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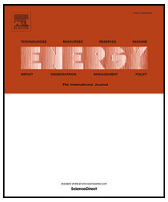

Potential savings in the cement industry using waste heat recovery technologies

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ABSTRACT

This work describes technologies especially suitable for enhancing cement production process efficiency and overall plant performance by preheating raw material or generating electricity, thus reducing thermal losses, costs, and carbon dioxide emissions. Assessed systems for this purpose include power cycles such as the Organic Rankine Cycle, Tri-lateral Cycle, and Kalina cycle, and alternatives currently under development, such as thermoelectric generators and supercritical fluid cycles. Likewise, the zones of the cement production process with the most significant waste-heat recovery potential are pointed out, focusing on clinkerisation, which accounts for most of the thermal energy expenditure of a cement plant. In addition, the total carbon dioxide emissions related to cement manufacture and the participation of each production stage are presented. Finally, the potential for waste heat recovery in the cement industry of the first six Latin American producers is reviewed, which covers 82% of the total production in the region, based on the thermal and electrical requirements reported in the literature. The potential for emissions savings of carbon dioxide is estimated under the emission factor for the electricity system in each country.

1. Introduction

Large industrial systems are often intensive in energy consumption, whether as heat or electricity and are accountable for vast environmental impacts. The most representative industries in this matter are iron and steel, petrochemical, food, glass, ceramics, pulp and paper, and cement [1]. Such sectors usually rely on using fossil fuels as their main energy source, making them primary targets for global policies to limit global warming [2]. Several technologies and strategies contribute to mitigating harmful effects through decarbonisation at low-temperature heat, use of alternative feedstock, and processes for carbon capture and storage, among others [3]. However, high electricity and heat-intensive industries, e.g. aluminium or copper production, should be addressed when it comes to improving their performance in energy-sourced decarbonisation because any potential improvement is associated with the power-generation sector [4,5]. Despite this, solidly addressing the aluminium industry performance has been presented in [6]. An enhancement in the overall performance of such sectors contributes positively to the goals set by international treaties, like the Paris Agreement, which aims to limit the average global temperature while balancing energy security, energy equity, and environmental sustainability. Security refers to the ability of suppliers to meet the current and future demand with equity to the accessibility and affordability of energy. But, environmental sustainability encompasses achieving energy efficiency on the side of providers and consumers and energy supply development from renewable and other low carbon sources [7].

There are different technologies available for the recovery of waste heat, and many industrial facilities have been improved by using waste heat to enhance their energy efficiency [8]. These systems can offer significant energy savings and substantial reductions in greenhouse gas emissions (GHGs) [9]. Waste-heat recovery systems include recuperative and regenerative burners, heat exchangers, waste heat boilers, air preheaters, and heat pumps. It can consist of low-temperature applications, below 100 °C; medium-temperature applications, between 100 °C and 400 °C; and high-temperature applications, above 400 °C [10]. Several works have been focused on establishing technologies and configurations for waste heat recovery, including the design

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Nomenclature

Chemical formulas

CO_2	Carbon dioxide
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
SiO_2	Silicon oxides
C_2S	Dicalcium silicate
C_3S	Tricalcium silicate
C_3A	Tricalcium aluminate
Bi_2Te_3	Bismuth telluride
PbTe	Lead telluride
MgOF	Magnesium oxide
Mg_3Sb_2	Magnesium antimonide

Abbreviations

ORC	Organic Rankine cycle
TLC	Trilateral cycle
KC	Kalina cycle
$TEGs$	Thermoelectric generators
PM	Particulate matter
CCP	Combined cooling and power
IHE	Internal Heat Exchanger
WHO	World Health Organization
PH	Preheating boiler
AQC	Air Quenching Cooler
VAM	Vapour Absorption Machine
$CSHP$	Combined solar heat and power
$LCOE$	Levelized cost of energy

of a system to recover waste energy from hot drain water coupled with a heat pump cycle using different scenarios [11], the experimental, theoretical, and numerical evaluation of a full-scale heat pipe heat exchanger in the ceramics industry for waste heat recovery [12,13], and the use of the heat pipe technology in thermal energy storage heat exchangers [14], among others.

Industrial waste-heat recovery technologies are assessed economically in [15]. The potential of industrial waste heat for heating and cooling applications is investigated, and their technical and economic potential is discussed. At the same time, relevant case studies are provided to illustrate for different consumers when a particular system, i.e. absorption chiller, the heat produced with compression and an absorption heat pump, would be profitable. A Thermal Energy Storage (TES) review for industrial waste-heat recovery is shown in [16]. In this regard, around 50 industrial case studies were reviewed in which on-site and off-site recovery systems were considered for analysis. Such technology solves some challenges in implementing waste-heat recovery systems, like the temporary or geographical mismatch between energy release and heat demand. Additionally, a review of the applications of Phase Change Materials (PCM) in cooling, heating and power generation in different temperature ranges are depicted in [17]. Latent heat thermal energy storage is an attractive technique as it can provide higher energy storage density than conventional systems and store the heat of fusion at a near-constant temperature. The authors provided an exhaustive analysis of PCMs considering performance, heat transfer enhancement techniques, environmental impacts, and economics for a wide range of operating temperatures.

It is important to highlight that energy-intensive processes represent 70% of the total global CO_2 emissions attributable to different industries as depicted in Fig. 1(a). Global cement production, which achieved 4,050 Mt in 2018, is accountable for 27% of CO_2 emissions, the largest contributor with around 2.3 Gt CO_2. Fig. 1(b) shows the distribution of the energy sources used for clinker production. It is found that fossil fuels represent the majority share, and just a 3% comes from renewable sources. However, non-renewable waste is gaining prominence, holding a share of roughly 6% of such input. It is also important to note that the energy intensity of cement is directly linked to the clinker-to-cement ratio, which has a global average of 0.7. Therefore, the total energy intensity of the cement production is about 4.86 GJ/tCement. The improvement of this parameter corresponds to an increase in the energy efficiency of the processes that make up cement production: reducing heat losses to the environment [20], improving insulation, enhancing control and energy management [21] or using waste-heat in a lower temperature application [22], potentially combined with a thermal storage unit to smooth down fluctuations in the waste-heat harvesting [23], or to overcome challenges inherent to renewable sources like solar-thermal harvesting [24]. According to [25], process inefficiencies translate into higher fuel consumption, declining into larger CO_2 emissions and higher production and environmental costs. Olabi et al. [26] analyse the digitalisation of energy in terms of prevalent technologies such as artificial intelligence, digital twins, and others. They also examine potential applications, obstacles, and challenges to increase industries' energy efficiency.

This work aims to overview the context of waste-heat recovery in the cement industry, focusing on the technologies that are especially suitable for enhancing process efficiency and overall plant performance. The following sections are organised to adequately address the process's characteristics and the waste-heat recovery technologies. First, Section 2 explores the cement production process and the stages from which it is reasonable to recover waste heat. Next, in Section 3, several waste-heat recovery applications directly related to the cement industry for gaseous effluents and radiation are depicted. Then, in Section 4 are portrayed some of the bottoming cycles for waste-heat recovery, starting with the Organic Rankine and Kalina cycles, also covering less common processes such as the Organic Rankine Flash Cycle, and other alternatives such as the Super-critical power cycles and thermoelectric generators. Finally, a systematic discussion on the context of waste-heat recovery is presented in Section 6. This section assesses the potential for waste-heat recovery in the cement industry in the top six Latin American producers, based on the thermal and electrical requirements reported in the literature and the potential for emission savings of CO_2 considering the emission factor for the electricity system in each country. Next, conclusions are shown in Section 7 and, finally, relevant works are summarised in Appendix.

2. Cement production

Cement has long been used as a binder by different civilisations around the world [27]. It can be classified into two types according to the hardening mechanism: hydraulic cement, which needs water to harden through a chemical hydration process [28], and non-hydraulic cement, which hardens when it reacts with the carbon dioxide in the atmosphere. Non-hydraulic cement is composed mainly of gypsum plasters and lime. Still, it can contain oxychloride because of its liquid properties. Non-hydraulic cement is especially suited for applications that require high chemical stability. This is because, after setting, non-hydraulic cement develops a high resistance to chemical attack. However, its drawback is that it requires a long setting time and must be kept dry to develop strength. Because of this added complexity and the advancements in the additives to enhance chemical resistance in hydraulic cement, non-hydraulic cement has been rendered almost obsolete. The most commonly used hydraulic cement is Portland cement [29], which will be the focus of this work and will be referred to as "cement" for simplicity.

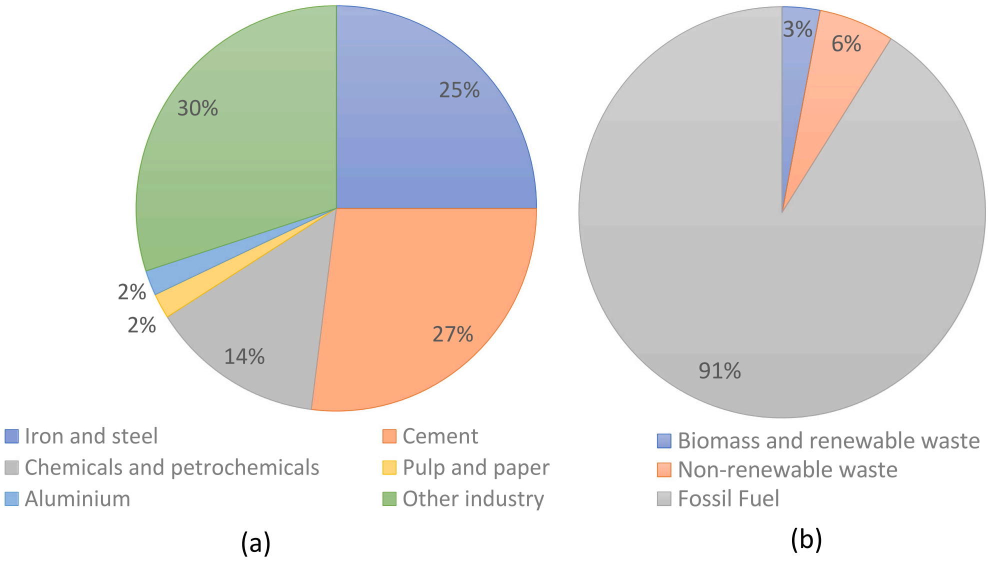

Fig. 1. Direct CO_2 emissions by industry in 2018 (8.5 Gt) (a) and global thermal energy intensity and fuel consumption of clinker production in 2018 (3.4 GJ/t) (b) [18,19].

Table 1
Clinker kiln processes main characteristics [28].

Process	Route type			
	Wet	Semi wet	Semi dry	Dry
Moisture feed	>25%	17%–21%	10%–12%	<1%
Heat consumption	>6000 kJ/kg clinker	–	–	2900 kJ/kg clinker[a]
Production capacity	From 300 tonnes/day	–	–	Up to 15000 tonnes/day[a]
Power consumption[b]	>65 kWh/tonne clinker	–	–	<20 kWh/tonne clinker[a]

[a] For the state-of-the-art suspension-preheater calciner. For a long dry process, numbers are similar to the wet process.

[b] From kiln feed to cooler discharge.

2.1. Production process description

There are several "routes" to produce cement. Those routes are classified by how the feeding preparation to the clinkerization process is done. The most common is the wet process and the dry pre-calciner process. In the former, water is added until the moisture content in the raw material reaches 35 to 40% when entering the kiln. This will help to have a homogeneous mix for the kiln. This mixing process is relatively simple and consumes less power than the homogenisation process required for other routes. However, the thermal energy consumption is much higher because the water in the slurry must evaporate. Despite this, the wet route is still used in several developing countries. Nevertheless, most of them are migrating to dry cement production since this method is more energy-efficient, making this type of plant more competitive [30]. The cement production process begins in quarries. There, drilling or explosions extract raw material mainly composed of calcium carbonate ($CaCO_3$), limestone, and silicon oxide (SiO_2). Also, other materials that could or could not be on the quarry site are required. Those materials must have a high aluminium oxide content (Al_2O_3) and iron oxide (Fe_2O_3). The first phase of cement production is raw meal preparation. Here, several materials are mixed to accomplish the proper proportions of the four oxides. Then the mix is ground and dried to have appropriate conditions for burning.

