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Review

Review on Energy Efficiency Progresses, Technologies and Strategies in the Ceramic Sector Focusing on Waste Heat Recovery

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Abstract: Thermal processes represent a considerable part of the total energy consumption in manufacturing industry, in sectors such as steel, aluminium, cement, ceramic and glass, among others. It can even be the predominant type of energy consumption in some sectors. High thermal energy processes are mostly associated to high thermal losses, (commonly denominated as waste heat), reinforcing the need for waste heat recovery (WHR) strategies. WHR has therefore been identified as a relevant solution to increase energy efficiency in industrial thermal applications, namely in energy intensive consumers. The ceramic sector is a clear example within the manufacturing industry mainly due to the fuel consumption required for the following processes: firing, drying and spray drying. This paper reviews studies on energy efficiency improvement measures including WHR practices applied to the ceramic sector. This focuses on technologies and strategies which have significant potential to promote energy savings and carbon emissions reduction. The measures have been grouped into three main categories: (i) equipment level; (ii) plant level; and (iii) outer plant level. Some examples include: (i) high efficiency burners; (ii) hot air recycling from kilns to other processes and installation of heat exchangers; and (iii) installation of gas turbine for combined heat and power (CHP). It is observed that energy efficiency solutions allow savings up to 50–60% in the case of high efficiency burners; 15% energy savings for hot air recycling solutions and 30% in the when gas turbines are considered for CHP. Limitations to the implementation of some measures have been identified such as the high investment costs associated, for instance, with certain heat exchangers as well as the corrosive nature of certain available exhaust heat.

Keywords: waste heat recovery; energy efficiency; ceramic industry; thermal processes

1. Introduction

Industrial processes are overall associated to high energy consumption and industry holds about 25% of the final energy consumption in European Union (EU) [1]. Some industrial thermal processes require a significant energy demand and are usually associated with considerable heat losses (waste heat) [2]. In the EU, thermal energy can reach 70% of the total energy use [3]. Waste heat has been estimated to represent from 20 to 50% of overall industrial energy consumption [4] in the United States. In the EU, its potential for reuse means about 300 TWh/year, representing around 17% of the industrial energy consumption for process heat and 10% of the total industrial energy consumption [5]. In the prospect to improve the energy efficiency of industrial thermal processes, several sets of practices related to waste heat recovery (WHR) have been proposed and implemented [6].

The implementation of innovative measures for energy efficiency improvement reveals as a potential field of research to attain not only for the reduction in energy consumption but also in achieving clean and low carbon objectives regarding sustainability at the EU and worldwide level [6]. In this prospect, the adoption of a consistent energy management, in addition to the practices related to industrial symbiosis [7], the promotion of eco-efficiency [8] and the use of alternative fuels coming from renewable sources, attractive in energy-intensive sectors to reduce environmental impacts without compromising the technical requirements in the involved processes [9,10] are relevant to improve energy efficiency and promote sustainability in industry.

The ceramic industry is an energy intensive sector, similar to the steel, cement and glass industries [11]. A reference document for the best available techniques (BAT) is available in the EU for the ceramic industry [12] and its revision is currently ongoing. Overall, the improvement opportunities in this sector range from waste heat recovery, for which examples are given in [13], equipment optimisation examples are demonstrated in [14], and those for the use of renewable energy are expressed in [15]. The framework of energy efficiency improvement measures within the ceramic sector have been studied. However, as most recent studies have been focusing on the progresses achieved until the end of the 1990s [16], such frameworks are outdated. Furthermore, generalist studies have been performed for the framework of WHR technologies in the industry [17]. An updated review on energy efficiency technologies and strategies is therefore required for framing the most recent technological developments for energy efficiency improvement within the operation of ceramic industry plants, namely improvements at the equipment level, plant level and outer plant level for energy valorisation and cleaner thermal processes.

This paper aimed to review the most prominent energy efficiency technologies and strategies in the ceramic sector, focusing on waste heat recovery (WHR) and performing an analysis of improvements at the equipment level, plant level and outer plant level. This was set to establish a benchmark for the analysis of thermal processes in the ceramic industry, the assessment of energy efficiency improvement potential and the selection of the most favourable strategies for the distribution of waste heat within the plant processes attending to each process energy requirements.

2. Description of the Ceramic Sector

According to data from the European ceramic industry association, Ceramie-Unie (C-U) [18], the ceramic industry is an overall export-oriented sector (the EU exports 30% of its total production), it encompasses around 2000 companies, and it has an annual production value of EUR 30 billion. As an energy intensive sector, its competitiveness is highly dependent on fuel prices. Therefore, cost effective strategies that increase energy efficiency and reduce carbon emissions will highly improve both the environment and ceramic production costs.

The ceramic sector is categorised into several subsectors. A classification considered in the BAT reference document [12] considers the following subsectors: tiles (including *roof* and *wall and floor*); refractories; abrasives; household: technical and sanitaryware. There are also other subsectors with minor sales turnover and energy consumption (including *vitrified clay pipes* and *expanded clay aggregates*). The ceramic industry may also be characterised regarding sales turnover and energy consumption. Figure 1 presents the distribution of sales turnover for each subsector of the ceramic industry.

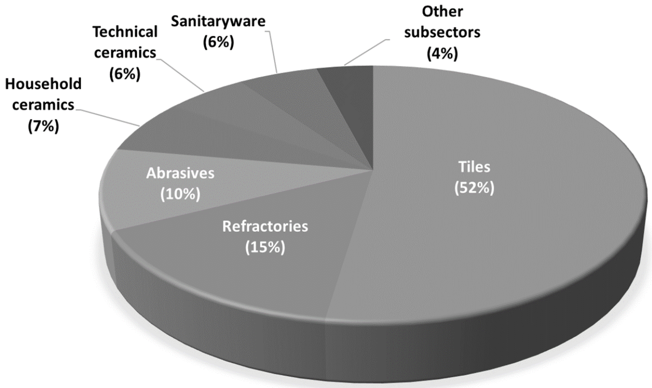


Figure 1. Distribution of the sales turnover in the ceramic industry in Europe considering the reference year 2015 (data gathered from [12,19,20]).

