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Supercritical carbon dioxide recovery system applied to cement industries

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Supercritical carbon dioxide recovery system applied to cement industries

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Abstract. The paper addresses the potential heat-to-power application of supercritical CO2 (sCO2) plants to the cement industry, thereby reducing their electricity demand and improving energy efficiency. The research was conducted as part of the European project CO2OLHEAT (G.A. 101022831), which involves the installation of a 2 MW Waste-Heat-to-Power (WH2P) skid based on a sCO2 cycle in a cement plant, the first of its kind with a MW-scale power output. The paper summarizes technologies and processes employed in the Italian cement production sector, detecting where the waste heat can be successfully extracted to feed the recovery plant without compromising the industrial process. Moreover, the paper discusses the national cement market and explores the potential advantages and limitations of integrating sCO2 recovery plants within the national cement context, considering production and energy-related data. The final finding reveals the percentage of recoverable electricity per technological class for the cement production sector in Italy with a potential application of the sCO2 recovery plant, aiming at identifying the potential market penetration of the CO2OLHEAT installation.

1. Introduction

Cement is one of the primary construction materials used in various sectors of the building industry due to its flexibility and high-performance characteristics. Its industrial production dates back to the mid-1800s, and currently, it ranks as the second most widely used material in the world, following water. The capacity of a modern cement plant exceeds 1 million tons per year and requires approximately 60 to 130 kg of fuel oil and an average of 110 kWh of electricity per ton of cement produced [1].

The cement production sector is one of the most energy-intensive industries in terms of primary energy consumption and electricity usage. It also represents a significant source of CO2 emissions due to the combustion reaction and the calcination process. Consequently, cement producers are increasingly paying attention to process sustainability, aiming to reduce environmental impact and optimize energy efficiency. In this context, the EU H2020 project CO2OLHEAT [2] is focused on improving energy efficiency and decarbonizing European Resource and Energy Intensive Industries (REIIs).

The project involves the construction of the first industrial-scale sCO2 cycle plant to recover residual heat from exhaust gases efficiently and economically to generate electricity. This allows for substantial savings in primary energy and CO2 emissions, the latter being associated with the non-renewable electric power generation required by the primary plant. More precisely, the 2 MWe power block of CO2OLHEAT is planned to be installed at the CEMEX cement plant in the Czech Republic to recover a significant amount of currently unused thermal power from the chimney exhaust and partially reduce the electricity demand of the primary plant.

The focus of this study is specifically on the cement production sector in Italy. The objective is to assess the pros & cons related to the installation of the sCO2 power cycle of CO2OLHEAT and provide a tool for future business cases. To acquire general data essential for the national analysis of the cement production sector, sources such as ISTAT, AITEC, Federbeton, Eurostat, and CSI-GNR[1] (GCCA) have been utilized since the validation through direct contribution from cement producers. The entire work refers to 2019, one of the latest available years within some databases, before the pandemic and the Russo-Ukrainian conflict, which have caused strong singularities and instabilities in both the industrial production sector and the electricity and gas supply market.

Following the statistical classification of economic activities in the European Community, NACE[2] (Rev. 2) groups the five main categories of cement defined by the EN 197-1 regulation [3] with the following classification [4]:

- Clinker (NACE Code C23511100), an intermediate product in the cement production chain;
- Portland cement (NACE Code C23511210), representing the two categories CEM I (Portland cement) and CEM II (Portland-composite cement);
- Other hydraulic types of cement (NACE Code 23511290), representing the three other categories CEM III (Blast-furnace cement), CEM IV (Pozzolanic cement) and CEM V (Composite cement).

Within this study, reference has been made to the total production of cement, utilizing the classification of "white and grey cements”, as documented in the GNR Database [5]. The distinction has been based on production technology rather than output type, considering the specific values per ton of clinker according to the clinker-to-cement ratio in Italy, referred to the year 2019.

2. CO2OLHEAT Concept

CO2OLHEAT is an EU-funded project under H2020 that focuses on improving energy efficiency and decarbonization in European Resource and Energy Intensive Industries (REIIs). It aims to address these challenges by utilizing waste heat from these industries and converting it into electricity in a cost-effective and efficient way. The project aims at demonstrating at TRL7 a sCO2 waste heat to power (WH2P) plant.