The next phase is the burning of the raw meal. Initially, the mix is subjected to preheating up to about 600–650 °C, calcined up to 900 °C, and clinkerized, where temperatures can be over 1400 °C. A heat source is required to increase the temperature of the raw meal to transform it into the clinker, which is usually the direct combustion of fuel. If the process has a calciner, up to 60% of the fuel would be burnt there. Combustion gases will move counter to the materials moving, transferring heat by direct contact. These gases would escape the process at 300–350 °C in the dry process, at the extreme point where the raw meal is fed. These gases can be used for drying in the raw mix preparation and later partially cleaned and emitted into the atmosphere. In the wet route, gases can be at around 150–200 °C, have some cleaning, and then will be cast into the atmosphere. Depending on the production route, drying, preheating, calcination, and clinkerization would occur in different machines and vessels. For example, they would happen inside the rotary kiln in the wet process. At the other extreme of the production technology spectrum, in the dry preheater pre-calciner process, only clinkerization occurs at the rotary kiln. The other operations each occur in a different equipment or vessel. The third phase is the cooling of the clinker. Here, direct contact with air cools the clinker from 1350 °C at the rotary kiln outlet to a temperature as low as around 100 °C in modern coolers. The air used to cool would have different uses according to the cement production route and cooling technology. For example, it can be used as air for combustion inside the rotary kiln and at the calciner. Also, it is used as drying air in the final drying process.

The last phase of production is the final grinding. Clinker must be mixed and finely ground with a material that contains high amounts of calcium sulphate ($CaSO_4$) to achieve all expected properties and behaviours of cement. Gypsum is the preferred source in this industry. But, natural gypsum contains calcium sulphate in a hydrated form. Because some materials have free moisture inside the finishing mill, they must have temperatures in the range of 100–120 °C. Sometimes, the heat in the clinker and the heat generated during the grinding process are enough. But, modern milling equipment is more efficient in using power. Therefore, the heat generated is not enough to fulfil the required temperature. Hot air from the clinker cooler sometimes provides the missing heat. Also, at this stage, clinker and gypsum could be mixed with some other filler or active materials to achieve specific needs. As mentioned, there are different production processes for cement. The criterion customarily used to distinguish the process

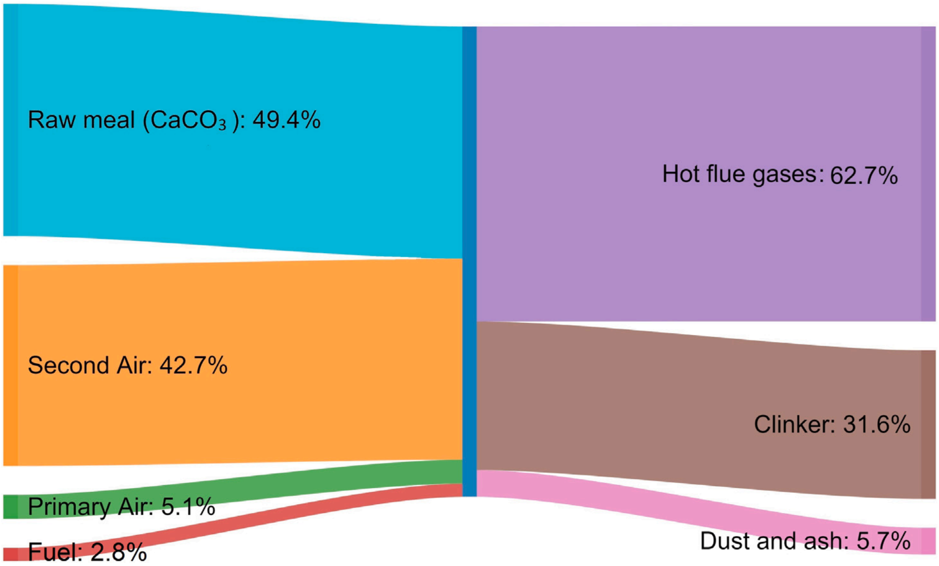

Fig. 2. Mass balance or *Sankey* diagram of clinkerization process [32].

types is the moisture of the kiln feed material. Four different process types for clinker burning can be defined. The wet and dry processes have already been discussed. Also, there are semi-dry and semi-wet techniques. In Table 1 a summary of the different Clinker kiln processes' main characteristics regarding the production route is presented.

2.2. Mass and energy flows in clinker production

As described in Section 2.1, clinker production consumes the highest heat in producing cement. So, it is common practise to analyse the behaviour of heat and mass in one combined process that includes preheating, calcining, clinkerization, and clinker cooling. In Fig. 2, the distribution of mass inlets and outlet of the rotary kiln is reported. Note that hot flue gases are almost 63% from all outlets [31]. This stream represents the combination of carbon dioxide (CO_2) freed from the decarbonisation of raw meal and combustion gases. Also, it means the primary source of waste heat is leaving the process. In modern clinkerization systems, only 31% of the input heat is used, transforming raw meal into clinker through the decarbonisation reaction. The rest is lost in different ways. About 38% leaves the process as hot gases at the feed point, and part of this heat is used to dry raw materials as they are ground. Another 26% is lost in the cooler's hot excess air, which is not used for combustion in the kiln or the calciner. But part of it is used as the heat source for cement grinding when vertical roller mills are used. About 3.3% is lost as radiation from the surface of the rotary kiln and the surfaces of the calciner and the preheater vessel. Lastly, something close to 1.1% leaves the process as dust and ash losses in the clinker (see Fig. 3). Table 1 summarises the main inlet and outlet heat flows during clinker production [31].

3. Waste-heat recovery in the cement industry

The cement industry is one of the most intensive in terms of energy use in the world, and of this energy, almost 50% of the total heat input of the clinker is lost mainly through gaseous effluents such as combustion gases, the air from the clinker cooler or radiation by the hot surfaces of the components involved in the cement production. Each of these waste heat sources is worth exploring in the following sections [33].

3.1. From effluents

The gaseous effluents can satisfy low-temperature heating needs (drying or heating) or generate electricity. In some cases, up to 30% of a cement plant's electrical requirement can be provided using this waste heat [34]. In [35,36] a thermodynamic and exergoeconomic analysis of a cement plant located in Turkey is shown as well as an overview of the cement manufacturing process: raw material preparation and raw material grinding; preheating; calcining and cooling; final grinding, and distribution. Then, the authors presented the energy and exergy relationships for the most common operating units in this type of plant and a procedure for estimating costs—finally, the potential for increasing the exergetic efficiency from point to point. Improvements in exergy utilisation at the preheating and calciner tower (thermal efficiency of η_{th} = 55.86%), rotary kiln (η_{th} = 52.14%) and clinker cooler were accomplished. The overall balance also showed that 71.87 MW, corresponding to 85.12% of the total energy input, was lost through the outer shell of the kiln and tower. This indicates that the rotary kiln is the unit that most destroys exergy in a cement production plant, where small changes can considerably increase plant performance.

An exergoeconomic analysis of heat recovery from a drying process in a ceramic plant is presented in [37]. Actual operational data were used for the kiln economic evaluation (i.e., η_{th} = 36.98%, η_{exg} = 16.41%), vertical dryer (η_{th} = 51.88%, η_{exg} = 44.96%) and spray dryer (η_{th} = 58.79%, η_{exg} = 49.4%), with a production capacity per year of 24 million m^3. Indicators such as total capital cost, potential improvement rate, energy efficiency, exergy efficiencies, and an exergoeconomic factor are used to understand the system's performance. The worst component performance occurs in the furnace because of high temperatures (up to 1250 °C) and large dimensions (85–100 m length) that cause more significant exergy destruction and energy losses to the ambient. A case study of waste heat recovery in a Colombian cement production facility is presented in [38]. Both drying/preheating and electricity generation applications are considered and compared. The comparison of energy, exergy and costs found that the best overall performance is achieved for a recuperated ORC. That alternative delivers 4.1 MW of net power output with a Net Present Value (NPV) equal to 0.42 MUSD, a rate of return of 15.58% and a payback time (PB) of 6.07 years. This represented 8.75% more work, with 13.51% better economic performance than a simple ORC.

Three waste heat recovery technologies (i.e., Organic Rankine Cycle (ORC), Trilateral Cycle (TLC) and Kalina Cycle (KC)) under different operating conditions and working fluids are analysed in [39]. The waste

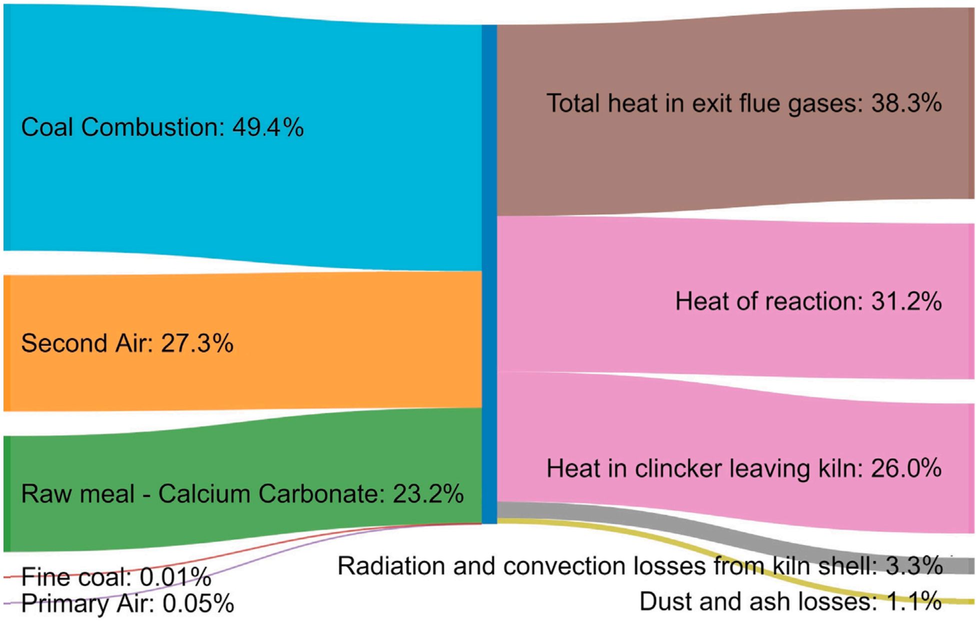

Fig. 3. Energy balance or *Sankey* diagram of clinkerization process [32].

heat source was a gaseous effluent from a cement rotary kiln. The ORC presented the best exergo-economic performance, the highest net power output and the lowest total capital cost. For the case of TLC, it is found that the exergetic performance is independent of the working fluid selected so that their critical temperature is close to but lower than the evaporation temperature. Finally, the Kalina Cycle is the one that exhibited the lowest destroyed exergy among all cycles. The higher the ammonia concentration, the lower the exergy destroyed. However, more is needed to compensate for the high costs of this technology due to the high operating pressures and overall complexity of the cycle.

An exergy life cycle assessment is carried out on a cement production plant, producing 4500 t/d in [40]. A series of waste heat recovery stations were implemented in this plant. These stations comprised two waste heat recovery boilers and one condensing steam turbine generator. In this plant, the excess air not used as combustion air at 340 °C is injected into an Air Quenching Cooler (AQC) boiler. On the other hand, a preheating boiler (PH) is installed after the preheating tower exhaust; these gases are at 330 °C . The outlet exhaust from the PH boiler is used as the drying heat of the raw mill and the coal mill. Finally, a third device was implemented. It was a 6400 kW-set condensing steam turbine generator that used the output of the AQC. Before this project was implemented, energy efficiencies of the raw material preparation line, coal preparation system and rotary kiln were 39.4%, 10.8% and 50.2%, respectively. After implementing the project, these efficiencies were 45.8%, 15.5% and 55.1%, respectively. Fig. 4 shows the arrangement of each residual heat recovery form applied in the case.