The energy use within a ceramic plant is highly significant, representing about 30% of the overall production costs [21], which accounts for the evidence that the ceramic industry is an energy intensive sector. In terms of the distribution between the subsectors, the tiles production represents 80% of the total energy consumption in the ceramic industry [21]. Considering this and considering the data present in Figure 1, it is possible to verify that the tile manufacturing industry is the most representative subsector in terms of sales turnover and energy consumption.

3. Characterisation of Thermal Processes in the Ceramic Industry

The ceramic production includes several processes: material storage, mixture and preparation, shaping (extrusion or pressing), drying, glazing, firing, quality check, and packaging [16]. The intensive energy consumption in a ceramic production plant is mainly related to processes of firing, drying and spray drying [22]. In most ceramic subsectors, the specific fuel consumption (per tonne of produced ceramic material) is superior to the electric energy consumption [23], which is for instance due to the operation of these energy intensive thermal processes. The firing process is at the highest energy consumption level, due to the high annual operational times of the kilns and consequent high operational temperatures [22]. Figure 2 presents the distribution of thermal energy consumption per process for the ceramic tile manufacturing industry—the most significant ceramic subsector.

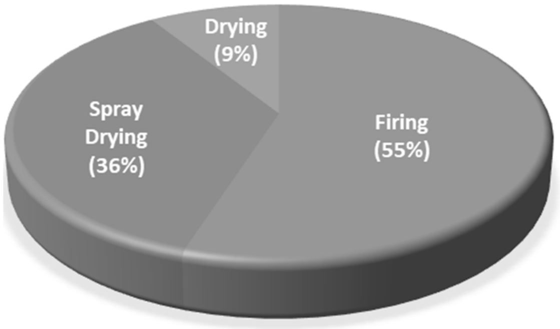


Figure 2. Distribution of thermal energy consumption for each thermal process in the tiles manufacturing subsector (adapted from [24]).

The firing process is operated in ceramic kilns, including tunnel kilns [24], rotary kilns [16], roller kilns [25] and intermittent kilns [26]. Tunnel kilns are continuous kilns, in which the products to be fired, are transported in kiln cars, being normally open at the inlet and the outlet while heating occurs at the centre [24]. Rotary kilns use the process of calcination to heat up products in continuous operation [16], while roller kilns are constituted by a refractory roller conveyor for the transportation of products through a hot tunnel, enabling fast firing in rapid cycles [25]. Intermittent kilns are closed kilns, operating in discontinuous operation, and a schedule exists for the increase in temperature within the kiln [26]. The drying process may also occur in several types of dryers, which include vertical and horizontal dryers [27]. The tunnel dryer is an example of a horizontal dryer with a continuous operation [28]. In vertical dryers, the product is transported vertically within the dryer and is shaped by the press as it is placed into beds [29]. Figure 3 presents the most energy consuming operations in a ceramic plant, namely tunnel kiln, roller kiln, tunnel dryer and spray dryer.

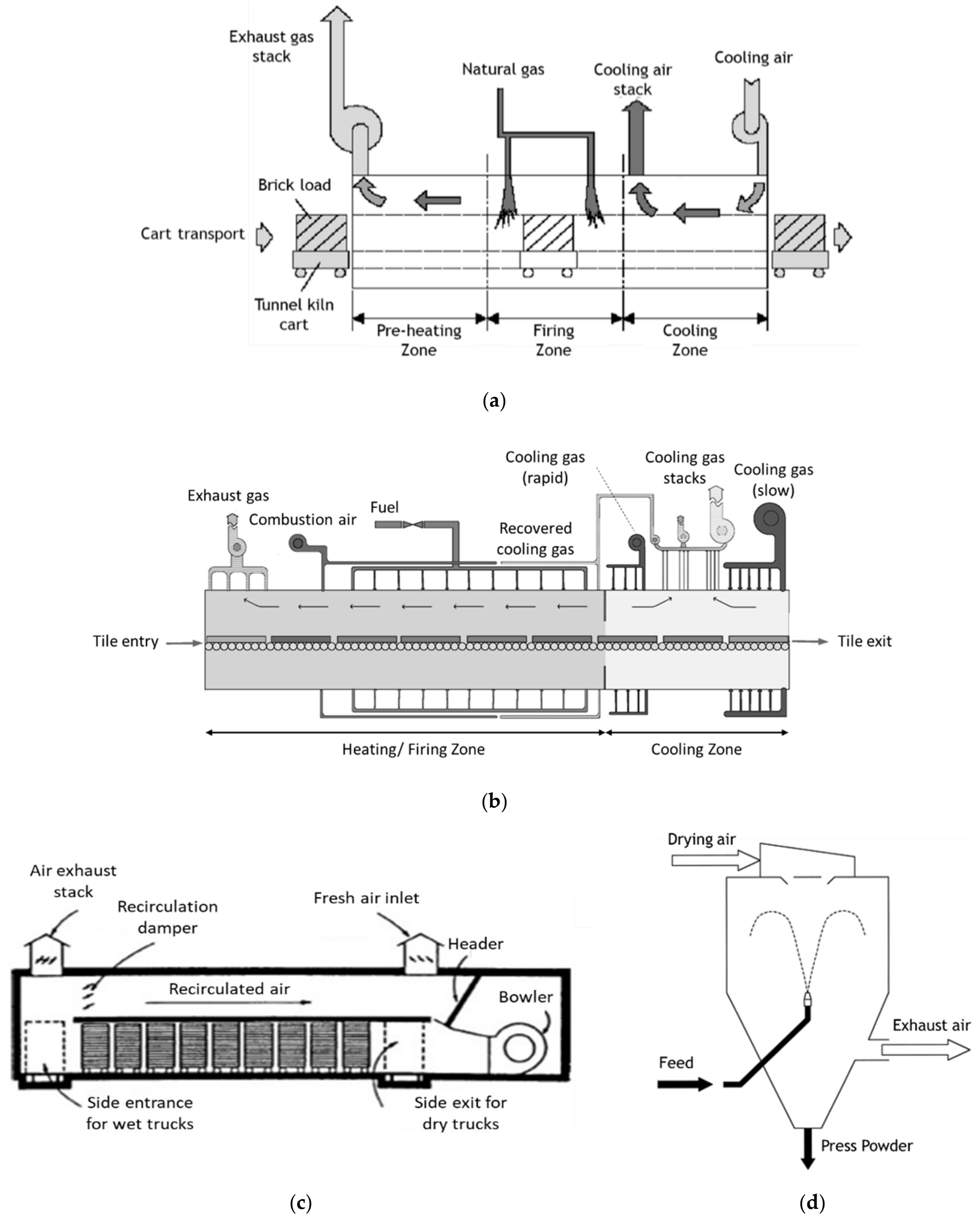


Figure 3. (**a**) Scheme of the operation of a tunnel kiln; (**b**) scheme of the operation of a roller kiln; (**c**) scheme of the operation of a tunnel dryer; and (**d**) scheme of the operation of a spray dryer (adapted from [28,30–32]).

