136 for the desulphurization process and USD 323 for the ultrahigh-purity process	ND	Up to 270 kg of CO_2 can be sequestered if 1 t of waste cement is completely carbonated	–
Strong energy efficiency and material efficiency	Sani and Nzihou (2017)	Production of clay ceramics using agricultural wastes	ND	Energy consumption decrease: from 36 to 72%, depending on organic fraction share	CO_2 emission savings: from 3.00 to 8.11%, depending on organic fraction share	Results of the lab tests performed in France
Strong energy efficiency and material efficiency	Choi et al. (2017)	Building construction design technology based on resizing method	Cost reduction of 29.2%	ND	CO_2 emission reduction of 13.5%	Results of the study for 37 story building in South Korea
Strong energy efficiency and material efficiency	Ahmadi et al. (2018)	Cement replacement by raw diatomite powder	ND	Cumulative energy demand decreased from 3520 for 100% cement to 2407 MJ/kg for a mixture of 40% diatomite (31.6% reduction)	Global warming potential decreased from 262 for 100% cement to 166 kg CO_2 eq. for a mixture of 40% diatomite (36.6% reduction)	–
Strong energy efficiency and material efficiency	Çankaya and Pekey (2019)	Substitution of 3% fossil fuel with alternative fuels (dried sludge, RDF, and residual oil)	ND	ND	CO_2 emission reduction: 12 kg CO_2-eq/tonne clinker	Results of LCA analysis for cement plant in Turkey

(*continued on next page*)

Table 9 (*continued*)

Topic	Source	Technology	Impact on costs	Impact on energy consumption	Impact on GHG emissions	Remarks
Waste heat utilization	Karellas et al. (2012)	Water-steam cycle	Gross profit (avoided cost of electricity): 4.25 million EUR	Net electricity production: 42,505 MWh/y	CO_2 emission avoided: 37,159 tonne/y	Results of a numerical simulation
Waste heat utilization	Fang et al. (2015)	Waste heat utilization for district heating network supply	Investment cost: 60.04 million RMB (~7.8 million EUR); Operation costs: 11.4 million RMB (~1.5 million EUR)	Energy recovery: 390,000 GJ/y	CO_2 emissions avoided: 34,857 tonne/y	Results of the technology application in China
Waste heat utilization	(H. Wang et al., 2015)	Organic Rankine Cycle integrated with cement production line	Payback period: 2.38–2.89 years	Electricity production: 6.8–8.1 GWh electricity per year	CO_2 emission avoided: 7743–9268 tonne/y	Results of the laboratory experiment for the 4000 t/d cement production line in China
Waste heat utilization	Dolianitis et al. (2016)	Waste heat recovery at the glass industry with the intervention of batch and cullet preheating	ND	Energy consumption reduction: 13.3%	CO_2 emission avoided: 8.9%	Results of a numerical simulation for real glass production plant of pull rate of the furnace of 90 t/d, the energy input of 3.99 MW, and the specific energy consumption of 3833 kJ/kg.
Waste heat utilization	Abdelaziz et al. (2017)	Conversion of carbon dioxide from industrial flue gas streams into methanol	Process profit (estimated) - 56.55 M $/y; payback time of 1.17 year	ND	CO_2 emissions avoided: 62%	Results of a numerical simulation
Waste heat utilization	Delpech et al. (2018)	Heat pipe technology	Avoided fuel costs: 22,120 Euro/y	Natural gas savings: 110,600 Sm3/y	CO_2 emission avoided: 164 t	Results of a numerical simulation for real ceramic production plant in Italy of production capacity of 5000 kg/h of tiles
Resource efficiency	Butler and Hooper (2005)	Replacing virgin feedstock with colored cullet in glass production	ND	−70 MJ/t	ND	–
Resource efficiency	Lechtenböhmer et al. (2015)	Use clinker substitutes to reduce the clinker-to-cement ratio in cement manufacturing	ND	13–16% energy demand reduction	ND	–
Resource efficiency	Islam et al. (2017)	Use of waste glass powder as partial replacement of cement	ND	ND	14% CO_2 emission reduction	optimum glass content in the cement-glass mixture was found to be 20%
Energy-intensive construction materials replacement	Lehmann (2013)	CLT panels (cross-laminated timber)	ND	ND	1400 tonnes of CO_2 reduction per building (10 stories, 23 apartments), compared with building in concrete and steel	25% less energy for heating and cooling required in building built with this technology; Building will be carbon neutral after 32 years, for at least 10 years
Energy-intensive construction materials replacement	(de Carvalho Pinto et al., 2015)	Partial replacement of lime by steel slag milk in the ammonia recovery step of the Solvay process	ND	ND	CO_2 emission reduction between 8 and 20%	–
Energy-intensive construction materials replacement	Teh et al. (2017)	Use of Engineered Wood Products (EWPs) in construction sector, including CLT panels	ND	ND	Carbon reduction potential 2009–2050: 39% (26 Mt CO_2e) if no sequestration is considered and 182% (119 Mt CO_2e) with sequestration. Both cases assume linear decrease of reinforced concrete use in construction sector from 100% to 0% between 2009 and 2050, compared to the BAU scenario.	Calculations performed for the Australian market
Energy-intensive construction materials replacement	Sinka et al. (2018)	Lime-hemp concrete (LHC), a bio-based composite material that contains residues from the hemp production	ND	ND	CO_2 uptake ranging from 36.08 to 1.6 kg CO_2eq/functional unit	–
Technology replacement	Barcelo et al. (2014)	Shift from a theoretical belitic (C_2S only) system towards C_3S + C_2S system	ND	ND	12% reduction of CO_2 emissions from 816 to 719 kg/t-PCC	–

(continued on next page)

Table 9 (*continued*)

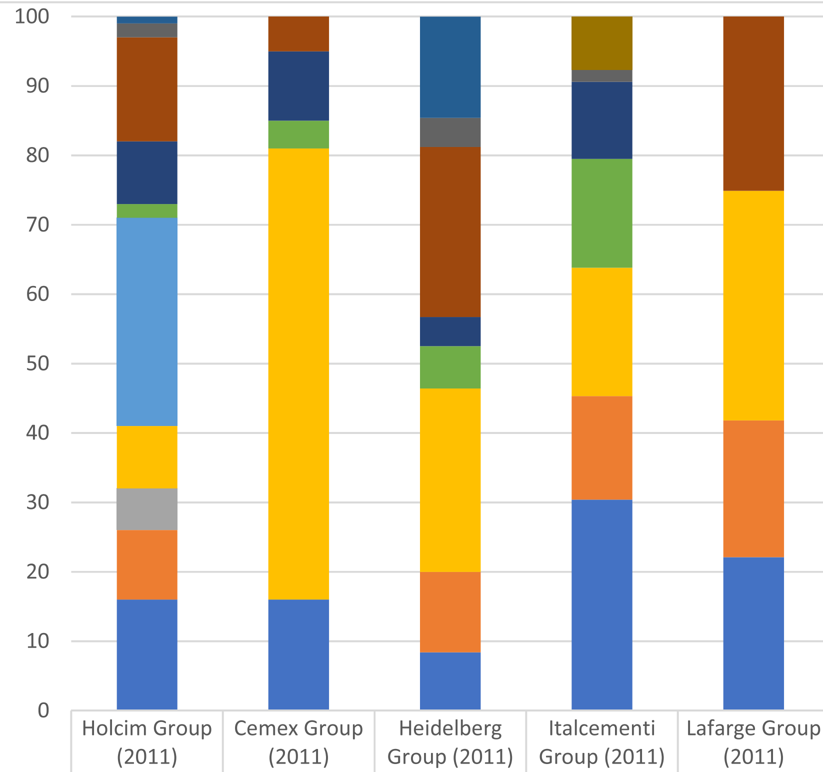
Topic	Source	Technology	Impact on costs	Impact on energy consumption	Impact on GHG emissions	Remarks
Technology replacement	Barcelo et al. (2014)	Development of a new class of clinker: BCSAF (belite-calcium sulfoaluminate-ferrite)	ND	ND	net direct 30% CO_2 saving	Full-scale demonstration in France showed that specific CO_2 emissions were reduced by about 25% relative to the manufacture of the standard Portland clinker in the same plant.
Technology replacement	Ditaranto and Bakken (2019)	Oxygen combustion in cement production	ND	Increased energy consumption of 117 kWh per tonne of clinker	ND	–
H_2 (feedstock and fuel) and clean synthetic methane	Weil et al. (2006)	Hydrogen energy from coupled waste gasification and cement production	ND	calculated hydrogen energy yield is 46% of fuel energy input	ND	thermochemical concept study
Energy management	Summerbell et al. (2016)	Cement plant performance improvement	ND	Energy consumption reduction: 8.5%	CO_2 emission reduction: 19.5%	Results of a case study of a plant in the UK, operating a pre-calciner type kiln commissioned in 1986. The plant was improved to 10th percentile best observed performance levels
CHP	(Hanak and Manovic 2018)	Combined heat and power generation with lime production for direct air capture (CHP-DAC process)	Capital investment: 744.6 £/kW_{ch}.	ND	CO_2 emission avoided: 88.6 $kgCO_2/MW_{ch}h$	Results of the feasibility study
Electrification of heat	Napp et al. (2019)	Electric kilns in ceramics production and electric glass smelters	ND	ND	ND	–