3.2. From radiation

An analysis of the parameters affecting the energy consumption of a rotary kiln in a cement plant in Gaziantep, Turkey, was conducted in [41]. It is estimated that 12.5 MW of energy was lost from the kiln's surface. It represented about 11% of the total input of this kiln. The effects on the specific energy consumption for clinker production (3735 kJ/kg) and the coating formation inside the rotary kiln were also studied. It is found that using high-quality magnesia spinel and high alumina refractory bricks provides 7% savings in energy consumption (about 271 kJ per kg of clinker). In [42], an integrated model was presented to estimate the coating thickness in the burning zone of a rotary cement kiln, were evaluated and scanned shell temperatures were in the range $T \sim 150$–310 °C. The steady-state one-dimensional model predicted the inside temperature profile along the kiln (i.e., $T \sim 750$–1400 °C). It was based on the balance equations of a plug flame model burning gas and fuel oil. Then, considering the temperature gradient between the inside and the shell, it estimated the formed coating thickness with an absolute error of 3.3 cm or less when validated in an operating kiln.

With improvements in shell cooling, numerical modelling of a rotary kiln was carried out in [43]. This one-dimensional model enabled consideration of the impact of shell-cooling fans via a composite resistance and a forced convection model. The latter's inclusion provided a better prediction of the shell temperature profile and decreased the estimation error by more than 20%. In [44], a waste-heat recovery system was evaluated. This system consisted of several interconnected heat exchangers distributed along the rotary kiln length. Design requirements, such as shell temperature (T 200–350 °C), and allowed shell heat loss (71–194 kW), were defined for nine kiln sections. Then, performance optimisation of these heat exchangers was executed using the total heat transfer area of the system, as the minimisation parameter, with a 15.6% reduction in the optimal case. Additionally, the technical and economic analysis of a heat recovery system based on the capture of radiation emitted by the surface of the rotary cement kiln shell through an absorber panel based on plant data and numerical simulations is presented in [45]. The system was economically evaluated to determine its feasibility based on the energy cost of the place where it will be located. The feasibility of implementing a waste heat recovery system based on the capture of radiation emitted from the surface of a rotary kiln was analysed by coupling CFD analysis and modelling processes, that is, material, energy, and exergy balances. The economic performance of a waste heat recovery alternative like this is tied to the price of electric energy for the industrial sector where the rotary kiln operates. In this way, the authors found that the best candidates were those with the highest electricity costs.

A study was also held in a cement production facility in Aalborg, Denmark [46]. Initially, an arc-absorber panel was proposed to recover heat from the radiation of a rotary kiln's isothermal outer shell (at about 500 °C). Numerical simulations were performed in 2D, using a finite volume approach and a surface-to-surface (S2S) radiation model. It accounted for both steady and unsteady flow regimes. A validation analysis, with constant heat flux, instead of constant temperature, was run to prevent hot spots on the surface of the rotary kiln and

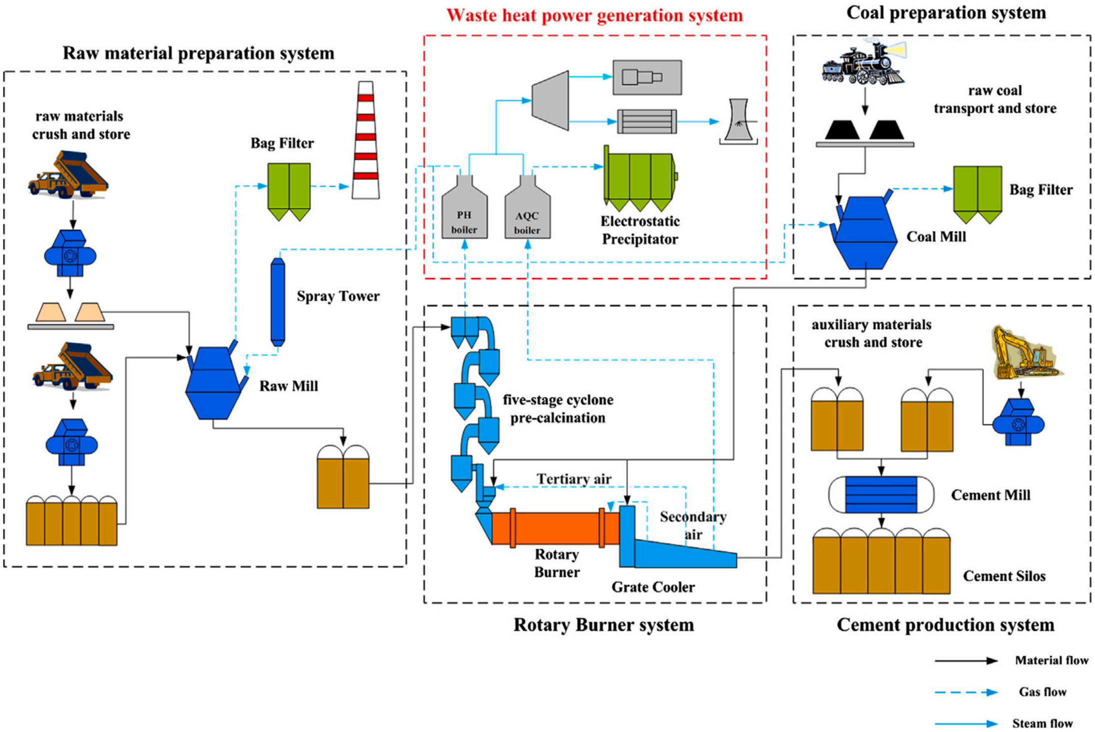

Fig. 4. Arrangement of each form of residual heat recovery applied in [40].

thus guarantee safety. The authors then continued their work in [47], where the absorber was enhanced to an annular shape that allowed the harvesting radiation from the whole cylinder surface. Later, this panel was connected to a thermoelectric generator (TEG) based on Zn_3Sb_4, with a payback time of 3.58 years. Finally, laboratory tests were performed [48]. They found that the outlined TEGs recovery system produced around 87–106 W/m^2, with an investment of 17.6–20.3 $/W.

A mathematical model to estimate the performance of a TEG heat recovery system was developed in [49] and then applied to a 4.8 m diameter, 72 m long rotary kiln. The system is formed by 20 thermoelectric generation units, with 3480 thermoelectric modules of 30 × 30 mm (see Fig. 5). All these modules were arranged longitudinally on a polygonal shell surface coaxial with the rotary kiln. They studied the heat converted into electricity by those thermoelectric modules made of different materials (Bi_2Te_3 and PbTe). They also estimated the heat saved due to the casing of the modules because it functioned as a thermal insulator. According to the authors, approximately 211 kW of electrical power and 3283 kW of heat loss due to insulation could be recovered using this system. In addition, they reported an average thermoelectric conversion efficiency of 2%, and a reduction in heat loss, due to the casing of 32.5%. Total energy savings because of the TEG recovery system was 3494 kW. This represented savings of 3090 tons of coal per year.

The feasibility of recovering radiation waste heat from the shell of a rotary cement kiln (4100 t/d) is presented in [32]. The proposed system used a Vapour Absorption Machine (VAM) to produce chilled water, which can be used for space cooling and cooling the gear sets of heavy machinery in the plant. A VAM does not compress the refrigerant vapour; instead, it dissolves in an absorbent and transfers it to a higher-pressure environment. Vertical radiative heat recovery panels were installed along the combustion zone of the furnace (18 m) with a separation of 0.5 m between the outer casing of the kiln and the inner face of the radiative recovery panel, see Fig. 6. In this area, the shell reaches temperatures between 280 and 300 °C . As a result, there were identified potential savings of 0.79 MJ/t of clinker. The VAM system used had a capacity of 70TR (tons of refrigeration), and total heat recovery was over 70 kW (1680 kWh/day).

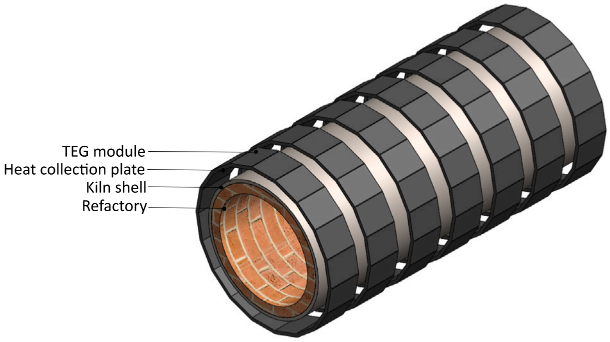

Fig. 5. Configuration of thermoelectric waste heat recovery system presented in [49].

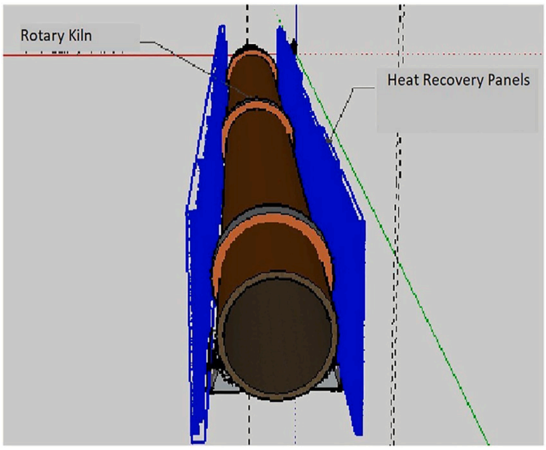

Fig. 6. Vapour Absorption Machine (VAM) presented in [32].

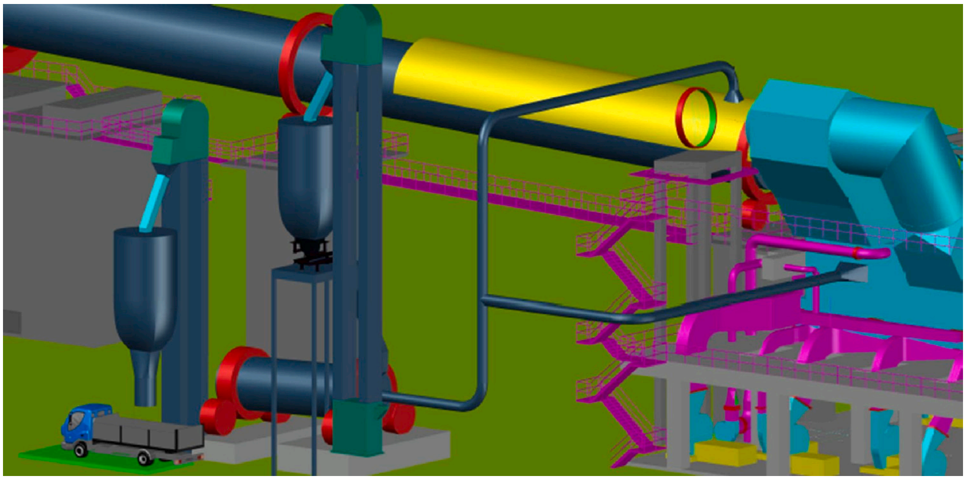

Fig. 7. Radiative heat recovery system presented in [50].

A study to evaluate the potential recover of waste heat from the kiln shell surface to be used for the heat treatment of phosphogypsum is explored in [50] and presented in Fig. 7. The authors proposed a semicircular cover located over the combustion zone of the furnace at 150 mm from the outer casing, with a length of 15 m. The idea was to inject air through one end of the casing using a fan and heat this air to 290 °C because of contact with the hot shell of the kiln. Then, the hot air was removed through a duct to use later to process phosphogypsum. However, the authors argue that the required temperature to complete the phosphogypsum calcination process was between 450 and 550 °C. Therefore, they proposed that additional heat could be obtained from the air used to cool the clinker, which was at 600 °C.

4. Bottoming cycles for waste-heat recovery

Traditionally, in cement production and other intensive-heat industries, waste heat in the gas streams leaving the clinkerization process unused is reclaimed for power generation. For that purpose, different bottoming cycles can be implemented to harvest the waste heat in the effluents [51]. Among the most common bottoming cycles used in industry are found Rankine, Organic Rankine, and Kalina, with different configurations, operating conditions, and working fluids [51]. However, alternatives have recently emerged, such as Trilateral Cycle/Trilateral Flash Cycle (TLC/TFC), super-critical CO_2 cycles, and thermoelectric generators (TEGs). Sections 4.1 tot 4.3 have a brief description of the most relevant cycles for waste-heat recovery systems used in different industries and applications. Also, high-temperature alternatives, such as large-capacity diesel engines usually installed on offshore platforms, could be adapted to the cement process. Additionally, Table 3, in the annexes section, summarises the most relevant work in WHR applied to the Cement industry and related high-intensive industries.