In the prospect of the improvement opportunities in ceramic thermal processes, several authors investigated the operation of tunnel kilns, intermittent kilns, rotary kilns and roller kilns, dryers and spray dryers. Such studies were based on the performance of mass and enthalpy balances [24,29], which were complemented by exergy analysis—applied to identify irreversibility to assess improvement opportunities [25,29,33] and thermal analysis—applied to identify potential improvements in heat transfer [26]. The performance of global balances to a process may be used to quantify the overall waste heat in a thermal process, and thus WHR opportunities. Considering the values presented by Mezquita et al. [24], it is possible to observe the heat losses associated to each stream of a ceramic kiln, as presented in Figure 4.

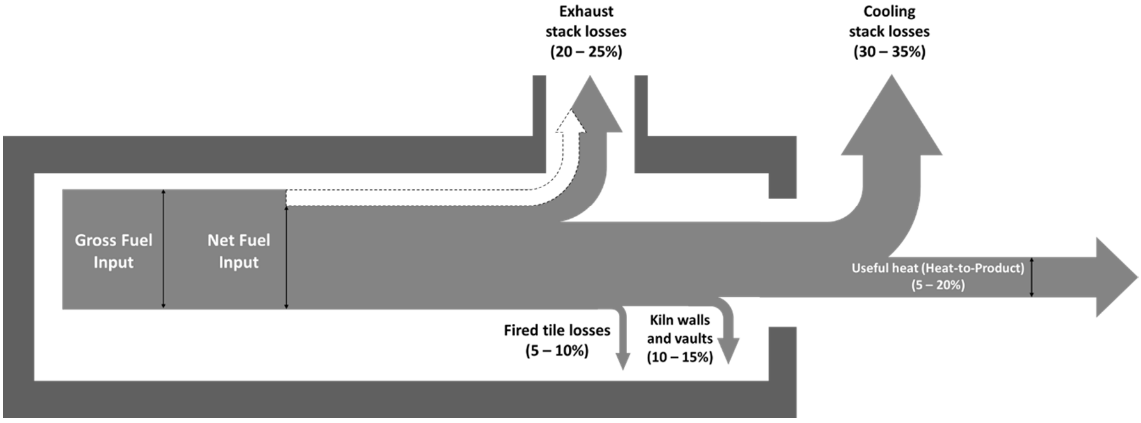


Figure 4. Thermal energy losses in ceramic kiln (adapted from [24,34]).

While a quantification of typical heat losses for the remaining thermal processes, such as drying and spray drying, remain to be performed, practical studies to quantify the energy inputs and outputs of specific dryers and spray dryers can be found in the literature [32,33].

4. Framework of Waste Heat Recovery for Industrial Applications

Industrial thermal energy is primarily generated by fuel combustion in different processes. Electric energy may also generate waste heat from compressing and grinding operations [35]. In both systems, high amounts of heat are lost to the environment, mainly heat losses in equipment and heat losses in exhaust gas stacks [4]. The implementation of WHR technologies and strategies make use of such waste heat to obtain several associated benefits [24], such as: reduction in energy consumption and associated CO_2 emissions; reduction in manufacturing costs; increase in company competitiveness; reduction in resource consumption and the associated environmental impacts, contributing to a low carbon economy. Several authors have been exploring the application of WHR technologies and strategies in the industry in general and in specific industrial sectors, exploring all its aspects and its framework within the area of energy efficiency. Table 1 presents the foremost progresses within the study of industrial WHR, studied by several authors, covering its contextualisation, optimisation through modelling and techno-economic assessment.

Table 1. Progresses in industrial waste heat recovery (WHR) research.

Categories	Progresses	Reference
Contextualisation of industrial WHR	Framework of WHR in industry contextualising opportunities, energy management, WHR technologies and industrial sectors.	[17,36–41]
WHR technologies	Description of WHR technologies applied in industry.	[42–72]
Optimisation and modelling of industrial WHR	Framework of smart energy systems and decision support tool development within the context of industrial WHR and the application of model-based approaches.	[73–76]
Practical achievements of WHR implementation	Design and application of several technologies and the assessment of achievements of WHR implementation, namely energy savings, economic savings and return on investment.	[77–80]
WHR-based industrial symbiosis	Framework of WHR within the practical implementation of industrial symbiosis, namely through the use of waste heat to fill demand at another industrial site or be integrated into district heating network.	[81–90]

According to Papapetrou et al. [5], Jouhara et al. [17] and Bruckner et al. [90], WHR technologies may be classified following their temperature range: high temperature (HT), medium temperature (MT) and low temperature (LT) as detailed in Table 2. Each category is also differentiated according to the origin of the waste heat, following Jouhara et al. [17]. While HT technologies are applied directly in combustion processes, MT technologies are applied to reuse the waste heat from exhaust gases and LT technologies are applied to use the waste heat from the products and equipment. The share over the total waste heat presented in Table 2 corresponds to the representativity of low-grade, medium-grade and high-grade waste heat over the total waste heat potential in the EU (300 TWh/year) [5].

Table 2. Classification of WHR technologies.