deep emissions reductions in sectors where other technology options are limited, such as in the production of cement, iron and steel or chemicals (OECD/IEA, 2020). While the efficiency of a single CCS installation might reach even 94% (Vega et al., 2017), it is expected that the total CO_2 emissions of the cement industry can be cut by 48% (International Energy Agency and Cement Sustainability Initiative, 2018) up to 60% (Müller et al., 2008). Any other technology considered has no such potential. Our analysis shows, however, that most of the research is based on numerical simulations, since only small-scale pilot installations are functioning, e.g. in Heping, Taiwan (Chang et al., 2013), Seville, Spain (Vega et al., 2017) or in Gubbio, Italy (Dai et al., 2019) and their operation is still challenging. There is a consensus in the literature that the CCS technology is not yet ready for full-scale implementation, and further research is necessary, but on the other hand, it is a crucial measure for full decarbonization of the industry. As (Farabi-Asl et al., 2020) notice, there are no obvious alternatives for CCS allowing for reaching decarbonization targets in the industry. Only 17 large-scale projects have so far been constructed and operated worldwide, 4 are in construction, and 26 are at earlier stages of development. None of these projects is located in the EU. Despite the progress made, new approaches, with TRL 3 ÷ 7, are still under development (Bui et al., 2018). The CCS's technology readiness level (TRL) is still too low to expect massive CCS deployment shortly. Furthermore, most research focuses on a capture phase only, while their integration with transport, storage and utilization phases is pending (Bui et al., 2018). Similar findings result from the work of (van der Spek et al., 2020), who also noticed that most of the work is developing new CCS technologies, and there are only a few running installations. A breakthrough might be possible when considering alternative carbon capture technologies, e.g. the use of CO_2 stream from the cement production as an input to other processes such as curing the hardened bricks (Abdel-Gawwad et al., 2021) or steel slag bricks (Hou et al., 2021). Also, the change in the economic environment might boost the development of CCS technology. According to (Obrist et al., 2021), the CO_2 emission tax exceeding 60 EUR/t_{CO2} positively affects the CCS investment's economic balance.

3.2. Strong energy efficiency and material efficiency

Strong energy and material efficiency is the second most popular research area related to the decarbonization of the non-metallic mineral sector in the analyzed papers. The level of CO_2 emission reduction reaches up to 14% (Table 9). As a partial replacement of fossil fuels, world-leading cement producers have already introduced various alternative fuels (Fig. 10). Research topics in this area include further developing technologies for producing heat from waste, such as industrial and household waste, wood chips, tires, or agricultural waste (Table 8). The main advantage of this method is that it utilizes industrial by-products and waste streams, which is beneficial from the economic point of view. As indicated by (Kaddatz et al., 2013), end-of-life tires are an especially interesting coal replacement due to their high energy density. Additionally, due to the inability to recycle all the used tires, their processing into the heat is a sustainable practice. As examined by ((Thanos) Bourtsalas et al. 2018), using municipal solid waste has no negative impact on cement quality. The biggest global cement manufacturers currently use alternative fuels for thermal energy generation (Rahman et al., 2013). However, the main challenge is the expected limited availability of these materials in the future. Another barrier is the unfavorable legal framework in some countries for using waste streams as a heating fuel (Benhelal et al., 2021).

Other material efficiency options discussed in the literature include recycling and reuse of products of the industry: glass and cementitious products and replacement of cement by alternative materials. According to (Butler and Hooper, 2005), replacing virgin glass feedstock with colored cullet decreases energy demand by 70 MJ/tonne of glass. The other solution in the cement production of replacing 20% of cement with waste glass powder reduces CO2 emissions by 14% (Islam et al., 2017).



	Holcim Group (2011)	Cemex Group (2011)	Heidelberg Group (2011)	Italcementi Group (2011)	Lafarge Group (2011)
Other alternative fuel	1	0	14.6	0	0
Refuse-derived fuel	0	0	0	7.8	0
Sewage sludge	2	0	4.2	1.7	0
Wood chip and other biomass	15	5	24.5	0	25.1
Agricultural waste	9	10	4.2	11.1	0
MBM	2	4	6.1	15.7	0
Industrial waste and other fossil-based fuel	30	0	0	0	0
Plastic & Industrial and household waste (solid)	9	65	26.4	18.5	33.1
Impregnated sawdust	6	0	0	0	0
Tires	10	0	11.6	14.9	19.7
Waste oil & Solvent and liquid waste	16	16	8.4	30.4	22.1

Fig. 10. Percentage of different types of waste used as alternative fuels (Rahman et al., 2013).

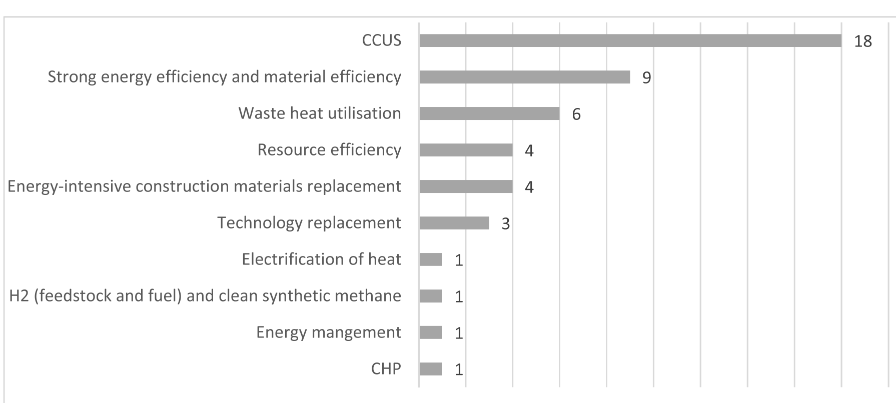


Fig. 11. Number of articles discussing decarbonization options in the non-metallic minerals sector, N = 48.