4.1. Traditional Steam Rankine Cycle, ORC, and Kalina

In the traditional power generation cycle, heat generated by different sources (e.g. burning fossil fuel) produces super-heated steam in a boiler fed at high pressure, with an expander/turbine attached to a power generator. This system typically consists of: a fuel firing system, boiler, turbine, condenser, boiler feed pump and cooling towers to cool down the condenser cooling water and send it back into the system [51]. When used for bottoming waste heat recovery, the boiler device in those cycles is replaced with a heat exchanger. That permits waste heat recovery from the stream, leaving the process and transferring it to the working substance. The working fluid of a traditional Rankine Cycle is water, the safest and most environmentally friendly alternative. However, water is limited to applications where the waste heat is at a high-enough temperature, allowing it to be used above saturation conditions [52]. Furthermore, a heat exchanger/boiler design has to be adapted to suit the condition of gases concerning dust burden and the fouling nature of the dust. An interesting and promising design for such a heat exchanger has been developed, which is simpler and cleaner and uses heat pipes [4].

The Organic Rankine Cycle works similarly to the conventional Steam Rankine Cycle but at lower heat source temperatures. That is possible by substituting water with an organic fluid as a working fluid, whether pure or a mixture [53]. Usually, refrigerants or alkanes achieve the super-heated state because of the usual temperature range of waste heat found in production processes [54]. A typical basic ORC constituted by an evaporator, expander, condenser and pump is depicted in Fig. 8. The working fluid within the ORC operates in the saturated/super-heated region so that the expansion never reaches the two-phase dome, protecting the expander from erosion damage. A thorough review of ORC architectures for waste-heat recovery is shown in [55]. Explored configurations include: (1) Recuperated ORC, (2) Regenerative ORC, (3) Organic flash Cycle (OFC), (4) Trilateral Cycle (TLC), (5) Zeotropic Mixtures as ORC working fluids, (6) ORC with multiple evaporation pressures, (7) Vapour injector, re-heater and cascade cycles. It outlines the current advantages of such systems and an overview of the challenges related to advanced ORC configurations. One is its feasibility of generating electricity from low-temperature sources and its consistent design for crew-less operation with little maintenance. Also, further development of this kind of technology has been explored by proposing more complex configurations to increase financial performance.

The optimal evaporation temperature and working fluid for an ORC were estimated for a sub-critical organic cycle in [56]. It should be noted that considerably more net power output is produced when the working fluid's critical temperature approaches the waste-heat source's temperature. Therefore, the research determined R245fa, R123, R601a, n-pentane, R141b and R113 as suitable working fluids for subcritical ORC; the heat source was also at $T = 150$ °C. Evaluating these substances relied on thermodynamic considerations and other criteria like maximum net power output, suitable working pressure, size of the heat exchanger and size of the expander. A genetic algorithm has been used to optimise the thermal efficiency and the specific investment cost of two regenerative ORCs (one-stage and two-stage) [57]. The working fluid R245fa showed the best performance under the operating conditions considered. Furthermore, the authors performed a sensitivity analysis that showed that evaporation pressure dramatically affects thermal efficiency and the specific investment cost of the technologies evaluated. Moreover, a thermodynamic comparison between pure

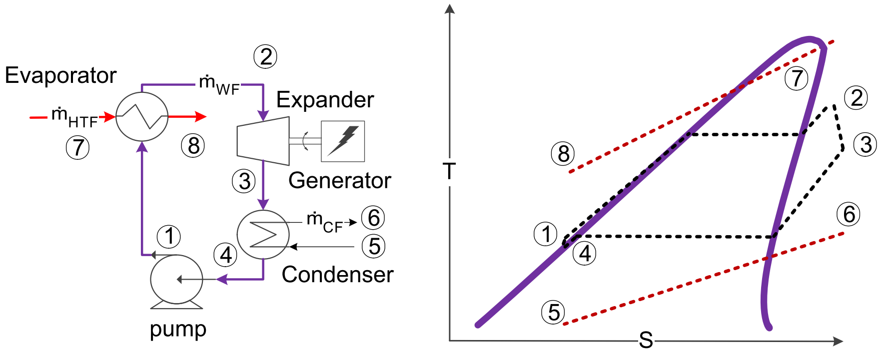

Fig. 8. ORC typical arrangement and $T-S$ diagram [55].

and mixed working fluids of ORCs was executed for low-temperature waste-heat recovery in [58]. Such a comparison was done regarding the proposed alternatives' exergy efficiency and the Levelized Cost of Energy (LCOE). It was found that mixtures are more exergy-efficient but perform worse in their LCOE.

Organic Rankine Cycles (ORCs) are also used in combination with thermochemical cycles to produce electricity and hydrogen simultaneously. Ishaq et al. [59] analyse the performance of a waste heat recovery system that recovers heat from cement slag combined with a copper-chlorine thermochemical cycle for hydrogen production, combined with hydrogen compression and a three-stage reheating Rankine cycle for electricity generation that uses the gaseous oxygen stream resulting from water molecule separation reactions as the heat source. The integrated system's overall energy efficiency was 32.5%, while the corresponding exergy efficiency was 31.8%, with a hydrogen production rate of 19.6 mol/s. The system's overall energy efficiency was 32.5%, while the exergy efficiency was 31.8%. On the other side, a novel waste heat recovery system was designed for the exhaust gases from a 5000 t/d cement plant, which is integrated with a large-scale coal-fired power plant using a Rankine cycle with a generating capacity of 350 MW is presented in [60]. In this hybrid scheme, the captured thermal energy from the cyclone preheater exhaust gases and clinker cooler discharge air of the cement plant is used to heat the partial feedwater of the coal-fired power plant. Consequently, the recovered waste heat is introduced into the coal-fired power plant's Rankine steam cycle and converted into electricity. They evaluated the thermal and economic performance of the proposed design. They found an improvement in the power generated using waste heat of 15.2 MW and an increase in the net thermal efficiency of the waste heat recovery system of 8.11%.

The work developed by Ghalandari et al. [61] analyzes the potential for heat recovery from gas streams in a cement plant through an energy audit that uses mass and energy balances of a pyroprocessing unit with a capacity of 3300 t/d with dry-process rotary kiln technology. The authors present the methodology applied for the system audit. They found that the exhaust gases from the preheater and grate cooler were the main sources of thermal energy loss. They studied the technical and economic feasibility of recovering thermal energy from the pyroprocessing unit's exhaust gases using a Waste Heat Recovery Power Generation (WHRPG) unit with a steam Rankine cycle. They found that the potential for electricity generation was 5.2 MWh, and the rate of return on capital would be around 15% per year, with an investment payback period of 6.67 years.

A comparative thermodynamic analysis of ORC and Kalina (KC) cycles for waste-heat recovery is developed in [62]. Thermodynamic modelling and optimisation are carried out to compare the advantages and disadvantages of both cycles as bottoming cycles for waste-heat recovery from the CGAM cogeneration system (named after the first initials of its researchers: C. Frangopoulos, G. Tsatsaronis, A Valero and M. von Spakovsky). It was concluded that the ORC has a much lower pressure level (11 bar) than the KC (46 bar), bringing advantages for waste-heat recovery compared with the KC. An energy and exergy assessment for modified ORCs is presented in [63]. Modifications include turbine bleeding and regeneration usage. It is found that the latter performs the best, with the highest thermal and exergy efficiencies (i.e., 22.8% and 33.5%, respectively) and the lowest exergy loss. Using computer-aided molecular design techniques, multi-objective thermo-economic optimisation of ORC power systems in waste-heat recovery applications is presented in [64]. The study searched for the optimal working fluids in a sub-critical ORC for different applications and varying heat-source temperatures (T = 150 °C, 250 °C, and 350 °C). When Specific Investment Cost (SIC) was minimised, it was found that the optimal molecular size of the working fluid is related to the heat-source temperature. Optimal working fluids for the temperatures mentioned above are propane ($SIC = 12326$ \$/kW), 2-butane ($SIC = 4919$ \$/kW) and 2-heptene ($SIC = 3543$ \$/kW), respectively. Nevertheless, the optimal fluids changed when mixed-integer nonlinear programming optimisation was applied. For T = 150 °C the best was 1.3-butadiene ($SIC = 11738$ \$/kW), and for T = 250 °C it was 4-methyl-2-pentene ($SIC = 4870$ \$/kW). In a traditional approach, these fluids would not be considered *a priori*.

Alternatives of ORC configurations for low-grade waste-heat recovery were considered in [65]: a two-phase flash expansion (TFC) and an ORC using zeotropic mixtures. TFC showed the most improvement from the ORC baseline, yet the expander efficiency was compromised. A multi-objective thermo-economic optimisation strategy to assess ORCs was applied in [66] to sub-critical and trans-critical cycles for waste-heat recovery. The minimum specific investment cost was used as a financial appraisal criterion in a post-processing step. As a result, the subcritical cycle performs better than the transcritical cycle. Such a result led to a lower payback time but not a higher NPV. Finally, a comprehensive estimate of ORC units for waste-heat recovery in European energy-intensive industries is presented in [67]. This study showed that up to 20,000 GWh of heat could be recovered annually using an ORC to help save 7.6 Mt of CO_2. Furthermore, it was estimated that at least 27 European cement industries analysed could install systems for recovering heat from the gases of the clinker cooler or the preheating cyclones, with more than 576 MW in ORCs.

Multi-criteria exergy-based optimisation of an ORC for waste-heat recovery in the cement industry is depicted in [68]. An ORC with three different working fluids was proposed for cogeneration. This optimisation considered exergy efficiency, cost and environmental impact per exergy unit of the net produced power as the objective functions. An energetic and exergetic optimised Rankine cycle for waste-heat recovery from the chimneys of the Sabzevar cement factory was proposed in [52]. It was found that if the boiler pressure is increased, the recovered energy decreases and the cycle efficiency increases. There was an optimum point at a pressure of 1,398 kPa, where the system's highest energy and exergetic efficiencies were achieved. Additionally, the authors investigated the effects of critical operating parameters, such as condenser pressure, ambient temperature, and maximum cycle temperature. They showed that the optimum boiler pressure is independent; it remained constant, even when the parameters mentioned above were modified.

Multi-objective optimisation and exergo-economic analysis of waste-heat recovery from Tehran's waste-to-energy plant integrated with an Organic Rankine Cycle (ORC) unit is achieved in [69] where the exergy efficiency and total product unit cost at the optimum point are 19.61% and 24.65 $/GJ, respectively. Additionally, a review of turbo-compounding as a waste-heat recovery system for internal combustion engines is presented in [70]. Such technology is equivalent to or even better than traditional bottoming cycles and thermoelectric generators. However, despite its benefits, it still needs to be widely applied to vehicular use. It will flourish among light and heavy-duty engines in the coming decades.

Finally, the feasibility of integrating a waste-heat recovery ORC system into an unconventional energy-intensive application is evaluated in [71]. It is worth mentioning that natural gas compressor stations consume enormous amounts of energy to compensate for the pressure losses in the pipelines that run from the individual producing stations to the users. The energy required generally comes from multiple gas turbines that discharge a significant portion of the primary energy introduced with natural gas into the atmosphere by exhaust gases as waste heat. Therefore, the authors evaluated the ORC designs with recovery with intermediate and direct heat exchange fluids. The results showed that by rehabilitating the gas turbine units, it is possible to generate from 20% to 50% of the mechanical energy the installation uses. Potential energy savings and CO_2 were equal 114 GWh/year and 29.6×10^3 tons/year in the RB211 (Rolls Royce commercial ORC) direct heat exchange configuration. In [72], a cascade absorption heat transformer is proposed to utilise industrial low-grade waste heat. Advanced exergy and exergo-economics analyses were conducted to determine the components' cause and avoidable degree of exergy destruction and cost rates. The research shows that only 21.3% of the exergy destruction rates are avoidable by improvement, while 80.2% of the investment cost rates are from the components themselves.