A 2 MWe recuperated closed-loop sCO2 Brayton cycle will be implemented to valorize the industrial waste heat at $T > 400°C$ of a cement plant, reducing electricity consumption and associated GHG emissions. Using sCO2 as a working fluid offers several advantages connected with fluid properties in supercritical conditions making it of interest for high-efficiency power plants and enabling the production of completely clean energy. Such thermodynamic properties overcome the limitations of traditional solutions, making sCO2 technology a potential choice for REIIs.

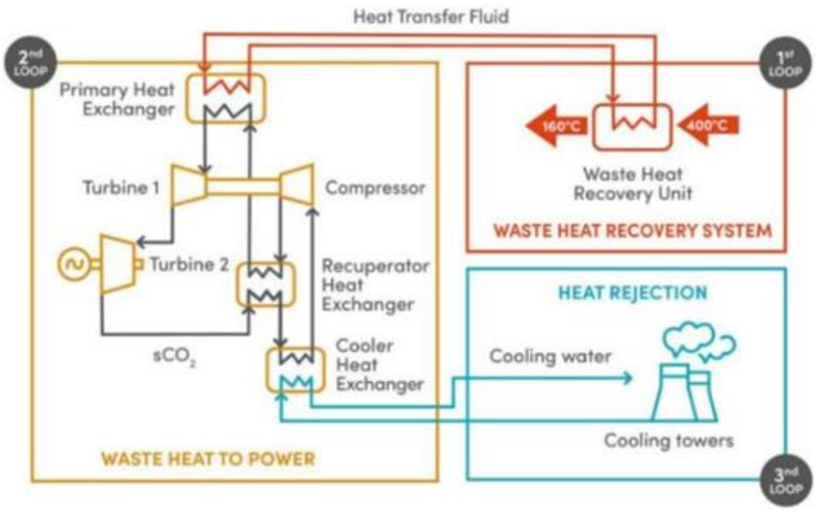

Figure 1. Recuperated closed-loop Brayton cycle with sCO2 as a working fluid for the CO2OLHEAT project *[6]*.

[1] Last consultation date of the CSI-GNR (Cement Sustainability Initiative – Getting the Numbers Right) database prior to version 2.0 is December 20, 2022

[2] The term NACE is derived from the French Nomenclature statistique des activités économiques dans la Communauté européenne

The recuperated Brayton cycle (RBC) designed for the CO2OLHEAT project stands out as one of the best configurations regarding conversion efficiency, simplicity, and cost-effectiveness, as deduced from numerous studies in the literature. The suitability of this configuration for waste heat recovery (WHR) applications in highly energy-intensive industrial sectors has generated considerable interest for potential investments in the near future, despite the need for further investigations on capital costs due to the lack of practical experience with prototype machines at an industrial power scale [7]. However, due to non-linear variations of certain physical properties, pinch points could occur within the recuperator. To mitigate this issue, increasing attention is being directed towards the recompression Brayton Cycle (RCBC), in which an appropriate modulation of the flow rate can alleviate pinch-related challenges within the recuperator. Multidimensional calculation algorithms are of primary importance for accurately determining the optimal plant configuration of indirect power cycles on a scale of tens of MW while adhering to fluid dynamics and mechanical constraints. [8].

3. Main processes and technologies in the cement production sector

The cement industry is a vital sector for a wide range of downstream industries, products, and services in the construction and civil engineering fields due to its strength, reliability, and durability characteristics. Four different types of cement production processes can be distinguished: dry, semi-dry, semi-wet, and wet, depending on the moisture content of the raw material once extracted from the mining site. Given the significant portion of cement cost attributed to fuel, in 2019, cement production in Italy and Europe was based on the dry thermal processes for about 76% [9] and 90% [10], respectively, which is why it is taken as reference technological class for this work. The process involves several steps for extraction, grinding, drying, heating, and cooling, and all of them require a considerable amount of electrical and, mainly, thermal energy.