WHR Type	Temperature Range [5]	Temperature Range [17]	Origin of Waste Heat [17]	Share Over Total Waste Heat [5,90]
High temperature (HT)	Above 500 °C	Above 400 °C	Direct combustion processes	42%
Medium temperature (MT)	200–500 °C	100–400 °C	Exhaust of combustion units	25%
Low temperature (LT)	Below 200 °C	Below 100 °C	Products and the equipment of process units	33%

5. Energy Efficiency Technologies and Strategies in the Ceramic Sector

The energy efficiency improvement opportunities in the ceramic sector include the optimisation of equipment performance, the use of material streams with considerable waste heat potential and the use of alternative fuels and renewable energy resources. Although opportunities are centred on processes of firing, drying and spray drying, improvement measures, in particular WHR technologies and strategies, may also be recovered from these processes to other thermal processes (such as boilers) and to produce electric energy. A summary on the progress of energy efficiency improvement in the ceramic sector focusing on WHR is presented in Table 3. The progress is categorised into energy efficiency improvement, the analysis of flow phenomena in thermal processes, modelling and the optimisation of thermal process and plants, the implementation of WHR strategies, WHR-based electricity generation, the use of alternative fuels and renewable energy resources and the application of water and energy integration.

Table 3. Progresses on research on energy efficiency improvement in the ceramic sector.

Categories	Progresses	Ref.
Best practices and limitations	Description of several types of best practices for energy efficiency improvement, with a focus on the different ceramic industry subsectors, ceramic plant operations and barriers for the implementation of measures.	[16,41,91–104]
Application of state-of-the-art technologies	Study on the application of energy efficiency technologies in the case of the ceramic plants.	[105–111]
Analysis of flow phenomena in thermal processes	Numerical analysis of the thermal and hydraulic phenomena occurring in kilns, dryers and spray dryers, focusing on assessments based on the optimisation of air flow rates and heat transfer.	[112–118]
Modelling and optimisation of thermal process and plants	Development of models which describe the specific thermal processes of a ceramic plant (more incidentally tunnel kilns) and the application of optimisation methods to improve the operation of plants.	[119–121]
Implementation of WHR strategies	Research on the implementation of several types of WHR strategies in ceramic industry plants and assessment of the performance of the new WHR systems.	[122–133]
WHR-based electricity generation	Implementation of WHR technologies and strategies for the production of electric energy.	[134–136]
Use of alternative fuels and renewable energy resources	Change in the operation of combustion processes to use alternative fuels (biogas, synthetic or bio-methane, syngas and hydrogen) and use of renewable energy resources (such as concentrated solar thermal energy) to generate thermal energy.	[137–158]
Application of water and energy integration	Application of WHR strategies related to process integration, involving pinch analysis application for several plant streams and the assessment of potential water and energy savings.	[159,160]
Framework of industrial symbiosis	Analysis of the potential for industrial symbiosis in industrial sites including ceramic plants, encompassing potential inputs from other plants to be used as waste heat sources in a ceramic plant.	[161–163]

In the following section, several energy efficiency technologies and strategies for the ceramic industry are presented, in three sub-sections: Equipment-Level Technologies and Strategies (Sub-Section 5.1), Plant-level Technologies and Strategies (Sub-Section 5.2) and Outer-Plant Systems (Sub-Section 5.3).

5.1. Equipment-Level Technologies and Strategies

The improvement of energy efficiency in a ceramic plant may be performed by the optimisation of the equipment operation. Authors have pointed in a generalist manner a set of best practices to be performed in a ceramic thermal processes [27,31,102,118] including: the automatic control of operational conditions (temperature and humidity); installation of fans in the zones of dryers with higher independent thermal contributions; improvement of thermal insulation of kilns by the application of refractory layers; control of the excess air at the inlet and outlet of kilns; automatic control of the kiln combustion regime; use of the kiln preheating zone to complete the drying and maximisation of the batch and continuous process synchronisation in the production flow. In this section, several technologies and strategies for the improvement of the operation of a ceramic plant's processes (kilns, dryers and spray dryers) are presented. These technologies and strategies are described in Table 4 into two main findings: technical; and energy and economic aspects.

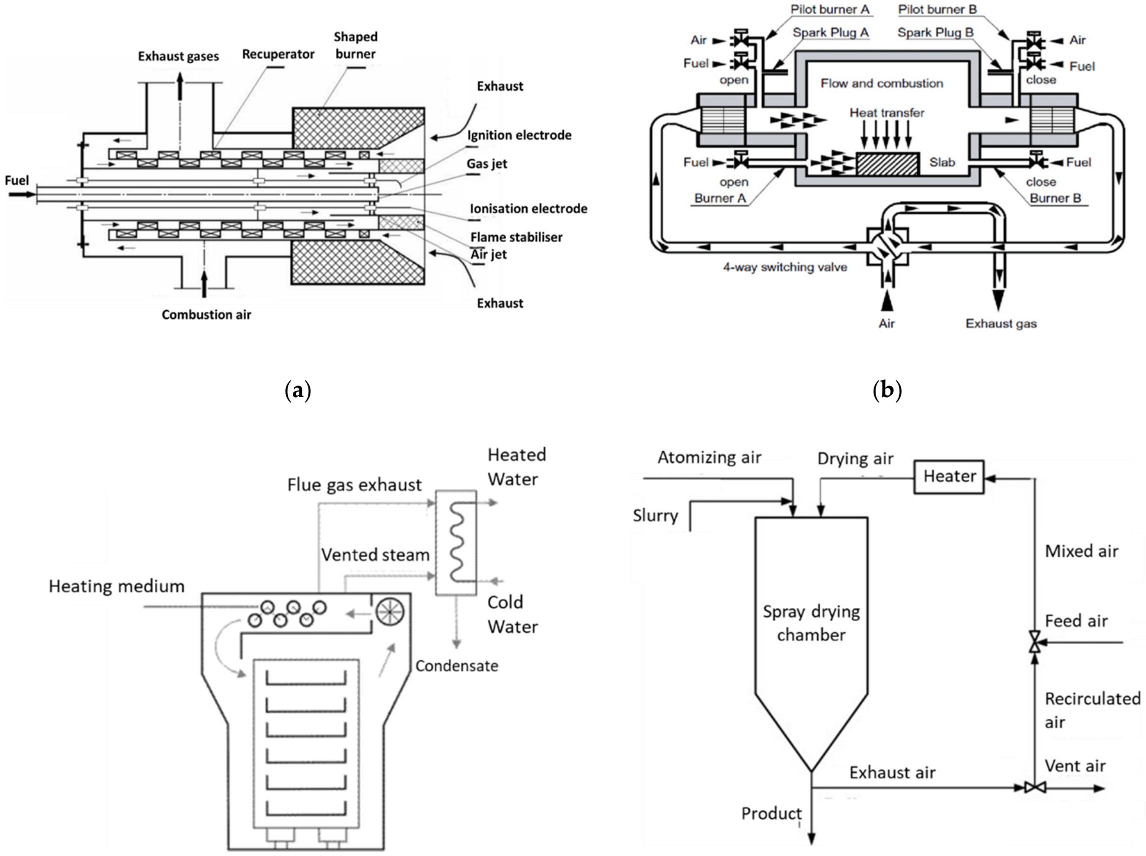
Table 4. Description of equipment-level technologies and strategies.