The thermo-economic performance of a simple ORC and a regenerative ORC, set up under subcritical conditions, using superheating and without, is investigated in [73]. They used it for waste heat recovery from the suspension preheater exhaust gas and the hot air from clinker cooler discharge. The interest was cogeneration in a Brazilian cement plant with a clinker capacity of 6,300 t/d. In that work, the Engineering Equation Solver (EES) software was used to model and optimise the cycles using a genetic algorithm. Initially, they had a list of 25 possible working fluids to use. They selected the fluid based on three criteria. First, fluids with an atmospheric life more significant than 100 years were discarded due to environmental considerations. Fluids with a quality lower than 0.8 at the turbine outlet were discarded to avoid erosion in the turbine blades. Finally, working fluids with a saturation pressure of 35 °C lower than atmospheric pressure were discarded. After applying these, only eight possible working fluids remained. They concluded that the total cost of capital was lower for the cycles evaluated with superheating than those evaluated without superheating. Also, for all the cycles analysed, the recovery time was less than two years, with a net present value between 25 and 32.5 US million and the internal rate of return exceeded 80%/year.

Over the years, there has been extensive research surrounding the ORC. One focus is selecting a suitable working fluid for a particular heat source or application. The other attention has been evaluating different ORC configurations in energy, exergy, and economic aspects. Usually, these categories overlap, as it is common practise to conduct a comprehensive analysis looking at the most satisfactory arrangement for each. These studies develop the best coupling between working fluid and cycle configuration. Some valuable work is presented below for ORCs used in waste-heat recovery, which could be addressed by heat source or application. Section 4.1.1 focuses mainly on low-temperature heat sources, and Section 4.1.2 presents some works about diesel engine effluents as their energy input to the ORC. Section 4.1.3 reports relevant work about the utilisation of solar-thermal energy while Section 4.1.4 depicts small-scale applications.

4.1.1. *Low-temperature*

A comparative assessment of ORC integration for low-temperature (160 °C) geothermal heat source applications appeared in [74]. This study focused on three ORC configurations for optimal operating conditions in terms of maximum exergetic efficiency and lowered specific investment costs. The authors observed that R245fa showed the highest exergetic efficiency (51.3%), corresponding to a minimum specific cost of 2423 $/kW for the base cycle, 53.7% with 2475 $/kW when it had recuperation, and 55.9% with 2567 $/kW for the regenerative cycle. A thorough comparison of TLC, ORC and Kalina cycles was carried out in [75]. This study focused on the thermo-economics of a heat source with a temperature of $T = 120$ °C. The results showed that, for TLC, if the temperature at the inlet of the expander is increased, a more significant amount of net energy is produced and a decrease in its production cost. On the other hand, it was observed that for Kalina and ORC systems, the operating conditions that maximise the net power output differ from the optimal conditions to minimise the cost. The cost estimate was made according to [76], considering the cost rates of the exergy destroyed and using the traditional exergo-economic factor.

A proposal to dynamically update the working fluid of an ORC based on a zeotropic mixture to adapt to changing ambient conditions that affect air-cooled condensers is displayed in [77]. The average thermal efficiency of the cycle was improved by 23% for a heat source at 100 °C. However, it had as a drawback the increased capital cost of up to 7%. The performance evaluation of an ORC module for power applications from low-grade heat sources was done in [78]. Results show that the ORC performances were improved for higher thermal oil temperatures, allowing them to recover more energy, produce more electricity, and achieve better cycle efficiencies, up to 12.32%, for a heat source at 155 °C. A parametric optimisation, and performance analysis, of a waste-heat recovery system from flue gas at $T = 140$ °C was described in [79]. R-12, R123 and R134a were considered for evaluation as suitable working fluids. Results showed that R-123 had the maximum work output and efficiency. The system can generate 19.09 MW at $\eta_{th} = 25.30\%$, which is close to the Carnot cycle efficiency, and a $\eta_{exg} = 64.40\%$.

A super-heated regenerative ORC system for low-temperature (160 °C) waste-heat recovery is presented in [80]. This system relies on an Internal Heat Exchanger (IHE) to preheat the evaporator feed, increasing the average evaporating temperature while the condensation temperature decreases. It was found that for different working fluids, an appropriate degree of super-heating improves working capacity and reduces the VFR, total capital cost, SIC, and LCOE. The best comprehensive performance of the cycle was achieved for n-butane with an optimal evaporation temperature of $T = 100$ °C and a degree of super-heating of 5 °C.

4.1.2. *Diesel engines effluent*

Diesel engine waste heat recovering with an ORC was proposed in [81]. Three organic working fluids were investigated: methanol, toluene and Solkatherm SES36. The system comprises preheater, evaporator, superheater, turbine, pump and two condensers. Methanol was found to have the best thermal performance but the most significant heat transfer area. The best compromise between the size of the heat exchanger and thermodynamic performance was found for Methanol ORC at intermediate temperatures and high pressures. However, flammability and toxicity remain obstacles to its safe implementation. The behaviour of an organic Rankine cycle operating with a zeotropic working fluid was studied with waste heat from a marine engine for an inverse osmosis desalination system in [82]. This study presented an exergo-economic and multi-objective optimisation. Results revealed that at the final optimum design point obtained by the Pareto frontier, the values of the objective functions, i.e., maximisation of the exergy efficiency and minimisation of the total product unit cost of the system, are 37% and 59 $/GJ, respectively.

A thermo-economic analysis and optimisation of a Combined Cooling and Power (CCP) system for engine waste-heat recovery was portrayed in [83]. The developed system comprises a CO_2 Brayton cycle, an ORC, and an ejector refrigeration cycle: cascade waste heat utilisation from an internal combustion engine. Results showed that the increases in the Brayton cycle turbine inlet temperature, the ORC turbine inlet pressure, and the ejector primary flow pressure benefit both the thermodynamic and exergo-economic performances of the CCP system. A thermodynamic analysis and performance optimisation of an ORC-based waste-heat recovery system for marine diesel engines appeared in [84]. In addition, an economic and off-design analysis of the optimised system was conducted. The simulation results revealed that the optimised system is technically feasible and economically attractive.

The exergo-economic analysis and optimisation of new combined power and freshwater system driven by the waste heat of a marine diesel engine are presented in [85]. The optimisation relied on a multi-objective genetic algorithm. It was focused on thermal efficiency, exergetic efficiency and the sum of unit costs of products. The results for the cogeneration system were 91.84%, 24.33% and 192.7 $/GJ, respectively. In addition, cost analyses were carried out as stated in [76]. Finally, an ORC-based waste-heat recovery system was proposed in [86]. The system is coupled with a turbocharged diesel engine propelling a light-duty vehicle. This work studied fuel consumption reduction, energy recovery and CO_2 as the most critical drivers. A case study of waste-heat recovery was displayed in [87] from a large diesel engine exhaust on an offshore platform. This was done by implementing an ORC system using zeotropic mixtures as working fluids. Different configurations of such a power cycle were evaluated regarding exergetic and economic performance. It was found that the highest efficiencies (16.81% energy, 40.75% exergy) were met for the recuperated ORC with a mixture of R236ea/Cyclohexane (0.6/0.4 split). However, most cases achieved the lowest specific investment cost at mass fractions of 0.1 and 0.5. Also, it was higher for the recuperated ORC.

4.1.3. *Solar-thermal*

Solar-power systems based on ORC technology have a significant potential for distributed power generation. A review of the advantages of converting thermal energy from simple, low-cost, non-concentrating or low-concentrating collectors to mechanical, hydraulic or electrical energy is performed in [88]. An assessment of solar-powered organic Rankine cycle systems is portrayed in [89]. This was for combined heating and power in UK domestic applications. Performance calculations were presented for a small-scale Combined Solar Heat and Power (CSHP) system based on an ORC. In addition, annual simulations of the system were carried out. It was found to supply 80–89 W of electricity and around 80% of the total hot water demand for a total system capital cost of £2700–3900. A thorough review of advanced Concentrated Solar Power (CSP) cycles was conducted in [90]. CSP with thermal energy storage is in an excellent position to provide low-cost stability and reliability to the grid; however, higher efficiency and lower costs are critical. Therefore, building knowledge of materials, configuration alternatives, component costs and performance, and demonstration facilities in the next few years is crucial [91]. A working fluid selection and electrical performance optimisation of a domestic solar-ORC combined heat and power system for year-round operation in the UK is presented in [92]. As the main conclusion, the authors identify that generating a continuous average power of 122 W, equivalent to approximately 32% of an average UK home electricity demand, was possible.

4.1.4. *Small scale applications*

A review of ORCs for small-scale applications was presented in [93]. It contains configurations, applications, working fluid selection, modelling and an experimental study of the ORC expansion devices. It is necessary to review the expander as the critical component that differs significantly between small-scale applications to assess low-grade heat and waste heat. A comprehensive review of volumetric expanders for low-grade heat and waste-heat recovery using an organic Rankine cycle is presented in [94]. It included a vane expander, screw expander, scroll expander, and piston expander applications. It was found that screw and scroll expanders are the most promising technologies in the range up to 50 kWe. Additionally, a design methodology for radial turbo-expanders in mobile ORC applications is depicted in [95]. On the other side, the thermo-economic optimisation for a waste-heat recovery using ORC was conducted in [96]. Several working fluids were considered, including R245fa, R123, n-butane, n-pentane, R1234yf and Solkatherm. It was found that economic profitability and thermodynamic efficiency objective functions led to different working conditions and evaporating temperatures for the same fluid. The economic optimum was obtained for n-butane, with a specific cost of about 2320 $/kW and net output power of 4.2 kW. Finally, a thermo-economic optimisation of a small-scale ORC based on screw or piston expanders was conducted in [97]. On this scale, expanders have a better economic performance than traditional turbines. The maximum net-work output found was 17.7 kW. The economic calculations showed a high sensitivity of the return on investment to the value of the electricity produced and the heat-demand intensity. The optimal case was for an energy cost of 0.14 $/kWh with a payback time of 4 years.

4.1.5. *Kalina cycle*

This cycle uses a binary mixture of ammonia water as a working fluid. First, it is evaporated, using the waste heat present in effluent gases, then expanded to generate power in a conventional non-condensing turbine [98]. However, the mixture's molar composition and the cycle's operating conditions could generate the presence of two phases after the evaporator [99]. In such cases, it is necessary to include a two-phase flash separator to route only the saturated/superheated steam to the turbine while the bottoms skip it. Next, its pressure is brought down through a valve [100]. Low-pressure vapour from the turbine is first passed through an intermediate heat exchanger that works as a recuperator where the condensed ammonia-water mixture returning to the boiler is preheated [101].

This cycle has several layouts, each dependent on the number of recuperators used, as explained in [102]. The Kalina cycle is one of the promising options for residual heat recovery. The potential for residual heat recovery of a Brazilian cement plant with a production capacity of 2100 t/d is evaluated in [103]. They studied the effects of changing the water–ammonia ratio and the heat exchanger's pinch point difference on the system's thermoeconomic performance. They also considered the net power output as a function to be optimised. They found a potential for generating 2430 kW, with an energy efficiency of 23% and an exergy efficiency of 48%.

The KC11, shown in Fig. 9 used just one recuperator, being a more straightforward yet powerful setup to recover low-temperature waste-heat according to [75]. A thermodynamic optimisation and analysis of four Kalina cycle layouts for high-temperature applications were performed in [102]. The setup includes a turbine inlet temperature as high as 500 °C, a solar-thermal power plant, and high pressures, over 100 bar. It was found that the most complex layout, KC1234 gives the highest efficiency. A comparative energy and exergy analysis of ORCs or Kalina cycles usage for waste-heat recovery from a hybrid SOFCGT (solid oxide fuel cell/gas turbine) system appeared in [104]. The use of the ORC proved to be better regarding exergy efficiency, 62.35%, (Kalina was 59.53%).