The grinding phase is closely dependent on the technological level of the specific production site, depending on whether it is a dry or wet process. Ensuring a particle's size distribution is an added advantage in the physicochemical transformations since the smaller the size of individual particles, the faster the heat exchange and activation of chemical reactions, improving the energy and economic efficiency of the cement production process.

The thermodynamic transformations and chemical reactions that characterize the cement production process, from ground raw materials to clinker production, occur within dedicated heating systems. The preheating tower is crucial to increase productivity and energy efficiency in the production process by recovering part of the heat from the hot gases exiting the kiln. At the bottom of the tower, the raw meal is diverted to the precalciner, a combustion chamber where up to 60% of pulverized coal is burned and where 90%-95% [11] of the limestone calcination process takes place at a temperature of about 900°C. This unit allows for halving the length of the kiln and increasing cement production in terms of quantity and final quality [12].

The kiln is made of steel lined with high alumina refractory bricks, positioned horizontally with a slight slope (from 2 to 4%), about 2-6 m in diameter and a rotation between 0.5 and 5 rpm. During this stage, the remaining 40% of pulverized coal undergoes combustion, leading to flue gases reaching temperatures as high as 2000°C, while the raw materials are melted at temperatures of up to 1450°C, required for the sintering reactions [13]. Once the clinker exits the kiln, it is cooled from 1300-1200°C to 100°C in the air cooler to allow safe handling and prevent further mineral transformation. A portion of the hot air from the cooler is recirculated to the kiln as secondary air, another part to the pre-calciner, both to save fuel and increase burning efficiency, and the final portion to the de-dusting filter [14] [15].

4. Cement market

4.1. Cement Production in Italy

The following data refers to the CSI-GNR database, which, for the year 2019, accounted for 83.5% coverage of cement production within the Italian territory, corresponding to 16 million tons of cement produced, against the actual 19,2 million tons [9]. The partial coverage of the database is attributed to the participation of 5 companies, representing 40 cement plants out of a total of 55 [16]. It allowed for differentiation in terms of thermal and electric energy consumption based on technological production process, a critical factor in analyzing the applicability of CO2OLHEAT.

The distribution of cement production in Italy remained consistent with previous years, with Portland cement (CEM I) and blended Portland cement (CEM II) comprising 86% of the overall production [16]. The kiln utilization factor was recorded at 63% (+3% compared to 2018), corresponding to a production capacity of 25.4 million tons, according to the CSI-GNR data.

For the present analysis, the authors decided to focus exclusively on cement integrated plants, excluding the grinding ones, since the CO2OLHEAT demo plant requires a medium-high temperature heat source, which is provided by the exhaust gases from the kiln. Analyzing the cement plant map from Federbeton's supply chain report for 2019 [16], it was possible to quantify the number of plants:

Table 1. Cement plants in Italy – 2019 *[16]*

2019	*Integrated plants*	*Grinding plants*
Northern Italy	11	12
Central Italy	7	1
Southern Italy	9	7
Italian Islands	5	3
TOTAL	32	23

4.2. The import/export of cement in the Italian market

For grinding-only plants, the input consists of clinker produced domestically within the EU or, increasingly in recent years, imported from foreign countries. As mentioned in some Cembureau reports [17], the European import of clinker from non-EU countries has undergone strong growth in recent years, with a 160% increase in the last five years, until 2019, a trend influenced mostly by new business models and increasing CO2 emission costs for EU cement producers [18]. Similarly, Italy has recorded a comparable trend, with particular reference to the year 2019, compared to previous years, as can be observed from the following graphs:

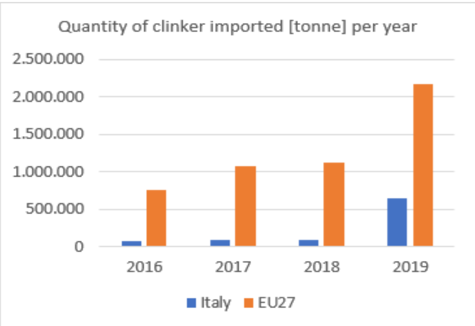

Figure 2. Eurostat: Quantity of clinker imported per year [24].