Measure	Main Findings		Reference
	Technical Aspects	**Energy and Economic Aspects**	
High-efficiency burners	New high efficient burners designed to allow preheating the combustion air with the exhaust gases (examples include self-recuperative and regenerative burners); these burners can replace old burners in ceramic tunnel kilns [105] and roller kilns [118] improving the fuel consumption.	Firing efficiency improvement by approximately 10% [45]; fuel savings of 25–30% in self-recuperative burners [47] and 50–60% in regenerative burners [46].	[42–50,105,118]
Microwave assisted firing and drying	The microwave processing has been studied for the drying and firing (sintering) of some ceramics; microwave applied for sintering of ceramics was identified to be a very interesting alternative achieving finer microstructure, improved mechanical properties, with lower processing times and energy consumption [106].	Eight times reduction in firing time leading to fuel savings [51]; 7–30 times reduction in drying time leading to fuel savings [95].	[51,95,106]
Kiln cars and furniture with low thermal mass	Use of low thermal mass (LTM) kiln cars to decrease the thermal energy requirement for the heating of supporting refractories; they offer similar strength and stability comparative to traditional construction materials with the advantage of having lower running costs, repairs, downtime and maintenance [52,53]; LTM materials include Si_3N_4 and SiC [111].	A 70% reduction in thermal mass leading to fuel savings [52].	[51–53,111]
Airless drying	While in a conventional dryer the vapour is lost to the environment with the outlet air stream, in here, it is made use of the steam as the heat transfer medium; the steam presents a higher specific heat and thermal conductivity relative to air, thus improving heat transfer [107]; this allows improving overheat control, the minimisation of the risk of explosion, avoidance of secondary contamination and an overall improved control system.	From 20 to 50% thermal energy savings and reduction in the drying time [107].	[54,55,107]
Controlled drying air recirculation	Use of more advanced ventilation systems, in which the control of the drying parameters is improved; the inlet and outlet air temperatures are maintained, while the drying agent recirculation coefficient increases (lowering the share of new air) by optimising the air flow and convention, and high energy savings are achieved [126]; due to variations in the evaporation rate, investment costs are highly variable.	Energy savings of 25% [96].	[96,126]

Table 4. *Cont.*

Measure	Main Findings		Reference
	Technical Aspects	Energy and Economic Aspects	
Controlled dehumidification	The water that condenses within the chamber releases its latent heat to be supplied to the drying process; this system is completely closed, and thus, highly energy-efficient [128].	Typical energy savings of 80%.	[128]
Hot air recycling as combustion air in the kiln	The hot air from the cooling zone of a kiln may be used as preheated combustion air in the kiln's combustion chamber; thermal shock caused by high temperature airflow may be reduced by the mixture of hot air and air at ambient temperature [30].	From 15 to 30% fuel savings [126]; payback time is negligible [117].	[24,30,117,122,123,126]
Exhaust air recirculation in spray dryers	The exhaust air of a spray dryer may be recycled to the process as drying air [124]. An air preheater may be installed in the recirculation process to further use the waste heat from the exhaust air stream [125]; within the recirculation process, the exhaust air stream is divided into a recirculated air stream and a vent air stream (which is purged), with the recirculated air stream being then mixed with ambient air in order to achieve the required drying air moisture content.	From 50 to 61% in energy savings [125].	[124,125]
Use of alternative fuels	Fossil fuels (such as natural gas) may be substituted by alternative fuels which supply the same amount of heat; alternate fuels include biogas [136–141] and hydrogen (pure, mixed or syngas) [142–149]; for hydrogen, its injection is feasible in existing gas networks [150–153] and it is the best choice for at-scale decarbonisation, being produced at high grade heat [154].	A 30% supply of energy input in a process (biogas) [142];and 80–100% supply of energy input in a process (hydrogen) [154].	[136–154]
Improvements at ceramic slip and design	New ceramic materials and product design have been developed in recent years to reduce ceramic weight, energy consumption and production cost; such materials are developed considering: product design that require less raw material and firing times, new material compositions incorporating pore-forming agents (such as carbon nanotubes) and incorporating residues to produce thermal energy [164,165]; additives such as incineration ashes, waste glass and low sintering clays contribute to lower sintering temperatures or lighter ceramics with identical mechanical properties [165].	A 15% increase in material porosity leading to increased water absorption and decreasing compressive strength, and thus considerable energy savings in the drying phase [164].	[164,165]

In Figure 5, the description of the operation of the technologies and strategies identified in Table 4 are presented, namely high efficiency burners, airless drying and exhaust air recirculation in spray dryers.



(**a**) (**b**)

(**c**) (**d**)

Figure 5. (**a**) Description of a self-recuperative burner; (**b**) description of a regenerative burner; (**c**) description of an airless drying operation; and (**d**) the description of exhaust air recirculation in a spray dryer (adapted from [42,43,54,124]).

5.2. Plant-Level Technologies and Strategies

The improvement of energy efficiency in a ceramic plant may be also performed by the application of several technologies and strategies. In these sections, several plant-level technologies and strategies are presented (Table 5).

Table 5. Description of plant-level technologies and strategies.