A second law analysis of novel working fluid pairs for waste-heat recovery through a Kalina cycle was carried out in [105]. It was

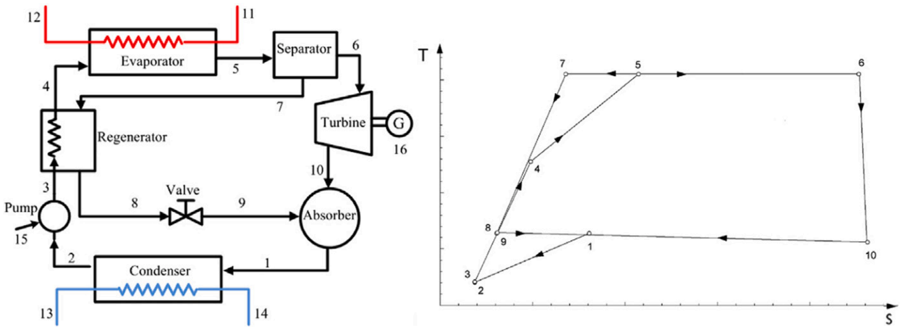

Fig. 9. Kalina cycle, KC11 arrangement and T-S diagram [75].

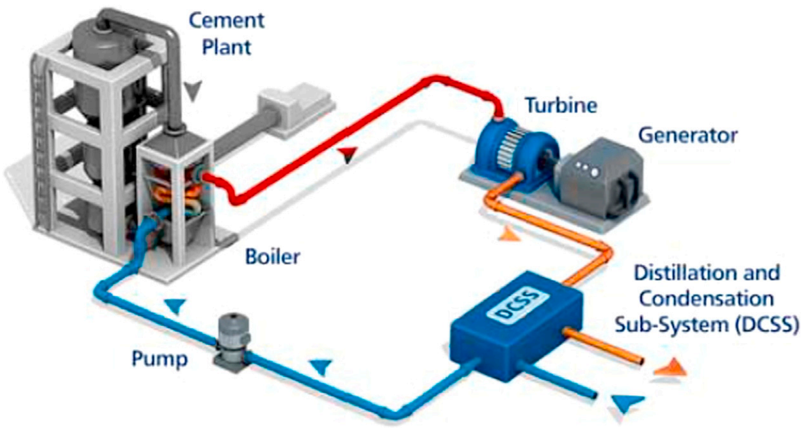

Fig. 10. Idealisation of WHR for electricity generation with Kalina cycle in cement industry shown in [40].

found that the Kalina cycle, using alcohol-alcohol pairings as working fluid performed better than traditional ammonia-water in terms of exergy efficiency for a range of 200 °C–400 °C. However, for those operating conditions, ORCs working with zeotropic mixtures showed better performance and lower complexity than the Kalina cycle. Therefore, ORCs had a more significant potential for waste-heat recovery. A numerical analysis of a composition-adjustable Kalina cycle power plant for power generation from low-temperature geothermal sources is shown in [106]. Such an adjustable composition was introduced to match the changing ambient conditions, improving the cycle's overall thermal efficiency. A thermodynamic performance comparison between ORC and Kalina cycles for multi-stream, close to industrial conditions, waste-heat recovery was carried out in [107]. Once a complex waste-heat source is characterised, it would facilitate the selection of an appropriate power cycle. Thermal efficiency is not recommended as a critical performance metric for waste-heat recovery applications. Therefore, the discussion should focus on achieving the maximum net power output. It would coincide with the maximum heat recovery, although it is not usually at optimal thermal efficiency.

The implementation of a Kalina cycle for converting residual heat into electricity (2.4 MW) from the exhaust gases of the cyclone preheater of a rotary kiln in a Brazilian cement plant was evaluated in [99], as shown in Fig. 10. The authors showed that reducing the pinch point and increasing the ammonia concentration at the evaporator outlet increases the delivered net power. On the other hand, an increase in the turbine inlet pressure can reduce the cost of electricity generated to approximately 0.05 $/kWh. The cycle reached a thermal efficiency of η_{th} = 23.3%, and an exergetic efficiency of η_{exg} = 47.8%. A comparative study of two Kalina cycle configurations (denominated KSC1 and KSC34) was carried out. These cycles used exhaust gases of the cyclone preheater as a waste heat source for electricity generation. The cycles were modelled in the Engineering Equations Solver software and optimised employing a genetic algorithm with net power output and total capital cost as objective functions. The KSC1 was more competitive for larger capacities in daily cement production, specifically, more than 5000 tonnes/d, using a medium-high-temperature heat source. KCS34 was more attractive for smaller capacities and lower-temperature heat sources.

4.2. Organic Rankine Flash Cycle

The Trilateral Cycle, Trilateral Flash Cycle, or Organic Rankine Flash Cycle is commonly abbreviated as TFC or TLC. It has the same components as a conventional ORC. The main difference is that instead of evaporating the working fluid, it brings its state to saturated liquid before expansion [108]. This change generates a two-phase expansion with its pros and cons. The main con is the sophisticated design of the expander, which has to handle both the large mass flows of the TFC and two phases, preventing the usage of conventional turbo-expanders. However, promising technologies for two-phase expansion have been appearing. Twin-screw expanders are an example. They are especially suited due to their "positive displacement" nature and ability to operate at high speed without losing efficiency [109]. On the other hand, the TFC is characterised by higher pumping power and larger heat exchangers than ORC. This has, as a consequence, an increase in construction costs. Nevertheless, this is compensated by the higher power generation [110]. Also, TFC cannot operate at supercritical temperatures with no saturated liquid phase.

A TLC, as portrayed in Fig. 11, was especially suitable for low-temperature applications since it has higher power output than other bottoming cycles. [111] presented a packaged, plug & play power unit for low-grade waste-heat recovery applications. This system was based on a TFC suitable for waste-heat sources at temperatures below 100 °C. R1233zd(E) and R245fa were considered the most suitable working

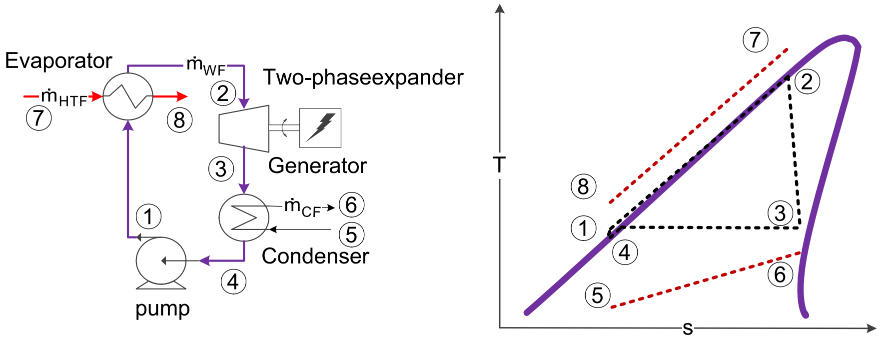

Fig. 11. TLC typical arrangement and T-S diagram [55].

fluids for that application. The designed TFC system was expected to recover 120 kWe, with an overall efficiency of 6%. The efficiency analysis of trilateral-cycle power systems for waste-heat recovery applications was performed in [112]. Results showed that a simple TLC, a recuperated TLC, a reheat TLC and a regenerative TLC, operating at sub-critical conditions, with a cycle high temperature of 200 °C, could attain thermal efficiencies of 21.97%, 23.91%, 22.07%, and 22.9%, respectively. Furthermore, an analysis of a combined TFC/ORC waste-heat recovery system was presented in [113]. Results showed a peak thermal efficiency of 24.2% and exergy efficiency of 63.2%. Finally, the thermodynamic potential of twelve working fluids in Rankine and flash cycles for waste-heat recovery in heavy-duty diesel engines was explored in [114]. It was found that there is a better cycle, in terms of net power delivered, for each waste-heat source.

4.3. *Other alternatives for waste-heat recovery*

Although cycles in sub-critical conditions are the most widely used for the recovery of waste heat, there are other strategies, like super-critical cycles Section 4.3.1, and devices such as thermoelectric generators Section 4.3.2, that are under active development.

4.3.1. *Super-critical power cycles*

A review of the supercritical CO_2 Brayton power cycle technology and their potential applications to the next generation nuclear reactors was developed in [115]. The advantages of this cycle may be summed up in the high efficiency in its mild turbine inlet temperature region and a small physical footprint with a compact layout. In [116] appeared an optimisation of a combined supercritical CO_2 cycle and ORC using zeotropic mixtures for gas turbine waste-heat recovery. The zeotropic mixtures used included Cyclo-Pentane/R365mfc. The results showed overall values of the exergo-economic factor, the optimal exergy efficiency and the optimal unit cost of electricity of this system of 31.88%, 62.23%, and 0.0395 USD/kWh, respectively. A case study applied to Mochovce 3 nuclear power plant to a heat source at a maximum temperature of 299 °C was carried out in [117]. A supercritical recompressed reheated regenerative CO_2 cycle would yield a net efficiency of 34.04%, similar to the 33.51% net efficiency of the existing Rankine cycle. However, the complete turbo set (2 turbines, 1 pump and 1 compressor) would be less than 11 m in length (versus two wet steam turbines of 22 m each for the same power), resulting in a reduction factor of 10 of the plant's footprint.

A thermodynamic analysis of a supercritical/trans-critical CO_2 based waste-heat recovery cycle for shipboard power and cooling applications appeared in [118]. This system could enhance power output by about 18%, increasing the efficiency of the shipboard system by 11%. An exergo-economic analysis of utilising a transcritical CO_2 cycle and an ORC for a recompression supercritical CO_2 cycle waste-heat recovery was developed in [119]. The two combined cogeneration cycles were examined, and it was found that their second-law efficiencies were comparable. However, the ORC had a slightly better economic performance. Performance comparison and parametric optimisation were made in [120]. A subcritical ORC and a transcritical power cycle are used in a low-temperature geothermal heat source (i.e. 80–100 °C). Five indicators were analysed: Levelized Cost of Energy (LCOE), thermal, exergy and recovery efficiency, and heat exchanger area per power unit. The results showed that R123, in a subcritical ORC system, obtained the highest thermal and exergetic efficiency, η_{th} = 11.1% and η_{th} = 54.1% respectively. The transcritical cycle performed better with R125, with a recovery efficiency 20.7% higher. Also, its LCOE value was relatively low. On the other hand, the transcritical cycle provided more significant savings in oil consumption and emissions of CO_2.

4.3.2. *Thermoelectric generators*

A review summarising the thermoelectric phenomena, applications, and parameter relationships, providing enough elements for a discussion about possible future strategies to further thermoelectric performance enhancement, is presented in [121]. Additionally, a review of applications for thermoelectric generators was presented in [122]. Such devices allow lost thermal energy to be recovered, energy to be produced in extreme environments, electric power to be generated in remote areas, micro-sensors to be powered, and direct solar-thermal energy use for power generation. A comprehensive approximation of the rare-earth elements recycling alternatives and sources to assess a zero-waste, product-centric valorisation scheme was portrayed in [123]. Further, a review of car waste-heat recovery systems utilising thermoelectric generators and heat pipes was found in [124]. Here, the internal combustion engine's efficiency is improved by including such devices that increase their reliability due to being solid-state, passive, silent, scalable, and durable. Although promising, TEGs must overcome limitations to develop their many potential applications. Potential applications of thermoelectric plastics and trends in this field are carefully summarised in [125].

A high-performance, low-cost n-type, Mg_3Sb_2-based, thermoelectric material with multi-valley conduction bands was described in [126]. Additionally, a high-temperature and high-power-density nanostructured thermoelectric generator for automotive waste-heat recovery was presented in [127]. An uncoupled device generates a high power density of 5.26 W/cm^2 with a 500 °C temperature difference between hot and cold sides. A 1 kW TEG system was experimentally demonstrated by recovering waste exhaust heat from an automotive diesel engine. This TEG system operated with a 2.1% heat-to-electricity efficiency and an average temperature difference of 339 °C between the hot- and cold-side surfaces at a 550 °C exhaust temperature. Performance analysis of a waste-heat recovery thermoelectric generation system was presented in [128]. This system was for automotive applications, which recovered heat from an exhaust pipe and turned it into electricity. A "Four-TEGs" system was designed and tested in a prototype vehicle with a maximum power delivered of 944 W. Another vehicle exhaust waste-heat recovery system based on thermoelectric generators was presented in [129]. The dynamic mode's influence was considered, finding that a higher

Table 2
Annual cement production, energy recovery potential and emission savings potential of CO_2 in the main producers in Latin America.