Most attention is given to further reducing clinker content, e.g. by using supplementary cementitious materials in cement and reducing concrete's clinker content by improving mix designs that allow for increased filler content. The articles that we analyzed show that the mitigation potential of this method reaches, depending on the added material, 18% (Islam et al., 2017), 37% (Ahmadi et al., 2018) and even 54% (Kwon et al., 2015). From this range, only lower reduction levels are considered achievable by independent organizations. The UN Environment report expects that reducing clinker content can decrease CO_2 emission by 20–30% (Scrivener et al., 2016), while according to experts of the International Energy Agency and Cement Sustainability Initiative, it can be even 37% (International Energy Agency and Cement Sustainability Initiative, 2018). Lower researcher interest in this topic might result from a relatively high technology readiness level (TRL 8–9), according to (Oberthur et al., 2020). As (Rissman et al., 2020) notice, a significant barrier to this mitigation option would be the limited availability of raw material resources used as alternative clinker materials. Material efficiency measures fit in with the circular economy concept, becoming a strategic objective for the EU economy (European Commission, 2020). It also supports the 12th Sustainable Development Goals by United Nations (United Nations, 2015). The circular economy shifts the linear cradle-to-grave consumption scheme to the closed-loop cycles (Morone and Yilan, 2020). Still, more research is needed to meet the more advanced concept of the multiple life cycles, e.g. composed of six life stages (6R methodology): reduce, reuse, recycle, recover, redesign, remanufacture, as proposed by (Jawahir and Bradley 2016). What is missing are the last three stages: technologies for restoring cementitious materials (recover), new design of products, mainly buildings, so that they use materials and resources from the previous phase (redesign), and reprocessing of already used materials to bring them as close to the original state as possible (remanufacturing). This, however, requires further work not only by the cement industry but mainly by the construction sector as a primary user of cementitious products.

3.3. Waste heat utilization

Considering waste heat utilization technologies, various solutions are tested as numerical simulations and then applications to existing production lines. Waste heat is used to preheat substrates, an energy source for external heating systems, or energy used for own needs. According to (Panayiotou et al., 2017), the waste heat potential for non-metallic minerals, as the percentage of the total consumed energy, equals 11.4%. Most energy could be recovered from heat streams of temperature between 100 and 200 °C and 500–1000 °C. Among all EU28 Member States, Germany, Italy, and Spain have the highest potential for waste heat utilization, reaching approx. 13, 11, and 8 TWh/year, respectively (Agathokleous et al., 2019). In addition to the method presented in the analyzed articles, waste heat can be utilized not only directly as thermal energy but also in the cogeneration units. As indicated by (Ishak and Hashim, 2015), this can cover up to 30% of the electricity demand by the cement plant. On the other hand, there is a major barrier to this method in some countries due to the exit charges for installing a cogeneration unit in a cement plant (Benhelal et al., 2021).

3.4. Replacement of cementitious materials with alternative construction technologies

Cement is one of the main construction materials. Replacement of cementitious materials (e.g. concrete), with alternative technologies would decrease the cement demand and indirectly partially decarbonize the non-metallic minerals sector. Several construction technologies have been recently developed and tested, mainly using bio-based materials and composites such as cross-laminated timber (CLT) (Lehmann, 2013) or engineered wood products (EWP) (Teh et al., 2017). Using bio-based construction materials affects GHG emission twofold: less emission is emitted during the production process and then during a use-stage since buildings require less energy for heating and cooling due to better insulation properties of these materials. Research from Australia shows that the embodied GHG emissions from the CLT building are two times lower during the product and construction phase than a traditional building constructed using reinforced concrete. The major disadvantage of this technology is the higher operating costs of a building, which is, however, compensated in the full life cycle (Jayalath et al., 2020). Another technology, not very frequent in the literature, is an alternative binder that would replace the traditional cement. Research shows that it is possible to produce a material that has similar properties to Portland cement but with a much lower environmental impact, reaching 30% (Negrão et al., 2021). Other technologies, however, need more research to replace the traditional cement, as showcased by (Okoye, 2017).

3.5. Heat electrification

Industrial heat electrification is gaining more attention in recent years, however, mainly as a result of utilising waste heat in low-temperature level thermodynamic cycles, such as Rankine or Kalina (Schneider, 2019). Electrification of high-temperature heat in the cement production process is technically feasible, with no significant impact on the process quality (Tokheim et al. 2019). In fact, according to (Napp et al., 2019), heat electrification might substantially contribute to the complete decarbonization of many industries. To this end, more research and development work is needed to achieve sufficiently high temperatures, improve efficiency and reduce costs. Considering the non-metallic minerals sector, electric kilns in ceramics production and electric glass smelters have the highest decarbonization potential (Table 9). However, as analyzed for Norway, the calciner electrification combined with the CO_2 capture is also considered as a promising option, allowing for achieving 70% of CO_2 emission reduction (Tokheim et al. 2019). Direct electrification (power-to-heat) is considered one of the most promising strategies for industry decarbonization. Electrification contributes to lowering emissions provided that the electricity is produced using low and zero-carbon energy sources. In general, despite opinions that the electrification of heat in cement production would not be economically beneficial (Napp et al., 2019), the transition towards a sustainable future is unavoidable. A shift towards renewable energy sources will require changes in the technological processes currently run by burning fossil fuels and substantial change in the energy mix of the non-metallic minerals industry.

3.6. Novel cement production technologies

Since the production of cement and other non-metallic minerals sector products involves mature technologies, no breakthrough manufacturing processes are foreseen that can significantly reduce thermal energy consumption (JRC European Commission, 2011). Still, several cases demonstrate that replacement of some parts of existing technologies has also decarbonization potential, e.g. development of a new class of clinker (belite-calcium sulfoaluminate-ferrite, BCSAF) or shift from a theoretical belitic (C_2S only) system towards $C_3S + C_2S$ system (Barcelo et al., 2014).

3.7. Other measures

Using hydrogen and clean methane, implementation of energy management procedures, as well as using energy from combined heat and power stations, are not popular decarbonization options – each of these technologies is discussed only once in the reviewed papers (**Error! Reference source not found.**). Still, using hydrogen has been gaining attention in recent years as a decarbonization option in many industries, including energy-intensive ones such as chemical or iron and steel industries (Skoczkowski et al., 2020). Hydrogen is particularly advantageous in the industry as an energy source for high-temperature processes, such as those used in steel, cement, refining and petrochemicals sectors. BP predicts that by 2050, hydrogen accounts for around 10% up to18% of total final energy consumption in the industry, depending on the scenario (British Petroleum, 2020). In the non-metallic minerals sector, however, it stays at a level of conceptual study, considering the use of waste heat for hydrogen production (Weil et al., 2006). Moreover, a major barrier for the wider use of hydrogen in the cement industry and other kiln-based heating processes is the lower radiation heat transfer of hydrogen flames, which requires fuel additives and new types of burners. Also, safety issues related to hydrogen storage and hydrogen burning process monitoring are challenging (Griffiths et al., 2021).

Energy management is a process of monitoring, controlling, and conserving energy. It also includes improving ongoing processes aimed at decreasing energy demand. The case study conducted by (Summerbell et al., 2016) shows that the improvement of the cement plant performance reduces energy consumption by 8.5% and CO_2 emissions by 19.5%.

Even though CHP is not a popular decarbonization option in non-metallic minerals production, lime production can be regarded as a prospective field of application of such technologies, e.g. through the integration of CHP with lime production for direct air capture (Hanak and Manovic 2018).

Finally, other decarbonization measures include using cement more efficiently and reducing materials wastage rate, leading to avoiding 15% of the cement consumption (Müller et al., 2008), switching to less carbon-intensive fuels, and improving energy efficiency (International Energy Agency and Cement Sustainability Initiative, 2018). They, however, have a moderate impact.