Measure	**Main Findings**		**Ref.**
	Technical Aspects	**Energy and Economic Aspects**	
Hot air recycling between kilns	Similar to the hot air recycling in a kiln, the hot air from the cooling zone of a kiln may be used and mixed as preheated combustion air in other kilns of the plant [117]; the more adequate use for a recovered heat air stream is the one that allows to recover the higher thermal energy from that stream (having the lowest thermal loss: that is the closest matching heating need).	From 15 to 30% in fuel savings [126]; payback time is negligible [117].	[117,126,129]
Hot air recycling as drying air	The hot air from the cooling zone of kilns may be used as an additional heat source in dryers; commonly implemented when part of the hot air is already recovered to the combustion chamber of kilns and a remaining part is recycled to the dryers [117]; in the case the hot air stream has a sufficient waste heat potential, the operation may be converted to disable the need to consume fuel [117].		
Drying air preheating	Installation of air–gas heat exchangers to heat up an air stream to be used as an additional heat source in a dryer may be alternatively performed instead of direct hot air recycling; this may be performed by either using the exhaust gas streams or hot air streams from the cooling zone of kilns [108]; the heat pipe heat exchanger is a typical air preheater type used for this application, due to its associated high heat transfer capability and economic viability [108].	About 110 dam^3/year fuel savings [108]; payback time of 2 years [108].	[78,79,108]
Phase change material Thermal energy storage (PCM–TES)	Implementation of a thermal energy storage-based phase change material unit for the preheating of combustion air at the inlet of a furnace; the air stream is heated in an air–gas heat exchanger followed by the PCM unit.	Fuel savings of 570 MWh/year [132].	[132,133]
Water heating and preheating	Exhaust gases from stacks of a kiln (either exhaust gas or hot air from the cooling zone) may be used to heat up a water stream in an water–gas heat exchanger, such as the water stream at the inlet of a boiler.	Fuel savings of 3.1 MWh/year; payback time less than a year [74].	[74,80,117]
Inertising	Drying stage is eliminated, with energy savings being achieved through the use of dry grinding instead of wet grinding [98]; the inertising operation has a common duration of 10–15 min, using a maximum operation temperature of 900 °C and allows the use of raw materials of worse quality [98].	Overall energy savings of 40% [97].	[97,98]
Use of dry route for raw material preparation	Substitution of the wet route by a dry route for the preparation of raw materials.	74% water savings; 78% fuel savings; 36% electricity savings [104].	[104]
Use of concentrated solar thermal energy	Concentrated solar power (CSP) technologies include solar dish, parabolic trough, and solar power towers; the solar radiation may be used to produce a valuable heat stream with temperatures up to 70–320 °C [155]; the CSP systems may be integrated or adapted to the existing heating systems [156–158], with the drying processes being pointed for potential application.	Compensate 10% of industrial energy demand [155].	[155–158]

In Figure 6, the flowsheets of some of the WHR strategies and process integration within a plant are presented. In the flowsheet presented in Figure 6, previously published by the authors [123], it is observable that the project of the implementation of a plant-level WHR strategy encompassing the most energy-consuming processes of the plant, contemplating the hot air recycling from the cooling zone of the kilns as combustion air between kilns and as drying air and the use of the waste heat potential from exhaust gas streams in a water–gas heat exchanger.

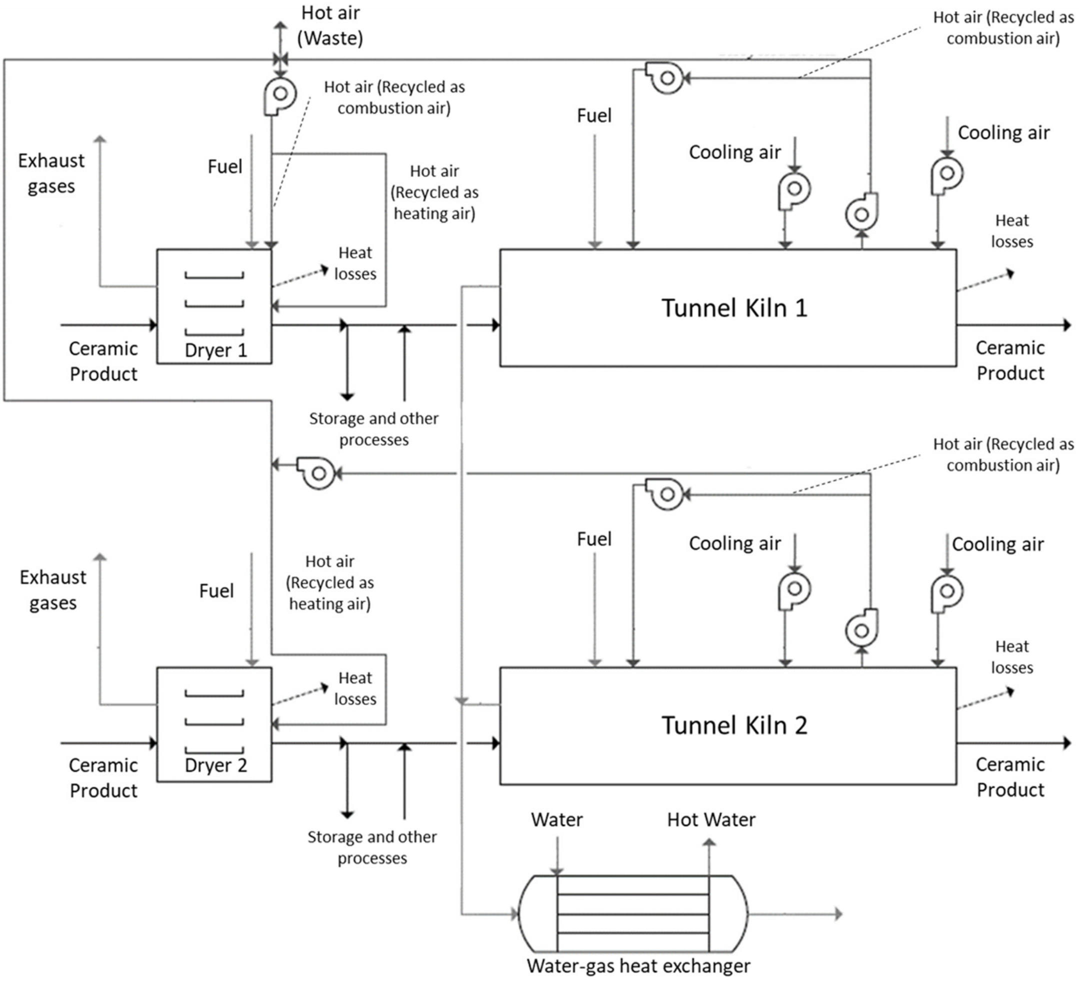


Figure 6. Flowsheet of an integrated WHR strategy encompassing hot air recycling from tunnel kilns' cooling zone to the respective combustion chambers and to two dryers and the use of an economiser (adapted from [117]).