Country	Cement production (Mtonnes/y)	CO_2 production (Mtonnes/y)	Total thermal requirement (TJ/y)	Total Lost Heat kiln (TJ/y)	10% Utilisation (GWh/y)	Emission factor electricity $(\frac{TonnesCO_2}{MWh\cdot y})$	Potential to save CO_2 emissions $(\frac{MTonnesCO_2}{y})$
Brasil	54.4	29.4	244.8	99.9	2773.9	0.07	0.21
México	39.9	21.5	179.6	73.3	2034.9	0.45	0.91
Colombia	13.0	7.0	58.5	23.9	662.7	0.21	0.14
Argentina	11.1	6.0	49.9	20.3	565.2	0.31	0.18
Perú	10.6	5.7	47.6	19.4	539.3	0.42	0.23
Ecuador	6.3	3.4	28.2	11.5	319.8	0.34	0.11
Total	135.2	73.0	608.4	248.2	6895.8	–	1.8

start-up current could speed up the dynamic response of the TEG to reach steady-state operation. Other parameters, such as vehicle speed and ambient temperatures, were also explored. A simultaneous power generation and heat recovery application using a heat pipe-assisted thermoelectric generator were depicted in [130]. Modelling results showed that the HP-TEG system could recover 1.345 kW of waste-heat and generate 10.39 W of electrical power using eight installed Bismuth Telluride (Bi_2Te_3) based TEGs.

A comparison and parameter optimisation of a segmented thermoelectric generator was developed in [131]. Two cases for the generator were analysed: one used low-temperature thermoelectric material Bismuth Telluride, and the other medium-temperature thermoelectric material skutterudite. The waste heat source was a high-temperature exhaust of a diesel engine. The model simulated the impact of relevant factors, like exhaust temperature, cold source temperature, thermocouple length, and the length ratio between the two materials, on the output power and conversion efficiency. Results showed that the segmented TEG had more significant waste-heat recovery potential than the traditional TEG. Further, nanostructures of high-temperature thermoelectric materials were reviewed for waste-heat recovery in [132]. It discussed the potential heat resources for thermoelectric conversion and recent material, process, and technology progress. Finally, a solar concentrating solar-TEG system was presented in [133] with a peak efficiency of 7.4%.

5. Methodology

This work aims to summarise the context of residual heat recovery in the cement industry, focusing on technologies particularly suitable for improving process efficiency and overall plant performance. Therefore, it begins with a literature review covering the cement manufacturing process and the mass and energy balances presented in that process to identify areas with significant energy losses. Subsequently, a review is carried out of the different technologies for recovering residual heat in the cement industry for gas effluents and radiation. Some bottoming cycles for residual heat recovery are described, starting with the Organic Rankine Cycle and Kalina cycles, covering less common processes such as the Organic Rankine Flash Cycle and other alternatives such as supercritical power cycles and thermoelectric generators. Finally, a systematic discussion is presented regarding residual heat recovery. This section evaluates the potential for residual heat recovery in the cement industry in the six leading producers in Latin America Table 2, based on the thermal and electrical requirements reported in the literature and the potential for CO_2 emissions savings considering the emission factor for each country's electrical system. The column's content of Table 2 is as follows:

- Column 1: Countries that account for 82% of cement production in Latin America.
- Column 2: Corresponds to cement production for the Latin American countries that account for 82% of production [134].
- Column 3: CO_2 generation based on annual cement production, considering an emission factor (EmF) of 0.54 tons of CO_2 per ton of cement [135], given as

$$\mathrm{CO_2}\ production = EmF * Cement\ production \tag{1}$$

- Column 4: Total thermal requirement for annual production using a specific thermal energy consumption factor per ton of cement (TeF) ranging from 4 to 5 GJ/ton [136]; an intermediate TeF of 4.5 GJ/ton was used.

$$Total\ thermal\ requirement = \mathrm{TeF} * Cement\ production \tag{2}$$

- Column 5: Estimated heat losses in the kiln, knowing that 80% of the total thermal energy of the process is used [32] and that 51% of this energy is converted into residual heat [136].

$$Total\ lost\ heat\ kiln = 0.8 * 0.51 * Total\ thermal\ requirement \tag{3}$$

- Column 6: Energy (electrical) generated in GWh if 10% of the residual heat from the kiln was used.

$$Electric\ power\ generated = Total\ lost\ heat\ kiln * 0.1 \tag{4}$$

- Column 7: Emission factors of the electrical systems (EmE) of each country taken from [137–140].
- Column 8: Potential for CO_2 emission savings using each country's specific emission factors.

$$Potential\ to\ save\ \mathrm{CO_2}\ emissions = Electric\ power\ generated * EmE \tag{5}$$

6. Discussion

Once the trend shown by all the information collected in Sections 2 to 3 has been studied, the authors address what, in their opinion, corresponds to the current context and the future of waste-heat recovery in the cement industry. There are many possibilities regarding waste-heat recovery and electricity generation from thermal sources of different origins, such as fossil fuels, solar-thermal, waste-heat, and nuclear energy. Depending on the heat source being accessed, the appropriate technology must be selected to allow the maximum use of such heat in terms of energy, exergy, and economics. In this sense, even though all the cases present their exclusive subtleties, it is valid to affirm that the most widely used technology for the recovery of waste heat is the implementation of a power cycle with those effluents of a medium-high degree of temperature. However, although ORC is the most widespread, a whole set of alternatives is found in different places of maturity that point to more specific sectors or temperature ranges. It was found that the Kalina cycle and the TFC overlap with the ORC for low-grade waste-heat recovery, the ORC overlaps with the steam Rankine cycle for medium-grade heat recovery, and novel alternatives with adequate performance in a wide temperature range, such as CO_2 cycles and thermoelectric generators. However, the immaturity of the latter forces a delay in their implementation on an industrial scale, lagging largely behind until sufficient technological advances are made to guarantee their complete reliability and profitability. Research to overcome the current limitations of such technologies is highly active due to their promising capabilities and wide applications.

Now, it is essential to note that the discussion focuses on mitigating harmful environmental effects caused by CO_2 emissions in the

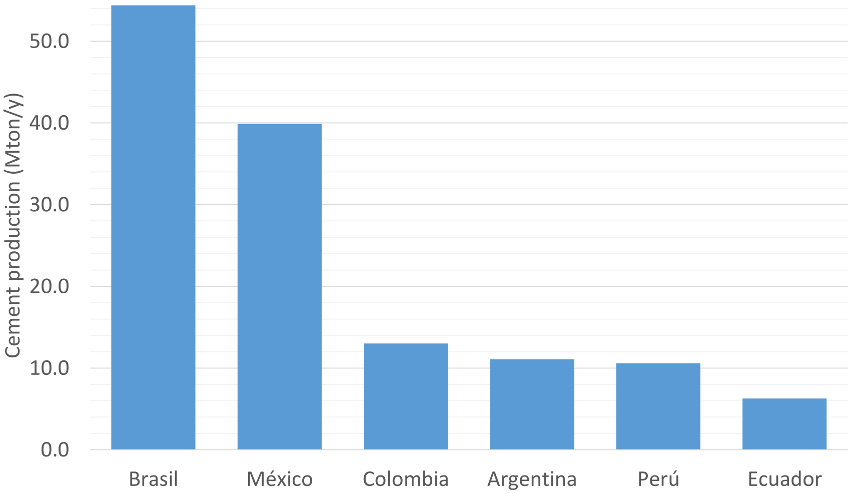

Fig. 12. Cement production in the main producing countries of Latin America for the year 2019 [134].

cement industry and other energy-intensive industries (see Fig. 13). Under this consideration, waste heat usage contributes positively to this goal. Other strategies include using novel raw materials with a lower carbon footprint, advanced processing technologies, or acceptable energy use. Regarding waste energy, those streams that leave the production process towards the environment are valuable targets for implementing waste-heat recovery systems. In this sense, those streams can be exploited using the technologies discussed above, whether they are mass or radiation fluxes. In general, the direct use of heat in preheating or drying applications is well established in the design of existing plants. However, options can be explored when the reliability of the production process should be increased or when a technical or regulatory restriction has been imposed. Despite its simplicity, the direct application of waste heat has given space to the indirect use for the generation of electricity that can become comparatively more expensive; ergo, potential savings could be higher.

Table 3 summarises relevant works on waste heat recovery that can be applied in the cement industry. The table provides information on the temperatures at which the technologies were evaluated, the type of technology, the working fluid, the energy recovered, the associated costs and energy efficiency. A range of efficiencies was observed that goes from 1.34% for thermoelectric generators (the least efficient) to 25.3% for steam Rankine cycles (the most efficient). The Kalina cycles reported efficiencies up to 23.5%, and the ORC reported efficiencies up to 16.8%. However, the implementation and selection of each of these technologies do not only depend on its energy efficiency but also depend on the temperature range of the heat source, the type of waste heat source, the technology and capacity of the plant, the availability and amount of waste heat, among other parameters. On the other side, the performance of different configurations of Rankine organic cycles and the possibility of directly using heat with a drying unit that acts as a kiln feed preheater had been evaluated [38]. It was noted that none of the drying units presented a positive net present value since the unit cost of fuel saved in the kiln was less than the unit cost of electricity due to electricity prices in Colombia. Regardless, some benefits can be gained when using a drying unit that cannot be directly quantified, such as increasing available grinding capacity by feeding drier material into the mill.

Finally, the aim of this study covers a comprehensive study of waste heat recovery technologies focused on the cement industry; from the data collected in the comprehensive review, the potential for waste heat recovery to generate electricity in the Latin American cement industry was estimated, as well as a potential for reducing carbon emissions taking into account the emission factors of the electrical system of each country. The cement industry is a crucial activity in many Latin American countries, so assessing the potential for waste heat recovery in the region is particularly important, aiming to reduce greenhouse gas emissions and improve the industry’s competitiveness in the region by reducing operating costs. In addition, providing cement companies with an estimate of the savings potential may lead to their interest in investing in waste heat recovery technologies to increase their energy efficiency.

6.1. *Potential use of waste heat in the kiln in Latin America*

The most energy-intensive process during cement production is clinkerization. In this process, the energy required is approximately 80% of the thermal energy used [32]. Approximately half of this energy is lost to the environment, either by radiation through the exposed surfaces of the equipment or within gaseous effluents [136]. Additionally, the specific thermal energy consumption per cement tonne ranges between 4 and 5 GJ/tonne. The specific consumption of electrical energy ranges between 88–141 kWh/tonne [30,141]. Fig. 12 shows the annual cement production of the six principal Latin American producing countries in millions of tonnes for 2019 [134]. These countries account for 82% of the total cement production in the region. Brazil is in the lead with 54.4 million tonnes per year, followed by Mexico and Colombia with 39.9 and 13 million tonnes per year, respectively. However, the cement industry in Latin America and the Caribbean (29 countries) only contributes 5% of world cement production [142]. Countries like China produce more than 50% of the world’s cement [143].

It is essential to understand the great potential for recovery of residual heat that the cement industry presents to begin applying techniques or technologies to recover this heat, either for direct use or for electricity generation. In this sense, if only 10% of the thermal energy lost during the clinkerization process (6895.8 GWh/y) were used in these six Latin American countries to generate electricity, and to consider a specific consumption of electrical energy per tonnes of cement (88–141 kWh/tonnes) reported in [30], it is possible to satisfy between 36% and 58% of the plant’s power requirement. This value is close to that estimated by [34], which says that if the heat from the gaseous effluents of a cement plant were used, it would be possible to supply up to 30% of the electrical requirement of the process. However, the previously calculated value is higher since it considers the total energy losses, including radiation and convection losses on the kiln walls.