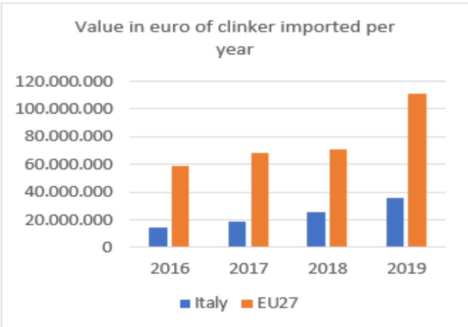

Figure 3. Eurostat: Value in Euro of clinker imported per year [24].

Such issue becomes even more evident in the integrated plants sector when comparing the European (EU27) trade balances for clinker and Portland cement. It can be observed that the economic difference between clinker imports and exports reached an almost zero net value in 2020, unlike Portland cement, which remained rather stable.

Contrary to clinker imports, the Portland cement market is much less at risk, since the grinding plants will continue to operate at full capacity, as they are not subject to stringent regulations or increasing European costs in terms of CO2 emissions.

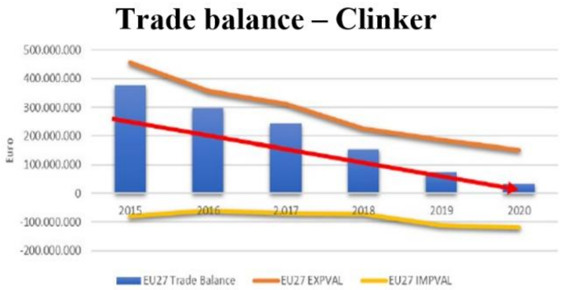

Figure 4. Export Value, Import Value and Trade Balance of Clinker in EU27, 2015-2020 [20].

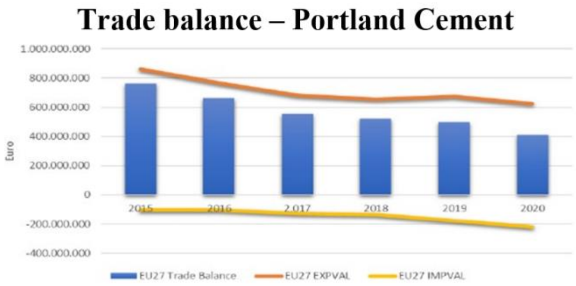

Figure 5. Export Value, Import Value and Trade Balance of Portland cement in EU27, 2015-2020 [20].

5. Energy balance in the cement production sector

5.1. Thermal energy consumption

The cement industry is one of the most energy-intensive sectors, with energy consumption accounting for approximately 50% to 60% of the total manufacturing cost, out of which thermal energy constitutes about 20-25% [19] [20] [21]. It also significantly contributes to artificial CO2 emissions, with 7% of global emissions [22], amounting to around 2,3 Gt CO2 in 2019. Within this total, 61% is attributed to process emissions from calcination, 26% to fuel usage and 13% to electricity consumption [23].

Since 2015, in Italy, cement plants based on "semi-wet/semi-dry" and "dry processes without preheater and precalciner" have been converted to "dry processes with preheater and precalciner", as well as "mixed kiln type processes" [24].

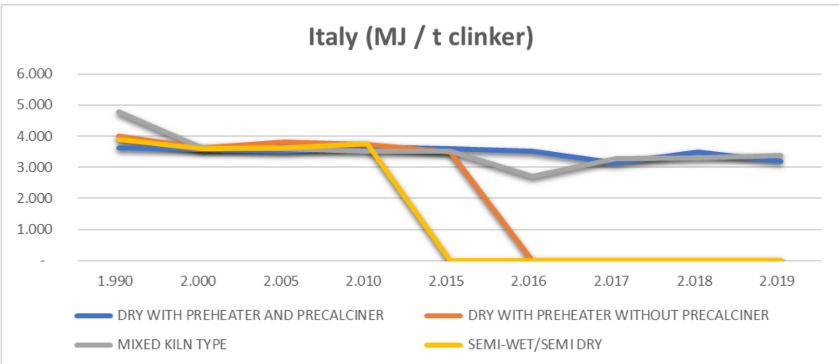

Figure 6. *CSI-GNR*: Thermal energy consumption - Italy - Weighted average / excluding drying of fuels - Grey clinker - by kiln type (MJ / t clinker) - Code 25aAGK