In the ceramic sector, for plant-level technologies and strategies, two main types of heat exchangers can be installed, namely water–gas heat exchangers (also called economisers) and air–gas heat exchangers (air preheaters) [17]. Water–gas heat exchangers are finned tube heat exchangers applied for the heating of water through the heat recovered from a gas stream [80], normally exhaust gases as exemplified in Figure 6. While air–gas heat exchangers are mostly applied for the heating of an air stream, such as the preheating of a combustion air stream [108], these may present several configurations [166], such as: regenerators, recuperators, rotary regenerators and run around coil. Moreover, different designs exist [17], such as: plate heat exchangers and heat pipe heat exchangers. The application of heat exchangers is conditional to the type of fluid, namely if corrosive. Corrosion can be caused by the passage of acidic gases originating from combustion and due to the potential production of foaming; for hot air recycling usually this is not applicable, in which an equivalent amount of waste heat may be recovered to tunnel kilns or other processes within the plant, without the risk of corrosion or foaming formation [22].

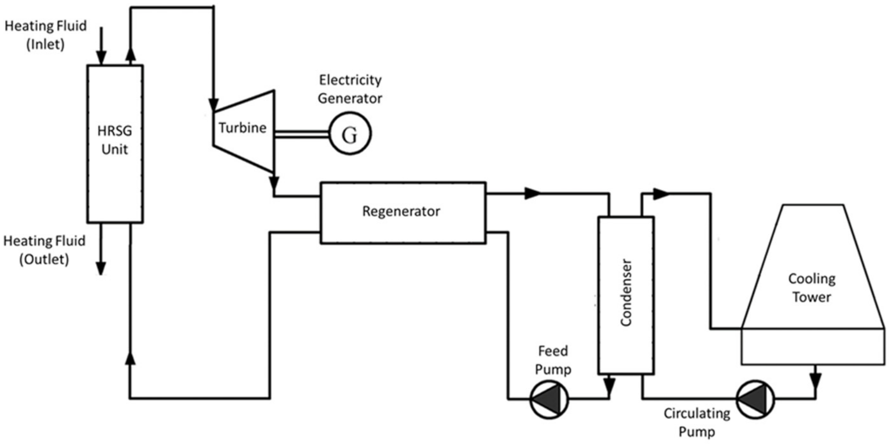
5.3. Outer-Plant Technologies and Strategies

In addition to plant-level measures, namely WHR strategies encompassing the recycling of several streams may be applicable if there are significant remaining waste streams to furtherly improve energy efficiency beyond by directly reducing fuel consumption. Such an approach is based on the application of technologies for the generation of electric energy and the combined heat and power (CHP) generation [56]. These are methods of selection to increase the self-sufficiency of a plant [6]. In this section, the description of two measures which produce benefits to be used in outer-plant are detailed, namely through the measures presented in Table 6. The approached technologies consider the organic Rankine cycle—a system similar to a Clausius–Rankine cycle suitable for low-grade heat sources and; gas turbine cogeneration—a system that produces both heat and electric energy using a system containing a gas turbine).

Table 6. Description of outer-plant technologies and strategies.

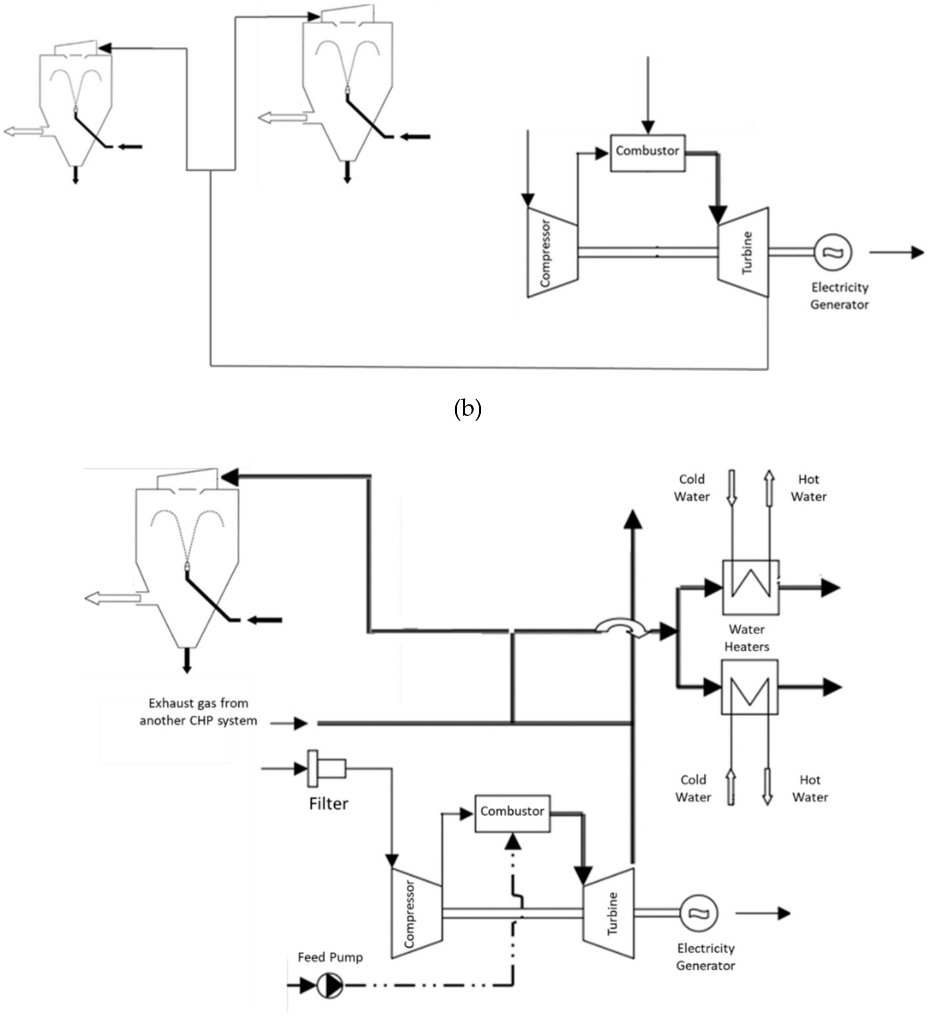
Measure	**Main Findings**		**Reference**
	Technical Aspects	**Energy and Economic Aspects**	
Organic Rankine cycle (ORC)	It may have installed a regenerator to even further increase the system efficiency by transferring heat from the outlet gas stream from the turbine to the liquid stream at the entrance of the Heat recovery steam generator (HRSG) unit (regenerative ORC); due to the high availability of low-grade heat sources (20% of overall applications of ORC) [134], such as the exhaust gas stream of ceramic kilns, the implementation of this system is highly opportune.	Payback time of 4–5 years [22].	[22,58–67,134]
Gas turbine cogeneration	Gas turbine cogeneration produces electric energy and thermal energy (which may be used in the operations of firing, drying and spray drying) [135,136].	Electric energy savings of 25%; 30% of fuel savings [68].	[68–72,135,136]