4. Conclusions

Cement is the most popular construction material and the most significant product manufactured on Earth in terms of mass. However, due to the high energy intensity of production processes, the non-metallic sector is responsible for about 7% of global CO_2 emissions and is the third-largest industrial energy consumer. Therefore, decarbonization of this sector is one of the keys to reaching the goals of the Paris Agreement. Creating a decarbonization pathway for the industry requires selecting various GHG mitigation options available and balancing emission reduction potential, technology readiness level, and implementation costs.

Previous works present the general approaches to decarbonization, focusing on issues related to policy and economic instruments, identification of the decarbonization or adaptation strategies, present case studies or country-specific situations. There was a knowledge gap in terms of the review of the most innovative technologies that would be used by the non-metallic minerals industry for its decarbonization, showing their costs and environmental features. To fill in this gap, we asked in our study the following research questions: (Q1) which decarbonization measures are already applied or under development in the non-metallic minerals sector?, (Q2) which of these measures might bring breakthrough to this sector?, and (Q3) what is the impact of these measures on costs, energy consumption and GHG emissions? We performed a systematic literature review following the PRISMA 2009 approach to answer these questions. We identified and screened 2964 previous works, out of which we assessed 270 full-text, to finally include 48 papers in a qualitative synthesis. We analyzed ten decarbonization measures: resource efficiency; energy-intensive construction materials replacement; H_2 (feedstock and fuel) and clean synthetic methane; carbon capture, utilization, and storage (CCUS); electrification of heat; strong energy efficiency and material efficiency; waste heat utilization; combined heat and power production (CHP); energy management (strong energy efficiency); technology replacement. This article shows directions followed by researchers, popularity, and potential of given decarbonization options. Policymakers can use it in developing the industry decarbonization policies and the following action plans, as well as people deciding on a budget for research on specific topics. It also shows the cement industry the directions that the technology evolves. The main conclusions of our work are:

1) Q1: All of the ten decarbonization measures analyzed have been applied by the non-metallic minerals sectors, however, they differ in terms of their applicability, CO_2 mitigation potential, technology readiness level, implementation costs, and complexity of their application. Energy, material and resource efficiencies are mature solutions that are widely used by the industry. However, their impact on emissivity is limited, and further emission reduction requires the use of additional measures. CCUS, waste heat utilization, and heat electrification technologies are of interest to researchers and engineers due to their high decarbonization potential, however, they still need more research that would allow for a full-scale deployment. Other measures, such as using alternative materials for cement in the construction sector or switching to hydrogen, are of moderate interest and/or also emission reduction potential.
2) Q2&3: CCS/CCUS has the highest potential for CO_2 mitigation, allowing for the decrease of up to 60% emissions globally. It is also the most discussed option in the literature, showing that the capture rate of selected CCS technologies reaches 94%. CCS technology is, however, not yet ready for full-scale commercialization and further research, in particular in an industrial environment, is necessary.
3) Q2&3: The second most promising technology in terms of its decarbonization potential is further lowering the clinker to cement ratio from the current 90–95% to at least 75%. Depending on the research, it can decrease industry CO_2 emissions from 20% to 37% globally. However, since it is a mature technology (TRL8-9), this option is rarely examined in the literature.
4) Q2: Despite the relatively low representation in scientific literature, heat electrification is technically feasible for cement production. It is also an unavoidable direction for the industry in the long term, resulting from the global shift towards sustainable energy from renewables.
5) Q1&2: Options such as using alternative fuels for heat generation (e.g. industrial, agricultural and households waste streams), utilization of waste heat, using hydrogen as a fuel, and using energy from CHP can be considered additional options, implemented on top of the other measures. Developing countries must provide sufficient financial resources and technology aside from the policy framework and research on less advanced technologies to reach notable emission reduction.

We are aware of the limitations of our work. This article is written from the technology perspective, analyzing each measure separately and focusing only on the non-metallic minerals sector. The combination of several technologies might bring a different effect than a simple sum of individual impacts. Furthermore, we are aware that the successful shift towards a low-carbon economy, particularly in energy-intensive industries such as non-metallic minerals, requires a comprehensive approach comprising technology, policy, economic and social perspective. More research is needed to develop the transition pathways acceptable by various stakeholders and legally adopted at the international level. Without the global agreement, there is a risk that only the most straightforward measures with short payback time will be implemented (e.g. waste heat utilization with a 3-year payback period), which, however, bring limited environmental benefits. Also, future work on technologies that are underrepresented in the literature and are promising from the decarbonization point of view is necessary. Another important aspect is cross-sectoral collaboration, both in terms of the development of technologies that are equally important for different industries (e.g. CCS for the energy sector), in terms of by-products upcycling (e.g. carbon capture in bricks production), and also in the development of novel products and services that decrease the demand for carbon-intensive products such as cement (e.g. novel construction technologies and products reducing the cement use). Finally, further research on technologies at a low technology readiness level is necessary to boost their commercialization potential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The article has been prepared under the projects: (1) INNOPATHS: Innovation pathways, strategies and policies for the Low-Carbon Transition in Europe. The project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 730403; (2) NEWTRENDS: New trends in energy demand modeling. The project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 893311; (3) The project has received funding from an internal grant from the Warsaw University of Technology.

References

Abdel-Gawwad, Hamdy, A., Rashad, Alaa M., Mohammed, Mona S., Tawfik, Taher A., 2021. The potential application of cement kiln dust-red clay brick waste-silica fume composites as unfired building bricks with outstanding properties and high ability to CO2-capture. J. Build. Eng. 42 (January), 102479 https://doi.org/10.1016/j.jobe.2021.102479.

Abdelaziz, Omar Y., Hosny, Wafaa M., Gadalla, Mamdouh A., Ashour, Fatma H., Ashour, Ibrahim A., Hulteberg, Christian P., 2017. Novel process technologies for conversion of carbon dioxide from industrial flue gas streams into methanol. J. CO2 Util. 21 (July), 52–63. https://doi.org/10.1016/j.jcou.2017.06.018.

Agathokleous, Rafaela, Panayiotou, Gregoris, Aresti, Lazaros, Argyrou, Maria C., Georgiou, Giorgos S., Jouhara, Hussam, Kalogirou, Soteris A., Florides, Georgios A., Paul, Christodoulides, 2019. Waste heat recovery in the EU industry and proposed new technologies. Energy Proc. 161 (March), 489–496. https://doi.org/10.1016/J.EGYPRO.2019.02.064.

Ahmadi, Zahra, Esmaeili, Jamshid, Kasaei, Jamil, Hajialioghli, Robab, 2018. Properties of sustainable cement mortars containing high volume of raw diatomite. Sustain. Mater. Technol. 16, 47–53. https://doi.org/10.1016/j.susmat.2018.05.001.

Andersson, R H Stripple, Gustafsson, T., Ljungkrantz, C., 2019. Carbonation as a method to improve climate performance for cement based material. Cement Concr. Res. 124, 105819 https://doi.org/10.1016/j.cemconres.2019.105819.

Barcelo, Laurent, Kline, John, Gunther, Walenta, Gartner, Ellis, 2014. Cement and carbon emissions. Mater. Struct. Mater. Construct. 47 (6), 1055–1065. https://doi.org/10.1617/s11527-013-0114-5.

Barker, D.J., Turner, S.A., Napier-Moore, P.A., Clark, M., Davison, J.E., 2009. CO2 capture in the cement industry. Energy Proc. 1 (1), 87–94. https://doi.org/10.1016/j.egypro.2009.01.014.