The theoretical minimum energy consumption is 1.76 GJ per ton of clinker [25], but an additional 200 to 1000 MJ/ton of clinker is added for drying raw materials (with moisture content ranging from 3% to 15%) [26]. The remaining heat is inevitably dissipated, resulting in energy consumption exceeding 3500 MJ/ton clinker. High-efficiency kilns equipped with preheaters and pre-calciners use approximately 3.06 GJ of energy per ton of clinker, while wet kilns absorb between 5.3 and 7.1 GJ per ton [27]. Within the European Union, the average energy consumption per ton of clinker produced is approximately 3.7 GJ (*GNR Code 93AG*) [9].

5.2. Electrical energy consumption

Even though most of the primary energy consumed by a cement production plant is derived from fuel combustion in the kiln, the use of electricity is also a significant factor, accounting for approximately 12% to 20% of the energy requirements for cement production and comprising around 30% of the cost for cement manufacture [19]. The total electricity consumption in a dry kiln plant is divided into preparing the raw materials and the production of clinker (25% each) and 43% for the final grinding phase to obtain the cement. The remaining 7% is for extracting the raw material, grinding fuel, and packing [28].

In 2019, Italy produced 16 million tons of cement, for a total electricity consumption of 2 TWh_{el}, equivalent to 122 kWh/t_{cement}. This was higher than the European average of 117 kWh/ton of cement and 80 kWh/ton for the best possible performance [9]. Various changes and retrofits can be considered to further reduce specific energy consumption, such as replacing ball mills with more efficient vertical or high-pressure roller mills. However, energy consumption also depends on the properties of the final product: the higher the strength required for the concrete, the finer the grinding process needs to be, resulting in increased energy consumption for the operation of the rollers.

In the coming years, a reconfiguration of the cement production process may be required due to the growing need for Carbon Capture, Storage, and Utilization (CCSU) systems. These have high energy intensity and will lead to significant increases in the electricity consumption of a cement plant, ranging from 50% to 120% more than the current average consumption [28]. Many cement producers are investing in photovoltaic and wind park installations near the production facilities to ensure a reliable electricity supply in grid instability and residual heat recovery systems from the exhaust gases exiting the preheating tower for electricity generation [29].

5.3. Waste Heat Recovery

Cement plants face numerous challenges in terms of energy consumption, which is why several attempts have been made to optimize resources and machinery to improve process efficiency and reduce costs. Typically, clinker coolers release large amounts of hot air ranging from 250 to 340 °C directly into the atmosphere. On the other hand, exhaust gases from the kiln exit between 300 and 450°C from the preheaters are commonly used to dry raw materials or coal [30].

A typical energy balance for a modern dry kiln indicates that approximately 23% of the heat is lost through exhaust gases, 11% through excess air, and 10% due to radiation across the entire system. The calculation of available heat for each technological class in the cement industry is based on the estimated assumption of 23% waste heat from exhaust gases, as referenced in the study "Evaluation of waste heat recovery technologies for the cement industry" [31]. This evaluation was carried out using the average specific consumption per ton of clinker produced, obtained from the CSI-GNR database. The consumption values for each technological class are presented below:

Table 2. Average specific heat consumption by technological class, range of flue gas temperature and specific heat consumption in Italy (from CSI-GNR database)

2019	*Number of cyclones*	*Average specific heat consumption [GJ/$t_{clinker}$]*	*Flue gas temperature range [°C]*	*η CO2OLHEAT Cycle*	*Specific heat consumption in Italy [GJ/$t_{clinker}$]*
Dry with preheater and precalciner	4	3,14	300 - 380	19,4% - 24,3%	3,203
	5	3,01	250 - 350	15,8% - 22,6%	
	6	2,93	200 - 300	11,5% - 19,4%	
Mixed kiln type	-	3,36	300 - 420	19,4% - 26,5%	3,396

Table 2 presents a technological classification of production processes based on the CSI-GNR database, with a distinction regarding the number of cyclone stages in the preheating tower. The second column provides specific heat consumption values obtained from the literature, while the third column lists the associated temperature ranges of the exhaust gases for each technology, sourced from literature references [32]. The technological class "mixed kiln type" in cement production refers to a type of cement manufacturing process that combines elements of both the "dry" and "wet" processes. In this type of process, the raw material is fed in a dry state into the initial part of the kiln, where it is dried and preheated, while water is injected in the later part of the kiln to moisten the material and complete the clinker synthesis reaction.