In Figure 7, the schematic of an organic Rankine cycle (ORC)and two gas turbine CHP installations is presented.



(**a**)

Figure 7. *Cont.*



(b)

(**c**)

Figure 7. (**a**) Organic Rankine cycle (ORC); (**b**) gas turbine combined heat and power (CHP) to reduce spray dryer fuel consumption; and (**c**) gas turbine CHP to reduce spray dryer fuel consumption and heat up water (adapted from [66,135,136]).

5.4. Future Goals

The improvement measures in the industry and in particular the implementation of WHR technologies and strategies presented in this paper, have been evolving in the scope of the requirements of each single plant to reduce its investment in energy use. Nonetheless, such requirements have been emerging under more far-reaching goals which comprise the need of promoting industrial sustainability in a worldwide perspective, namely of manufacturing industry. Within the EU, these sustainable goals may be linked to the 2030 climate and energy framework [167] and in a furthermost perspective, the 2050 long-term strategy [168]. Table 7 summarises the future goals regarding energy efficiency improvement in the European and the National industry—Portugal—correlating these goals with the current energy policies, with a focus on WHR and in the light of the improvement measures approached for the case of the ceramic industry.

Table 7. Description of future goals and its association to EU and national-level policies.

Policies	Framework of Future Goals
European Green Deal [169]	A roadmap developed by the European Commission for 2019–2024, aiming to promote circular economy, sustainability, and reach the objectives for the 2050 long-term strategy [169]; in line with this deal, two sets of strategies were conceptualised: energy system integration and hydrogen strategy [170]; the energy system integration is based on the promotion of the circularity of the energy systems (for instance, with the reuse of waste heat from industrial sites and the energy produced from the application of waste-to-energy technologies) and the promotion of clean fuel use (such as including renewable hydrogen, sustainable biofuels and biogas) [170]; the hydrogen strategy is based on a gradual transition of the use of hydrogen use between 2020 and 2030, aimed at the renewable hydrogen technologies to reach maturity within the timeframe of 2030 and 2050 [170].
EN-H_2: the National Strategy for Hydrogen in Portugal [171]	The strategy in Portugal to promote the use of hydrogen to increase energy transition and enforce it in the national economy, aligned with the objectives of the European Green Deal [171]; the overall aims for the use of H_2 consist of the enforcement of the use of renewable energy resources, the increase in the resilience of the energy system and the increase in decarbonisation [171]; in the context of industry, it is aimed to promote a representativity of 2–5% use of H_2 on the overall energy consumption for 2030 and 20–25% for 2050 [171].

6. Conclusions

In this paper, several technologies and strategies for energy efficiency improvement on the ceramic industry are presented:

- At the equipment level, several WHR technologies and strategies are applicable for the improvement of firing, drying and spray drying operations, such as the application of high efficiency burners (typical fuel savings of 50–60% for regenerative burners) and airless drying (typical thermal energy savings of 20–50%), in addition to the application of alternative fuels and improvement in ceramic material design;
- At plant-level implementation, there is great potential for measures such as hot air recycling from kilns to other processes (low associated payback time for implementation) and the use of dry routes instead of wet routes in raw material preparation (associated 78% of thermal energy savings and 36% reduction in electric energy savings), in addition to the use of renewable energy resources (such as CSP);
- At the outer-plant level, technologies and strategies, two main applications were presented: electricity production systems, namely the organic Rankine cycle (with an associated payback time of 4–5 years) and gas turbine CHP (with associated typical 25% electric energy savings and 30% fuel savings).

Throughout the paper, gaps regarding the existence of specific studies were also identified. These are mostly associated to techno-economic limitations, for instance:

- The practice of hot air recycling is generally favoured relatively to the installation of heat exchangers—higher investment costs and the problem of corrosion by the passing of exhaust gases and; as most of the performed studies focus on hot air recycling, with a verifiable lack of studies for the application of several types of heat exchangers;
- Despite the potential of industrial symbiosis encompassing this sector, namely regarding WHR, a lack of existing studies on the assessment of energy efficiency improvement caused by the implementation of an industrial symbiosis-based measure is observed.

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Nomenclature

Abbreviations

BAT	Best available technologies
CHP	Combined heat and power
CSP	Concentrated solar power
HT	High temperature
LT	Low temperature
MT	Medium temperature
ORC	Organic Rankine cycle
PCM	Phase change materials
TES	Thermal energy storage
WHR	Waste heat recovery

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