Benhelal, Emad, Shamsaei, Ezzatollah, Rashid, Muhammad Imran, 2021. Challenges against CO2 abatement strategies in cement industry: a review. J. Environ. Sci. (China) 104, 84–101. https://doi.org/10.1016/j.jes.2020.11.020.

British Petroleum, 2020. Energy Outlook 2020 Edition Explores the Forces Shaping the Global Energy Transition Out to 2050 and the Surrounding That." BP Energy Outlook 2030, Statistical Review. British Petroleum., London, p. 81.

Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., et al., 2018. Carbon capture and storage (CCS): the way forward. Energy Environ. Sci. 11 (5), 1062–1176. https://doi.org/10.1039/c7ee02342a.

Butler, John, Hooper, Paul, 2005. Dilemmas in optimising the environmental benefit from recycling: a case study of glass container waste management in the UK. Resour. Conserv. Recycl. 45 (4), 331–355. https://doi.org/10.1016/j.resconrec.2005.02.006.

Çankaya, Simge, Pekey, Beyhan, 2019. A comparative life cycle assessment for sustainable cement production in Turkey. J. Environ. Manag. 249, 109362 https://doi.org/10.1016/j.jenvman.2019.109362.

CEMBUREAU, 2021. World cement production 2019. https://cembureau.eu/media/4m1bqf3f/world-cement-production-by-region-2019.jpg.

Chang, M.H., Huang, C.M., Liu, W.H., Chen, W.C., Cheng, J.Y., Chen, W., Wen, T.W., Ouyang, S., Shen, C.H., Hsu, H.W., 2013. Design and experimental investigation of calcium looping process for 3-KW Th and 1.9-MW Th facilities. Chem. Eng. Technol. 36 (9), 1525–1532. https://doi.org/10.1002/ceat.201300081.

Choi, Se Woon, Oh, Byung Kwan, Park, Hyo Seon, 2017. Design technology based on resizing method for reduction of costs and carbon dioxide emissions of high-rise buildings. Energy Build. 138, 612–620. https://doi.org/10.1016/j.enbuild.2016.12.095.

Cormos, Ana-maria, Calin-cristian, Cormos, 2014. Chemical engineering research and design reducing the carbon footprint of cement industry by post-combustion CO 2 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.

Cruz, Tatiane Tobias da, José, A., Balestieri, Perrella, João, M., Silva, de Toledo, Vilanova, Mateus R.N., Oliveira, Otávio J., Ávila, Ivonete, 2021. Life cycle assessment of carbon capture and storage/utilization: from current state to future research directions and opportunities. Int. J. Greenh. Gas Control 108. https://doi.org/10.1016/j.ijggc.2021.103309. March 2020.

Daehn, Katrin, Basuhi, R., Gregory, Jeremy, Berlinger, Maya, Somjit, Vrindaa, Olivetti, Elsa A., 2021. Innovations to decarbonize materials industries. Nat. Rev. Mater. (October), 1–20. https://doi.org/10.1038/s41578-021-00376-y.

Dai, Zhongde, Fabio, Santinelli, Marino, Nardelli Giuseppe, Riccardo, Costi, Deng, Liyuan, 2019. Field test of a pre-pilot scale hollow fiber facilitated transport membrane for CO2 capture. Int. J. Greenh. Gas Control 86, 191–200. https://doi.org/10.1016/j.ijggc.2019.04.027.

Delpech, Bertrand, Milani, Massimo, Montorsi, Luca, Boscardin, Davide, Chauhan, Amisha, Almahmoud, Sulaiman, Axcell, Brian, Jouhara, Hussam, 2018. Energy efficiency enhancement and waste heat recovery in industrial processes by means of the heat pipe technology: case of the ceramic industry. Energy 158, 656–665. https://doi.org/10.1016/j.energy.2018.06.041.

Department for Business Energy, Industrial Strategy, 2021. Combined heat and power: pathway to decarbonisation – call for evidence. London. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1020816/chp-pathway-to-decarbonisation-call-for-evidence.pdf.

Ditaranto, Mario, Bakken, Jørn, 2019. Study of a full scale oxy-fuel cement rotary kiln. Int. J. Greenh. Gas Control 83, 166–175. https://doi.org/10.1016/j.ijggc.2019.02.008.

Dolianitis, Ioannis, Giannakopoulos, Dionysios, Hatzilau, Christina Stavrula, Karellas, Sotirios, Kakaras, Emmanuil, Nikolova, Evelina, Skarpetis, Georgios, Christodoulou, Nikolaos, Giannoulas, Nikolaos, Zitounis, Theodoros, 2016. Waste heat recovery at the glass industry with the intervention of batch and cullet preheating. Therm. Sci. 20 (4), 1245–1258. https://doi.org/10.2298/TSCI151127079D.

Dubois, Lionel, Laribi, Sinda, Mouhoubi, Seloua, De Weireld, Guy, Thomas, Diane, 2017. Study of the post-combustion CO2 capture applied to conventional and partial oxy-fuel cement plants. Energy Proc. 114, 6181–6196. https://doi.org/10.1016/j.egypro.2017.03.1756.

ECRA, 2017. Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead, Revision 2017. European Cement Research Academy. http://docs.wbcsd.org/2017/06/CSI_ECRA_Technology_Papers_2017.pdf.

European Commission, 2011. Energy Roadmap 2050. COMMISSION STAFF WORKING PAPER {COM(2011) 885} {SEC(2011) 1566}.

European Commission, 2014. Guidelines on State Aid for Environmental Protection and Energy 2014-2020 (2014/C 200/01).

European Commission, 2017. INDUSTRIAL POLICY Making Europe's Industry Stronger. Key Initiatives.

European Commission, 2019. Non-metallic products and industries, 2019. https://ec.europa.eu/growth/sectors/raw-materials/industries/non-metals_en.

European Commission, 2020. COM(2020) 98 Final A New Circular Economy Action Plan for a Cleaner and More Competitive Europe. European Commission, Brussels. https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF.

European Environment Agency, 2019. Annual European Union Greenhouse Gas Inventory 1990–2009 and Inventory Report 2019.

Fang, Hao, Xia, Jianjun, Jiang, Yi, 2015. Key issues and solutions in a district heating system using low-grade industrial waste heat. Energy 86, 589–602. https://doi.org/10.1016/j.energy.2015.04.052.

Farabi-Asl, Hadi, Itaoka, Kenshi, Chapman, Andrew, Kato, Etsushi, Kurosawa, Atsushi, 2020. Key factors for achieving emission reduction goals cognizant of CCS. Int. J. Greenh. Gas Control 99 (August), 103097. https://doi.org/10.1016/j.ijggc.2020.103097.

Ford, James D., Pearce, Tristan, Prno, Jason, Frank, Duerden, Ford, Lea Berrang, Beaumier, Maude, Smith, Tanya, 2010. Perceptions of climate change risks in primary resource use industries: a survey of the Canadian mining sector. Reg. Environ. Change 10 (1), 65–81. https://doi.org/10.1007/s10113-009-0094-8.

Gerres, Timo, Ávila, José Pablo Chaves, Linares Llamas, Pedro, Gómez San Román, Tomás, 2019. A review of cross-sector decarbonisation potentials in the European energy intensive industry. J. Clean. Prod. 210 (February), 585–601. https://doi.org/10.1016/j.jclepro.2018.11.036.

GNR Project, 2018. WBCSD cement sustainability initiative. Getting the numbers right project. Emissions report 2017. https://gccassociation.org/gnr/.

Griffin, Paul W., Hammond, Geoffrey P., Norman, Jonathan B., 2018. Industrial decarbonisation of the pulp and paper sector: a UK perspective. Appl. Therm. Eng. 134 (September 2017), 152–162. https://doi.org/10.1016/j.applthermaleng.2018.01.126.