6.2. *Barriers to the implementation of waste heat recovery technologies*

The implementation of heat recovery technologies in the Latin American cement industry may face specific barriers that must be

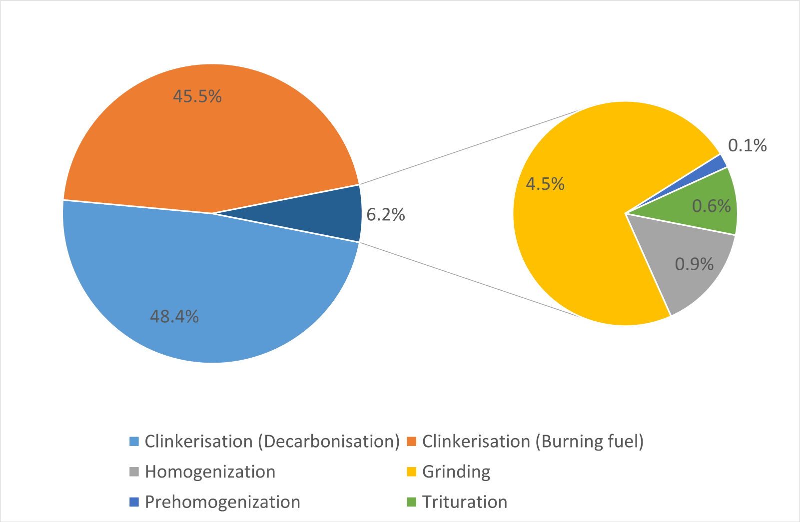

Fig. 13. Direct CO_2 emissions by process. Total emissions 0.8 tCO_2/t cement [144].

overcome to achieve broader adoption. Some of these barriers are presented in the following sections.

6.2.1. *Investment costs*

Implementing waste heat recovery technologies in the cement industry may require a significant initial investment. Moreover, the complexity of the cement industry processes makes waste heat recovery technologies implementation even more costly. Therefore, companies may only invest in these technologies if they see a clear and quick return on investment. [59].

6.2.2. *Lax environmental regulations*

In many Latin American countries, environmental regulations for the cement industry may need to be revised or better enforced, which can decrease companies' motivation to invest in waste heat recovery technologies [145].

6.2.3. *Lack of incentives*

Governments and companies often need to offer adequate incentives for adopting waste heat recovery technologies. Incentives, such as subsidies and tax exemptions, can help reduce investment costs and make the adoption of these technologies more attractive to companies [146].

It becomes essential for governments to incentivise energy efficiency measures through fiscal policies, tax benefits, or recognitions. These can come from both public policies and private initiatives. An example could be the energy efficiency award given in Colombia [147]. This award aims to recognise commitment and actions taken in energy efficiency through projects that demonstrate results over the past three years. Also, in Colombia, the law 1715 [148] establishes a series of benefits for companies that implement energy efficiency measures such as:

- Income tax deduction: Companies can deduct up to 50% of the investment in energy efficiency projects from income tax. This deduction can be made in a fiscal year or over several years.
- Exemption from sales tax (IVA): Goods and services necessary for implementing energy efficiency projects are exempt from sales tax.
- Accelerated depreciation: Equipment and machinery intended for implementing energy efficiency projects can be depreciated at an accelerated rate, allowing for a greater deduction from income tax.
- Tariff reduction: Imported equipment and machinery intended to implement energy efficiency projects may be exempt from tariff payments.

6.2.4. *Lack of trained personnel*

Implementing and operating waste heat recovery technologies may require trained and experienced personnel, which can be challenging to find in some regions. The lack of trained personnel can limit companies' capacity to implement and operate these technologies effectively.

6.2.5. *Resistance to change*

Companies may hesitate to change their established production processes and adopt new technologies. Resistance to change may be due to concerns about the impact on production and product quality, as well as uncertainty about the profitability of the investment. To overcome these barriers, measures such as offering incentives for the adoption of waste heat recovery technologies, promoting research and development of industry-specific technologies, fostering collaboration between governments, organisations, and companies to address regulatory and financial barriers, and providing technical training for equipment maintenance and repair can be taken. Additionally, raising awareness about the importance of environmental sustainability and the long-term benefits of waste-heat-recovery technology implementation in the cement industry is important to help overcome resistance to change.

7. Conclusions

Conducting studies that estimate the potential for recovering waste heat in the Latin American cement industry is relevant because this is an energy-intensive industrial activity, which makes it highly dependent on external energy sources and a significant source of greenhouse gas emissions, especially CO_2. Therefore, any improvement in this industry's energy efficiency could significantly impact reducing emissions and mitigating climate change. Furthermore, since a large part of the cement production process involves generating and dissipating heat, recovering waste heat can provide an essential source of thermal energy for other uses within the plant. Additionally, the cement industry is a crucial activity in many Latin American countries, making it particularly important to evaluate the potential for recovering waste heat in the region. This could help reduce greenhouse gas emissions and improve the industry's competitiveness in the region by reducing energy costs. Furthermore, providing cement companies with an estimate of the potential for savings may generate their interest in investing in waste heat recovery technologies to increase their energy efficiency.

Techniques and technologies have been developed over the years to improve the energy efficiency of processes with high thermal requirements as governments create policies related to climate change. Regarding the energy requirement for the cement industry, it is estimated that

Table 3
Summary of relevant work on waste-heat recovery.

#	Reference	Analysis type	Industrial sector	Heat source	Heat source temperature
1	[35,36]	Exergo-economic	Cement		
2	[52]	Energy + Exergy	Cement	Chimney exhaust	315–380~°C
3	[99]	Energy + Exergy	Cement	Exhaust gas	390~°C
4	[79]	Energy + Exergy	Power plant	Flue gas	140~°C
5	[96]	Exergo-economic	Generic	Exhaust gas	180~°C
6	[120]	Exergo-economic	Power plant	Geothermal	80–100~°C
7	[56]	Energy	Generic	Generic waste-heat	150~°C
8	[67]	Review	Energy intensive industries Cement	Generic waste-heat Generic waste-heat	-
9	[57]	Exergo-economic	Generic	Generic waste-heat	–
10	[66]	Exergo-economic	Generic	Exhaust gas	180~°C
11	[75]	Exergo-economic	Generic	Hot water	120~°C
12	[74]	Exergo-economic	Power plant	Geothermal	160~°C
13	[87]	Exergo-economic	Offshore	Exhaust gas	425~°C
14	[80]	Exergo-economic	Generic	Flue gas	160~°C
15	[97]	Exergo-economic	Generic	Exhaust gas	570~°C
16	[64]	Exergo-economic	Generic	Generic	150/250/350~°C
17	[71]	Energy	Natural gas	Stack exhaust	150~°C
18	[85]	Exergo-economic	Marine	Exhaust gas	300~°C
19	[37]	Exergo-economic	Ceramics	–	–
20	[41]	Energy + Exergy	Cement	Kiln surface radiation	200–350~°C
31	[44]	Energy + Exergy	Cement	Kiln surface radiation	200–350~°C
32	[46–48]	Exergo-economic	Cement	Kiln surface radiation	500~°C

#	Reference	Technology	Working fluid	Potential savings	Costs	Efficiency
1	[35,36]	–	–	71.87~MW Energy lost through the shell of the kiln and pyroprocessing tower. system of the plant	–	–
2	[52]	Rankine	Steam	4.25~MW net work.	–	16.0%
3	[99]	Kalina	Ammonia-water	2.4~MW net work.	–	23.3%
4	[79]	ORC	R123	19.09~MW net work.	–	25.3%
5	[96]	ORC	n-butane	4.2~kW net work.	2320~\USD/kW	8.4%
6	[120]	ORC	R123 (sub), R125 (trans)	5.4–7.9~kW net work.	LEC = 0.062-0.056~USD/kWh	11.1%, 8.9%
7	[56]	ORC	R114	9.61~kW net work.	–	-
8	[67]	ORC	–	20000~GWh/year of thermal power in European energy intensive industries.	–	-
		ORC	–	576~MW in European preheating cyclones or clinker cooler gases.	–	9.4%
9	[57]	ORC	R245fa	30–120~kW net work.	3453~USD/kW	-
10	[66]	ORC	R245fa (sub), R245fa (trans)	791.5–1040~W net work.	4707–8137~euro/kW	10.2%, 7.2%, 9.5%
11	[75]	ORC/TLC/Kalina	n-butane/R152a/Ammonia-water	1816/1557/1321~kW net work.	17.7/23.55/18.65~USD/GJ	11.6%
12	[74]	ORC	R245fa	79.77~kW net work.	2423~USD/kW	14.5%
13	[87]	ORC	Zeotropic mixture of R236ea/Cyclohexane	72.86~kW net work.	9240–10480~USD/kW	-
14	[80]	ORC	n-butane	120~kW net work.	6000~USD/kW	15.0%
15	[97]	ORC	acetone	17.7~kW net work.	1630~euro/kWh	-
16	[64]	ORC	1-butene/2-pentene/2-heptene	27.9/96/221,2~kW net work.	10369/4124/4560~\textsterling/kWh	16.8%
17	[71]	ORC	Cyclo-Pentane	6955~kW net work.	NPV = 12.9 MUSD, PB = 8 years.	10.7%
18	[85]	APC (Kalina)	Ammonia-water	431.9~kW net work.	sum unit cost of product = 192.7~USD/GJ	-
19	[37]	–	–	126.366–191.703~MJ/h improvement potential rate.	53.38–135.83~MW/USD thermodynamic loss to capital cost ratio.	-
20	[41]	Insulation	–	12.5~MW loss. Savings of 271.78 MJ per ton of clinker production when insulated.	–	-
31	[44]	–	–	71–194~kW required shell heat loss	–	-
32	[48]	TEGs	–	3867~W net work.	20.424 USD/W	1.34%

it consumes between 2% and 8% of total energy consumption in the world, with a specific thermal energy consumption of 2.94–6.28 GJ and 65–141 kWh of electrical energy for each tonne of cement produced.

Large thermal requirements are also associated with significant energy losses due to any energy transformation or use process. In the case of cement production through a dry process, these losses reach up to 45.6% of the required thermal energy. It is essential to understand this great potential for recovery of residual heat that this industry presents so that techniques or elements for the recovery of this heat can begin to be applied, either for direct use or for the generation of electricity.

Since the competitiveness of a cement production plant is directly related to the energy efficiency of its processes, waste heat recovery technologies must continue to be introduced and applied in this industry. In the case of heat recovery from gaseous effluents, technologies such as Kalina cycles and ORC cycles are quite mature technologies. Those technologies have been widely studied for all types of industries. However, technologies to harness radiation, such as thermoelectric generators, still have low energy conversion efficiencies compared to other waste heat recovery technologies.

The reduction potential of emissions related to electricity generation of the Latin American cement-producing countries was calculated. It showed a reduction potential of 1.8 million tonnes of CO_2 per year. Additionally, it was calculated that using 10% of energy losses satisfies between 36% and 58% of the energy requirement of a cement plant. That value is close to the estimate by [34] that says that if the heat from the gaseous effluents of a cement plant were used, it would be possible to supply up to 30% of the electrical requirement of the process.

Finally, regarding CO_2 emissions from the primary energy-intensive industries, the cement industry is the second highest worldwide with 25% of emissions, surpassed only by the steel industry with 27%. Among the processes associated with cement production, clinkerization is the one that contributes the most to direct emissions of CO_2. 48.4% of emissions from this process are associated with the calcium carbonate decarbonisation reaction ($CaCO_3$), and another 45.5% is associated with the burning of fuels to provide the necessary energy for the said endothermic reaction.

CRediT authorship contribution statement

Carlos A. Marenco-Porto: Validation, Investigation, Software, Investigation, Writing – original draft. **José J. Fierro:** Validation, Investigation, Software, Investigation, Writing – original draft. **César Nieto-Londoño:** Conceptualization, Investigation, Methodology, Supervision, Project administration, Funding acquisition, Writing – review & editing. **Leonardo Lopera:** Conceptualization, Methodology, Writing – review & editing. **Ana Escudero-Atehortua:** Conceptualization, Methodology, Writing – review & editing. **Mauricio Giraldo:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Hussam Jouhara:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

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Appendix. Summary of relevant work on waste-heat recovery

See Table 3.

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