By utilizing the established temperature ranges of the exhaust gases for each technological class, the cycle efficiency of CO2OLHEAT was calculated for each category, using the design efficiency values by the University of Roma Tre, referred to the project's reference cycle assuming equivalent efficiencies and head losses. It was then possible to reconstruct the performance curve through point interpolation:

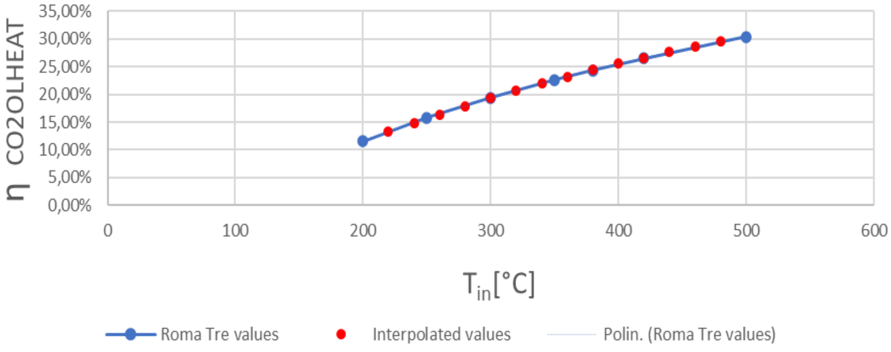

Figure 7. CO2OLHEAT Efficiency Curve

The rightmost column of the table displays the weighted average values of specific heat consumption in Italy, derived from the CSI-GNR database. Unfortunately, information regarding the number of plants for each technological class was not available.

6. Evaluation of the expected electricity savings achievable with CO2OLHEAT

The entire available heat in the temperature ranges from flue gases inlet (T_{in}) to ambient conditions ($T_{amb} = 25°C$) would have been too unreliable and overly optimistic compared to realistic scenarios and specific plant constraints, such as temperature requirement for drying processes, depending on the moisture content, energy efficiency and technological class.

Considering the mass balance model to produce 1 kg of cement [33], a sensitivity analysis was conducted in ChemCAD. This analysis utilized the chemical composition of the exhaust gases to calculate the useful heat exchanged for various combinations of temperature ranges in the waste heat recovery unit; for the inlet temperatures, a range between the maximum and minimum values was chosen, specifically 380°C and 200°C for the dry with preheater and precalciner process and 420°C and 300°C for the mixed kiln type, as presented in **Table 2**; for the outlet temperatures, a range was selected to cover the possible cases between the worst-case scenario, corresponding to the maximum inlet temperature of the specific technological class, and the best-realistic-case, corresponding to 140°C. Assuming the gas as ideal, it was evaluated a coefficient ε as the ratio of the corresponding useful heat, $Q_{\Delta T}$, to the available heat, $Q_{\Delta T_{ref}}$, referred to a $T_{out} = 25°C$. The evaluation of the ε coefficient was carried out for each ΔT_{Useful}, corresponding to multiple T_{out} values, every 20°C step.