Griffiths, Steve, Sovacool, Benjamin K., Kim, Jinsoo, Morgan, Bazilian, Joao, M., Uratani, 2021. Industrial decarbonization via hydrogen: a critical and systematic review of developments, socio-technical systems and policy options. Energy Res. Social Sci. 80 (October), 102208 https://doi.org/10.1016/J.ERSS.2021.102208.

Gutowski, Timothy G., Sahni, Sahil, Allwood, Julian M., Ashby, Michael F., Ernst, Worrell, 2013. The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. Phil. Trans. Math. Phys. Eng. Sci. 371, 1986 https://doi.org/10.1098/RSTA.2012.0003.

Habert, G., Miller, S.A., John, V.M., Provis, J.L., Favier, A., Horvath, A., Scrivener, K.L., 2020. Environmental impacts and decarbonization strategies in the cement and concrete industries. Nat. Rev. Earth Environ. 1 (11), 559–573. https://doi.org/10.1038/s43017-020-0093-3.

Hanak, Dawid, P., Manovic, Vasilije, 2018. Combined heat and power generation with lime production for direct air capture. Energy Convers. Manag. 160, 455–466. https://doi.org/10.1016/j.enconman.2018.01.037.

Hasanbeigi, A., Morrow, W., Sathaye, J., Masanet, E., Xu, T., 2013. A bottom-up model to estimate the energy efficiency improvement and CO2 emission reduction potentials in the Chinese iron and steel industry. Energy 50 (1), 315–325. https://doi.org/10.1016/j.energy.2012.10.062.

Herbst, Andrea, Fleiter, Tobias, Frank, Sensfuß, Ben, Pfluger, Maranon-Ledesma, Hector, 2018. Navigating the roadmap for clean, secure and efficient energy innovation low-carbon transition of EU industry by 2050. Paper on low-carbon transition of EU industry by 2050.pdf. http://www.set-nav.eu/sites/default/files/common_files/deliverables/wp5/Issue.

Hou, Guihua, Yan, Ziwei, Sun, Jinfeng, Naguib, Hamdy M., Lu, Bao, Zhang, Zuhua, 2021. Microstructure and mechanical properties of CO2-cured steel slag brick in pilot-scale. Construct. Build. Mater. 271, 121581 https://doi.org/10.1016/j.conbuildmat.2020.121581.

International Energy Agency, 2019. Tracking clean energy progress - cement." 2019. https://www.iea.org/tcep/industry/cement/.

International Energy Agency, 2020. Energy Efficiency 2020.

International Energy Agency, 2021. Driving energy efficiency in heavy industries. March 21, 2021. https://www.iea.org/articles/driving-energy-efficiency-in-heavy-industries.

International Energy Agency, Cement Sustainability Initiative, 2018. Technology Roadmap Low - Carbon Transition in the Cement Industry. Paris.

IPCC, 2018. Global Warming of 1.5 °C - Summary for Policymakers. Ipcc - Sr15.

Ishak, S.A., Hashim, H., 2015. Low carbon measures for cement plant - a review. J. Clean. Prod. 103, 260–274. https://doi.org/10.1016/j.jclepro.2014.11.003.

Islam, G. M.Sadiqul, Rahman, M.H., Kazi, Nayem, 2017. Waste glass powder as partial replacement of cement for sustainable concrete practice. Int. J. Sustain. Built Environ. 6 (1), 37–44. https://doi.org/10.1016/j.ijsbe.2016.10.005.

Jackson, R.B., Le Quéré, C., Andrew, R.M., Canadell, J.G., Korsbakken, J.I., Liu, Z., Peters, G.P., Zheng, B., 2018. Global energy growth is outpacing decarbonization. Environ. Res. Lett. 13 (12) https://doi.org/10.1088/1748-9326/aaf303.

Jawahir, I.S., Ryan, Bradley, 2016. Technological elements of circular economy and the principles of 6R-based closed-loop material flow in sustainable manufacturing. Procedia CIRP 40, 103–108. https://doi.org/10.1016/j.procir.2016.01.067.

Jayalath, Amitha, Navaratnam, Satheeskumar, Ngo, Tuan, Mendis, Priyan, Hewson, Nick, Lu, Aye, 2020. Life cycle performance of cross laminated timber mid-rise residential buildings in Australia. Energy Build. 223 (September), 110091 https://doi.org/10.1016/J.ENBUILD.2020.110091.

JRC European Commission, 2011. 2011 Technology Map of the European Strategic Energy Technology Plan (SET-Plan): Technology Description. https://doi.org/10.2790/37519.

Kabir, G., Abubakar, A.I., El-Nafaty, U.A., 2010. Energy audit and conservation opportunities for pyroprocessing unit of a typical dry process cement plant. Energy 35 (3), 1237–1243. https://doi.org/10.1016/j.energy.2009.11.003.

Kaddatz, K.T., Rasul, M.G., Rahman, Azad, 2013. Alternative fuels for use in cement kilns: process impact modelling. Procedia Eng. 56, 413–420. https://doi.org/10.1016/j.proeng.2013.03.141.

Kaliyavaradhan, Senthil Kumar, Ling, Tung-Chai, 2017. Potential of CO2 sequestration through construction and demolition (C&D) waste—an overview. J. CO2 Util. 20, 234–242. https://doi.org/10.1016/j.jcou.2017.05.014.

Karellas, S., Leontaritis, A.D., Panousis, G., Bellos, E., Kakaras, E., 2012. Energetic and exergetic analysis of waste heat recovery systems in the cement industry. In: Proceedings of the 25th International Conference on Efficiency, Cost, Optimization and Simulation of Energy Conversion Systems and Processes, ECOS, 1. https://doi.org/10.1016/j.energy.2013.03.097, 114–27.

Kemache, Nassima, Pasquier, Louis-César, Cecchi, Emmanuelle, Mouedhen, Ikbel, Jean-François, Blais, Mercier, Guy, 2017. Aqueous mineral carbonation for CO2 sequestration: from laboratory to pilot scale. Fuel Process. Technol. 166, 209–216. https://doi.org/10.1016/j.fuproc.2017.06.005.

Koasidis, Konstantinos, Nikas, Alexandros, Neofytou, Hera, Karamaneas, Anastasios, Gambhir, Ajay, Wachsmuth, Jakob, Doukas, Haris, 2020. The UK and German low-carbon industry transitions from a sectoral innovation and system failures perspective. Energies 13 (19), 4994. https://doi.org/10.3390/EN13194994, 4994 13.

Kwon, Eunhee, Ahn, Jaecheol, Cho, Bongsuk, Park, Dongcheon, 2015. A study on development of recycled cement made from waste cementitious powder. Construct. Build. Mater. 83, 174–180. https://doi.org/10.1016/j.conbuildmat.2015.02.086.

Lechtenböhmer, Stefan, Schneider, Clemens, Roche, María Yetano, Höller, Samuel, 2015. Re-industrialisation and low-carbon economy-can they go together? Results from stakeholder-based scenarios for energy-intensive industries in the German state of North rhine Westphalia. Energies 8 (10), 11404–11429. https://doi.org/10.3390/en81011404.

Lehmann, Steffen, 2013. Low carbon construction systems using prefabricated engineered solid wood panels for urban infill to significantly reduce greenhouse gas emissions. Sustain. Cities Soc. 6 (1), 57–67. https://doi.org/10.1016/j.scs.2012.08.004.

Lim, Chaeyeon, Jung, Euntae, Lee, Seongho, Jang, Changsun, Oh, Chaewoon, Shin, Kyung Nam, 2020. Global trend of cement production and utilization of circular resources. J. Energy Eng. 29 (3), 57–63. https://doi.org/10.5855/ENERGY.2020.29.3.057.

Lin, Boqiang, Ouyang, Xiaoling, 2014. Analysis of energy-related CO2 (carbon dioxide) emissions and reduction potential in the Chinese non-metallic mineral products industry. Energy 68, 688–697. https://doi.org/10.1016/j.energy.2014.01.069.

Liu, G.X., Yu, Y.S., 2017. Thermal-electrochemical Co-drive system for carbon capture. Energy Proc. 114, 25–31. https://doi.org/10.1016/j.egypro.2017.03.1142.

Ma, Xiaotong, Li, Yingjie, Duan, Lunbo, Anthony, Edward, Liu, Hantao, 2018. CO2 capture performance of calcium-based synthetic sorbent with hollow core-shell structure under calcium looping conditions. Appl. Energy 225, 402–412. https://doi.org/10.1016/j.apenergy.2018.05.008.

Mardani, Abbas, Streimikiene, Dalia, Cavallaro, Fausto, Loganathan, Nanthakumar, Khoshnoudi, Masoumeh, 2019. Carbon dioxide (CO2) emissions and economic growth: a systematic review of two decades of research from 1995 to 2017. Sci. Total Environ. 649, 31–49. https://doi.org/10.1016/j.scitotenv.2018.08.229.

Miró, Laia, Russell, McKenna, Tobias, Jäger, Luisa, F., Cabeza, 2018. Estimating the industrial waste heat recovery potential based on CO 2 emissions in the European non-metallic mineral industry. Energy Effic. 11 (2), 427–443. https://doi.org/10.1007/s12053-017-9575-7.

Moher, David, Liberati, Alessandro, Tetzlaff, Jennifer, Altman, Douglas G., 2009. Preferred reporting Items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 6 (7), e1000097 https://doi.org/10.1371/journal.pmed.1000097.

Monkman, S., MacDonald, Mark, 2016. Carbon dioxide upcycling into industrially produced concrete blocks. Construct. Build. Mater. 124, 127–132. https://doi.org/10.1016/j.conbuildmat.2016.07.046.

Morone, Piergiuseppe, Yilan, Gülşah, 2020. A paradigm shift in sustainability: from lines to circles. Acta Innovat. 36 (September), 5–16. https://doi.org/10.32933/ACTAINNOVATIONS.36.1.

Moya, José Antonio, Pardo, Nicolás, Mercier, Arnaud, 2011. The potential for improvements in energy efficiency and CO2 emissions in the EU27 cement industry and the relationship with the capital budgeting decision criteria. J. Clean. Prod. 19 (11), 1207–1215. https://doi.org/10.1016/j.jclepro.2011.03.003.

Müller, Nicolas, Harnisch, Jochen, Mesguen, Jean-Philippe, 2008. A blueprint for a climate friendly cement industry. https://awsassets.panda.org/downloads/englishsummary_lr_pdf.pdf.

Napp, T.A., Gambhir, A., Hills, T.P., Florin, N., Fennell, P.S., 2014. A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries. Renew. Sustain. Energy Rev. 30 (February), 616–640. https://doi.org/10.1016/J.RSER.2013.10.036.

Napp, T.A., Few, S., Sood, A., Bernie, D., Hawkes, A., Gambhir, A., 2019. The role of advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budgets. Appl. Energy 238 (December 2018), 351–367. https://doi.org/10.1016/j.apenergy.2019.01.033.

Negrão, Ayres, Leonardo Boiadeiro, Herbert, Pöllmann, Lima da Costa, Marcondes, 2021. Production of low-CO2 cements using abundant bauxite overburden 'Belterra clay. Sustain. Mater. Technol. 29 (September), e00299 https://doi.org/10.1016/J.SUSMAT.2021.E00299.

Nelson, Thomas O., Coleman, Luke J.I., Paul, Mobley, Kataria, Atish, Tanthana, Jak, Lesemann, Markus, 2014. Solid sorbent CO 2 capture technology evaluation and demonstration at Norcem ' s cement plant in Brevik , Norway. Energy Proc. 63, 6504–6516. https://doi.org/10.1016/j.egypro.2014.11.686.

Neuhoff, Karsten, Chiappinelli, Olga, Chris Bataille, Haußner, Manuel, Roland, Ismer, Joltreau, Eugénie, Jürgens, Ingmar, et al., 2018. Filling Gaps in the Policy Package to Decarbonise Production and Use of Materials. June.

Nurdiawati, Anissa, Urban, Frauke, 2021. Towards deep decarbonisation of energy-intensive industries: a review of current status, technologies and policies. Energies 14 (9). https://doi.org/10.3390/en14092408.

Oberthur, Sebastian, Khandekar, Gauri, Wyns, Tomas, 2020. Global governance for the decarbonization of energy-intensive industries: great potential underexploited. Earth Syst. Govern. https://doi.org/10.1016/j.esg.2020.100072.

Obrist, Michel D., Kannan, Ramachandran, Schmidt, Thomas J., Kober, Tom, 2021. Decarbonization pathways of the Swiss cement industry towards net zero emissions. J. Clean. Prod. 288 (March), 125413 https://doi.org/10.1016/J.JCLEPRO.2020.125413.

ODYSSEE, 2018. ODYSSEE Database.

OECD/IEA, 2020. Special report on carbon capture utilisation and storage. Energy Technol. Perspect. https://doi.org/10.1787/9789264109834-en.

Okoye, F.N., 2017. Geopolymer binder: a veritable Alternative to Portland cement. Mater. Today Proc. 4 (4), 5599–5604. https://doi.org/10.1016/J.MATPR.2017.06.017.

Ozcan, Dursun Can, Brandani, Stefano, Ahn, Hyungwoong, 2014. A hybrid carbon capture system of indirect calcination and amine absorption for a cement plant. Energy Proc. 63, 6428–6439. https://doi.org/10.1016/j.egypro.2014.11.678.

Panayiotou, Gregoris P., Bianchi, Giuseppe, Georgiou, Giorgos, Aresti, Lazaros, Argyrou, Maria, Agathokleous, Rafaela, Tsamos, Konstantinos M., et al., 2017. Preliminary assessment of waste heat potential in major European industries. Energy Proc. 123, 335–345. https://doi.org/10.1016/j.egypro.2017.07.263.

Pinto, Carvalho, de, P.C., de Oliveira Carvalho, M.M., Linhares, F.M., da Silva, T.R., de Lima, G.M., 2015. A cleaner production of sodium hydrogen carbonate: partial replacement of lime by steel slag milk in the ammonia recovery step of the solvay process. Clean Technol. Environ. Policy 17 (8), 2311–2321. https://doi.org/10.1007/s10098-015-0973-2.

Pinto, César de Carvalho, Pereira, Plínio Geison Voga, Rezende, Leonardo Schiavo de, Flávia, C., Moura, C., Belchior, Jadson Cláudio, 2019. CO2 capture performance and mechanical properties of Ca(OH)2-Based sorbent modified with MgO and (NH4) 2HPO4 for calcium looping cycle. Fuel 256, 115924. https://doi.org/10.1016/j.fuel.2019.115924.

PRISMA, 2015. Transparent reporting of systematic reviews and meta-analyses. http://www.prisma-statement.org.

Rahman, Azad, Rasul, M.G., Khan, M.M.K., Sharma, S., 2013. Impact of alternative fuels on the cement manufacturing plant performance: an overview. Procedia Eng. 56, 393–400. https://doi.org/10.1016/j.proeng.2013.03.138.