Therefore:

$$\varepsilon = \frac{Q_{Useful}}{Q_{Available}} = \frac{Q_{\Delta T}}{Q_{\Delta T_{Ref}}} \quad (1)$$

$$Q_{\Delta T} = Q(T_{in}; T_{out}) \quad (2)$$

$$Q_{\Delta T_{Ref}} = Q(T_{in}; T_{out} = 25°C) \quad (3)$$

Knowing the efficiency of CO2OLHEAT as a function of temperature and the ε parameter, the authors determined the electrical energy that can be obtained from the useful thermal energy of the exhaust gases. This is dependent on the temperature range, rather than the thermal energy available from T_{in} to 25°C ambient temperature, and is calculated as a product of:

$$\eta_{Actual} = \eta_{CO2OLHEAT} * \varepsilon = \frac{E_{El}}{E_{Th,Useful}} \quad (4)$$

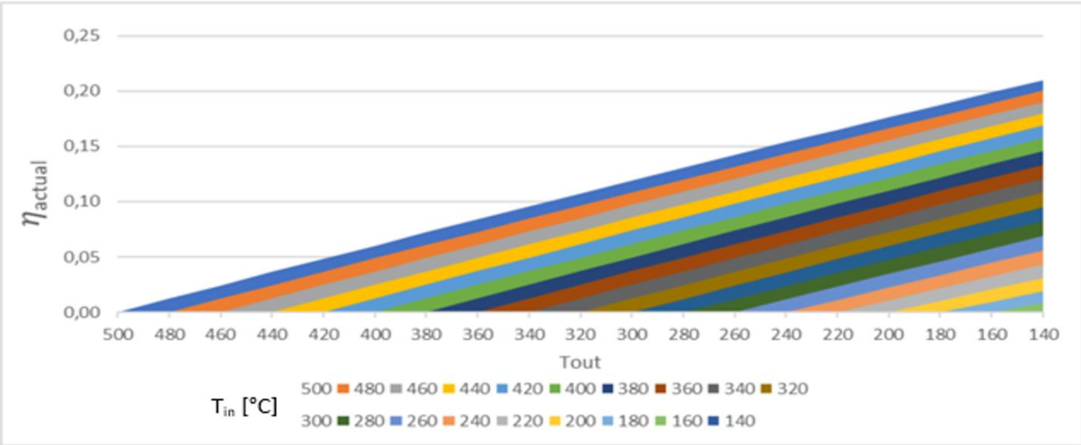

Figure 8. Actual Efficiency, depending on the CO2OLHEAT Efficiency and the Range of temperature useful.

In the following **Table 3**, the values of thermal energy consumption per ton of clinker produced, annual clinker production, and thus, the annual thermal energy consumption are reported:

Table 3. Specific Thermal energy consumption per ton of clinker produced (CSI-GNR – Weighted average | excluding drying of fuels - Clinker - by kiln type – 2019 – Code 25aAGK), Total clinker production per each country (CSI-GNR – 2019 – Code 8TG) and Annual thermal energy consumption.

Italy 2019	*Specific thermal energy consumption [MJ / $t_{clinker}$]*	*Total production volumes of clinker [$t_{clinker}$]*	*Annual thermal energy [GWh_{th}/ y]*
Dry with preheater and precalciner	3.202,6	10.233.957,1	9.104,2
Mixed kiln type	3.396,4	3.297.835,1	3.111,3

As previously mentioned, the thermal energy of the exhaust gases has been assumed to be equal to 23% of the total thermal energy supplied in the entire clinker production, resulting in 2093,9 GWh_{th}/y for the dry with preheater and precalciner technology and 715,6 GWh_{th}/y for the mixed kiln type. From these values, it was possible to determine the electricity savings achievable with CO2OLHEAT through the energy conversion efficiency, where $E_{El} = \eta_{Actual} * E_{Th}$.

In Italy, based on the CSI-GNR database, the average specific electrical consumption, $E_{el,t\ cement}$, was found to be 121.6 kWh/t cement, and the CCR (Clinker to Cement Ratio) was 0.77. From these values, the average specific electrical consumption per ton of clinker produced was calculated using the following equation:

$$\frac{E_{El,t\ cement}}{CCR} = E_{El,t\ clinker} = 157{,}1\ [\frac{kWh}{t_{clinker}}] \quad (5)$$

By multiplying this result by the tons of clinker produced per technological class, the annual electrical consumption of the entire cement production process was obtained as 1607.4 GWh_{el}/y for the "dry with preheater and precalciner" class and 518 GWh_{el}/y for the "mixed kiln type" class. By knowing the annual electricity savings achievable with CO2OLHEAT as a function of ΔT_{Useful} and the annual electrical consumption, the following indicative table of percentage electrical savings per technological class and per ΔT_{Useful} that could have been achieved with a hypothetical installation of CO2OLHEAT in 2019 was obtained:

Table 4. Percentage of electricity savings up to and including cement production – Italy – 2019

2019		Italy	Tout [°C]																			
			500	480	460	440	420	400	380	360	340	320	300	280	260	240	220	200	180	160	140	25
DRY WITH PREHEATER AND PRECALCINER	Tin [°C]	380							0%	2%	3%	5%	7%	8%	10%	11%	13%	14%	16%	17%	19%	32%
		300											0%	2%	3%	5%	6%	8%	9%	11%	12%	25%
		200																0%	1%	3%	4%	15%
MIXED KILN TYPE		420					0%	2%	3%	5%	7%	9%	10%	12%	14%	15%	17%	18%	20%	22%	23%	37%
		360								0%	2%	3%	5%	7%	9%	10%	12%	14%	15%	17%	18%	32%
		300											0%	2%	3%	5%	7%	8%	10%	12%	13%	27%

Three indicative inlet temperatures can be identified for each of the two technological classes of cement production, corresponding to the best case, the intermediate case, and the worst case. It was found that, in the best realistic case corresponding to the maximum T_{in} values in the second column from the right, it would be possible to achieve electrical energy savings of 19% and 23%.

7. Conclusion

The results of the potential application of CO2OLHEAT have shown relatively positive outcomes compared to state-of-the-art Waste Heat To Power (WH2P) technologies. Depending on the waste heat recovery process, which could be based on steam, ammonia or ORC, the energy savings range from 8 to 22 kWh per ton of clinker or up to 16% of a cement plant's energy consumption [28]. According to the literature, it has been estimated that the EU 27 could potentially install a power capacity of 576 MW from WHTP ORC plants in the cement industry [34]. In the Italian national context, up to 121 TWh of recoverable heat is available for district heating in Italy, based on an initial primary energy input of approximately 558 TWh [35]. The recoverable heat predominantly originates from power generation plants, petrochemical, and industrial sectors, but it is strongly dependant on the geographical matching between electricity supply and demand, and could be utilized to enhance further energy efficiency, such as chemical, steel, non-ferrous metals, glass and ceramic industries.

Despite the significant energy savings achievable with CO2OLHEAT, it still corresponds to an economic benefit associated with the portion of savable electricity required for the cement production process. Additionally, further economic benefits could be obtained through mechanisms enabling companies to offset their CO2 emissions through certified emission reduction projects. Carbon Offsetting[3] Credits would enable further economic advantages in terms of EUAs (European Union Allowances) that can be saved within the EU Emission Trading System (ETS), a "cap and trade" market of GHG emission allowances, particularly concerning Scope 2[4] indirect emissions. This market continues to expand due to the increasingly stringent regulations adopted by Europe and can serve as a source of profit or savings, depending on the sale or direct use of the allowed allowances, especially considering the ongoing upward trend in the price of EU Carbon Permits, which went from €11.6/tCO2e in March 2020 to nearly €105/tCO2e in March 2023 [36].

Beyond purely economic considerations, it is necessary to consider the inevitable increasing demand for electrical energy by individual cement plants for environmental prevention systems and emission management and control, particularly CCS (Carbon Capture and Storage) systems, given the emissions characteristic of the production process. Furthermore, the ongoing development of new eco-friendly production technologies aiming to transition to electrically powered kilns fueled by renewable sources [37], will result in a substantial increase in the plant's electrical requirements, thereby significantly amplifying the benefits offered by residual heat recovery systems.

[3] Where "offsetting" refers to "any activity that compensates for the emission of carbon dioxide (CO2) or other greenhouse gases (measured in carbon dioxide equivalents [CO2e]) by providing for an emission reduction elsewhere. [38]

[4] "*Scope 2 emissions are indirect GHG emissions associated with the purchase of electricity, steam, heat, or cooling. Although scope 2 emissions physically occur at the facility where they are generated, they are accounted for in an organization's GHG inventory because they are a result of the organization's energy use.*" [39]

Ackowlegments
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