Rahman, Azad, Rasul, M.G., Khan, M.M.K., Sharma, S., 2015. Recent development on the uses of alternative fuels in cement manufacturing process. Fuel 145 (April), 84–99. https://doi.org/10.1016/J.FUEL.2014.12.029.

Rissman, Jeffrey, Chris Bataille, Masanet, Eric, Aden, Nate, William, R., Morrow, Zhou, Nan, Elliott, Neal, et al., 2020. Technologies and policies to decarbonize global industry: review and assessment of mitigation drivers through 2070. Appl. Energy 266 (March), 114848. https://doi.org/10.1016/j.apenergy.2020.114848.

Sani, R., Nzihou, A., 2017. Production of clay ceramics using agricultural wastes: study of properties, energy savings and environmental indicators. Appl. Clay Sci. 146, 106–114. https://doi.org/10.1016/j.clay.2017.05.032.

Saponelli, Roberto, Milani, Massimo, Montorsi, Luca, Rimini, Bianca, Venturelli, Matteo, Stendardo, Stefano, Barbarossa, Vincenzo, 2019. A novel carbon capture and utilisation concept applied to the ceramic industry. E3S Web Conf. 116, 00069 https://doi.org/10.1051/e3sconf/201911600069.

Sartori, Nicolò, 2019. Five Pillars for a CO 2 -Free Industry in Europe and Italy.

Schneider, Martin, 2019. The cement industry on the way to a low-carbon future. Cement Concr. Res. 124 (October), 105792 https://doi.org/10.1016/J.CEMCONRES.2019.105792.

Schüwer, Dietmar, Schneider, Clemens, 2018. Electrification of industrial process heat: long-term applications, potentials and impacts. In: Eceee Industrial Summer Study Proceedings 2018-June, 411–22.

Scrivener, K.L., John, V.M., Gartner, E.M., 2016. Eco-efficient cements: potential, economically viable solutions for a low-CO2 cement based industry. Paris. https://wedocs.unep.org/bitstream/handle/20.500.11822/25281/eco_efficient_cements.pdf?sequence=1&isAllowed=y.

Scrivener, Karen L., John, Vanderley M., Gartner, Ellis M., 2018. Eco-efficient cements: potential economically viable solutions for a low-CO2 cement-based materials industry. Cement Concr. Res. 114 (March), 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015.

Sinka, Maris, Philip Van den Heede, De Belie, Nele, Bajare, Diana, Sahmenko, Genadijs, Korjakins, Aleksandrs, 2018. Comparative life cycle assessment of magnesium binders as an alternative for hemp concrete. Resour. Conserv. Recycl. 133 (November 2017), 288–299. https://doi.org/10.1016/j.resconrec.2018.02.024.

Skoczkowski, Tadeusz, Elena, Verdolini, Bielecki, Sławomir, Kochański, Maksymilian, Korczak, Katarzyna, Węglarz, Arkadiusz, 2020. Technology innovation system Analysis of decarbonisation options in the EU steel industry. Energy 212, 118688. https://doi.org/10.1016/J.ENERGY.2020.118688.

Song, Xiao Ping, Tan, Puay Yok, Edwards, Peter, Richards, Daniel, 2018. The economic benefits and costs of trees in urban forest stewardship: a systematic review. Urban For. Urban Green. 29 (January), 162–170. https://doi.org/10.1016/J.UFUG.2017.11.017.

Spek, der, Mijndert van, Fout, Timothy, Garcia, Monica, Kuncheekanna, Vishalini Nair, Matuszewski, Michael, McCoy, Sean, Morgan, Joshua, et al., 2020. Uncertainty analysis in the techno-economic assessment of CO2 capture and storage technologies. Critical review and guidelines for use. Int. J. Greenh. Gas Control 100 (September), 103113. https://doi.org/10.1016/j.ijggc.2020.103113.

Spinelli, Maurizio, Martínez, Isabel, Romano, Matteo C., 2018. One-dimensional model of entrained-flow carbonator for CO2 capture in cement kilns by calcium looping process. Chem. Eng. Sci. 191, 100–114. https://doi.org/10.1016/j.ces.2018.06.051.

Summerbell, Daniel L., Claire, Y Barlow, Cullen, Jonathan M., 2016. Potential reduction of carbon emissions by performance improvement: a cement industry case study. J. Clean. Prod. 135, 1327–1339. https://doi.org/10.1016/j.jclepro.2016.06.155.

Tagliapietra, Simone, Zachmann, Georg, Edenhofer, Ottmar, Glachant, Jean-Michel, Linares, Pedro, Loeschel, Andreas, 2019. The European union energy transition: key priorities for the next five years. Energy Pol. 132, 950–954. https://doi.org/10.1016/j.enpol.2019.06.060.

Talaei, Alireza, Pier, David, Iyer, Aishwarya V., Ahiduzzaman, Md, Amit, Kumar, 2019. Assessment of long-term energy efficiency improvement and greenhouse gas emissions mitigation options for the cement industry. Energy 170, 1051–1066. https://doi.org/10.1016/j.energy.2018.12.088.

Teh, Soo Huey, Wiedmann, Thomas, Schinabeck, Judith, Moore, Stephen, 2017. Replacement scenarios for construction materials based on economy-wide hybrid LCA. Procedia Eng. 180, 179–189. https://doi.org/10.1016/j.proeng.2017.04.177.

United Nations, 2015. Sustainable development goals. https://www.undp.org/sustainable-development-goals?utm_source=EN&utm_medium=GSR&utm_content=US_UNDP_PaidSearch_Brand_English&utm_campaign=CENTRAL&c_src=CENTRAL&c_src2=GSR&gclid=Cj0KCQiAt8WOBhDbARIsANQLp965VXL7PO3jyIvzVfSjh8uj_kVQ5s0xHTQeLeONqaopNBesI-grgkYaAvVJEALw_wcB#industry-innovation-and-infrastructure.

United Nations Framework Convention on Climate Change, 2019. Greenhouse gas inventory data - flexible queries annex I parties." 2019. https://di.unfccc.int/flex_annex1.

Vega, Fernando, Cano, Mercedes, Marina Gallego, Luz, Camino, Sara, Camino, Jose Antonio, Navarrete, Benito, 2017. Evaluation of MEA 5 M performance at different CO2 concentrations of flue gas tested at a CO2 capture lab-scale plant. Energy Proc. 114, 6222–6228. https://doi.org/10.1016/j.egypro.2017.03.1760.

Wang, Huarong, Xu, Jinliang, Yang, Xufei, Zheng, Miao, Yu, Chao, 2015. Organic rankine cycle saves energy and reduces gas emissions for cement production. Energy 86, 59–73. https://doi.org/10.1016/j.energy.2015.03.112.

Wang, Jin Wei, Liao, Hua, Tang, Bao Jun, Ke, Ruo Yu, Wei, Yi Ming, 2017. Is the CO2 emissions reduction from scale change, structural change or technology change? Evidence from non-metallic sector of 11 major economies in 1995–2009. J. Clean. Prod. 148, 148–157. https://doi.org/10.1016/j.jclepro.2017.01.123.

Weil, Steffen, Hamel, Stefan, Krumm, Wolfgang, 2006. Hydrogen energy from coupled waste gasification and cement production- a thermochemical concept study. Int. J. Hydrogen Energy 31 (12), 1674–1689. https://doi.org/10.1016/j.ijhydene.2005.12.015.

Wesseling, J.H., Lechtenböhmer, S., Åhman, M., Nilsson, L.J., Worrell, E., Coenen, L., 2017. The transition of energy intensive processing industries towards deep decarbonization: characteristics and implications for future research. Renew. Sustain. Energy Rev. 79 (January), 1303–1313. https://doi.org/10.1016/j.rser.2017.05.156.