Article

Cogeneration Supporting the Energy Transition in the Italian Ceramic Tile Industry

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Abstract: Ceramic tile production is an industrial process where energy efficiency management is crucial, given the high amount of energy (electrical and thermal) required by the production cycle. This study presents the preliminary results of a research project aimed at defining the benefits of using combined heat and power (CHP) systems in the ceramic sector. Data collected from ten CHP installations allowed us to outline the average characteristics of prime movers, and to quantify the contribution of CHP thermal energy supporting the dryer process. The electric size of the installed CHP units resulted in being between 3.4 MW and 4.9 MW, with an average value of 4 MW. Data revealed that when the goal is to maximize the generation of electricity for self-consumption, internal combustion engines are the preferred choice due to higher conversion efficiency. In contrast, gas turbines allowed us to minimize the consumption of natural gas input to the spray dryer. Indeed, the fraction of the dryer thermal demand (between 600–950 kcal/kgH$_2$O), covered by CHP discharged heat, is strictly dependent on the type of prime mover installed: lower values, in the range of 30–45%, are characteristic of combustion engines, whereas the use of gas turbines can contribute up to 77% of the process's total consumption.

Keywords: cogeneration; energy efficiency; ceramic industry; spray dryer; energy analysis; process thermal consumption; gas turbine; internal combustion engine

1. Introduction

The topic of energy efficiency in industry is rising to the top of the agendas of the European Union (EU) and Member States, primarily for environmental (need to reduce greenhouse gas emissions) and economic (i.e., unstable energy prices and reliability of supply) arguments [1,2].

The Energy Efficiency Directive 2012/27/EU (EED) is a solid cornerstone of Europe's energy legislation. It includes a balanced set of binding measures planned to help the EU reach its 20% energy efficiency target by 2020. The EED establishes a common framework of measures for the promotion of energy efficiency (EE) to ensure the achievement of the European targets and to pave the way for further EE improvements beyond 2020. The Italian Government transposed the EED in 2014 (by issuing the Legislative Decree no. 102/2014, recently updated by Legislative Decree no. 73/2020), also extending the obligation to a specific group of energy-intensive enterprises (mostly small and medium enterprises, SME). The ENEA (Italian National Agency for New Technologies, Energy, and

the Sustainable Economic Development) was appointed to manage the obligation of EED Article 8 [3], which is dedicated to energy audits, a tool used to assess the existing energy consumption and identify the whole range of opportunities to save energy.

In the EED, energy audit (EA) is defined as a systematic procedure aimed at obtaining adequate knowledge on the existing energy consumption profile of a building or group of buildings, an industrial or commercial operation, or installation for private or public service, identifying and quantifying cost-effective energy savings opportunities, and reporting the findings.

According to Article 8 of Legislative Decree 102/14, two categories of companies, namely large enterprises and energy-intensive enterprises, have been targeted as obliged to carry out energy audits on their sites, first by the 5 December 2015, and then at least every four years.

Obliged enterprises that do not carry out an energy audit observing Annex II of the EED within the above-mentioned deadlines will be subject to administrative monetary penalties. According to Article 8 of the Italian Legislative Decree 102/2014 implementing the Energy Efficiency Directive, as of 31 December 2019, ENEA received 11,172 energy audits of production sites, related to 6434 companies [4].

Over 53% of the audits were carried out on sites related to the manufacturing sector and over 14% in trade. A total of 70% of the audits collected by ENEA are equipped with specific monitoring of energy consumption.

Despite relevant efforts having been deployed in terms of both innovation technologies and regulatory frameworks in enabling it, the full potential for energy efficiency in the industrial sector remains significant.

According to [5], in 2011, industry was the largest heat-consuming sector (79 EJ), accounting for 46% of the world total thermal energy demand. Based on recent IEA Outlooks [6,7], however, the industrial heat makes up two-thirds of industrial energy demand and 20% of global energy consumption.

In Italy, in 2018 [8], about 2234 ktoe of heat was consumed by industry, representing 53% of the national heat demand, 7% of the total national energy need, and 17.5% of the industry energy need. Most of the required heat comes from the direct combustion of fuels, with natural gas as the main supplier followed by petroleum and coal products. The electricity consumption of the Italian industrial sector, according to [9], with reference to 2018, was equal to 126.4 10^9 kWh, representing about 42% of the national electricity request.

Within the framework of the described scenario, the reduction in energy consumption in the industrial sector, together with the increment of the efficiency of energy generation technologies, are fundamental aspects to meet the EU targets. The industrial sector offers tremendous opportunity for low-cost energy savings and carbon reductions through energy efficiency improvements.

In this context, cogeneration, or combined heat and power (CHP) (i.e., the combined generation of electricity and useful heat from a single primary energy source), still plays a significant role while maintaining long-term prospects in the global energy markets, primarily due to its numerous operational, environmental, and economic benefits. Since the 1970s, cogeneration has been used to improve the efficiency of production systems, both in the industrial and civil fields. In Italy, industry is the sector that invested the most in cogeneration technologies in the past decades. The higher value of the electricity price paid by Italian industries compared to other EU members was one of the main drivers toward the diffusion of CHP. Indeed, the sum of investments in energy efficiency in 2018 in Italy was about 7.1 billion €, of which about 7% (about 480 M€) was in cogeneration technologies [10]. The industrial sector has contributed for 443 million € of investments in CHP technologies.

According to the latest annual report on cogeneration [11], the total number of CHP units installed in Italy is equal to 1737, more than 89% of which are represented by internal combustion engine (ICE) units. The overall installed generation capacity is equal to 13,233 MW. The annual gross electricity generation with CHP units equals 58,722 GWh/y,

while useful heat generation reached 36,076 GWh/y. Natural gas is the main source, with about 119,000 GWh/y of primary energy supplied.

Application of CHP technologies in the industrial sector is preferred in manufacturing processes that require a significant amount of electricity and heat simultaneously, throughout the whole year. In this respect, the ceramic tile production is one among the industrial processes where energy efficiency management is crucial, given the high energy demand necessary for the production cycle (covered, at the present, for about 70% by natural gas), and the incidence of the energy item on the final production cost, close to 20%.

In 2016, Confindustria Ceramica, the association of Italian ceramics, conducted research on thermal efficiency strategies developed to optimize the energy consumption of the ceramic tiles industry [12]. The research analyzed a sample of 64 production sites covering 59.6% of national production. A first energy saving solution, started in the early 1980s, was the recovery of the indirect cooling air of kilns to the dryers. In 2016, this strategy concerned 43.2% of vertical dryers and 35.2% of horizontal dryers. The second and most effective energy efficiency strategy was the introduction of the CHP units in the 90s, and their diffusion had another strong impulse around 2008 (see Figure 1), thanks to the establishment in Italy of the TEE ("Titoli di Efficienza Energetica"). The TEE is a mechanism introduced by D.M. 24 April 2001 to incentivize the implementation of energy efficiency interventions that comply with the national energy savings targets (2001/77/CE). The most adopted configuration provides for the spray dryer as the thermal user for the CHP plant, while the prime movers are gas turbines and internal combustion engines. The study reported in [12] also highlighted that most parts of the CHP units with gas turbine technology was closer to their end life (17.4 years compared to a hypothetical end life of 24 years) than CHP units with an internal combustion engine (eight years compared to a hypothetical end life of 20 years). This means that this latter technology has generally been installed more frequently since 2008.
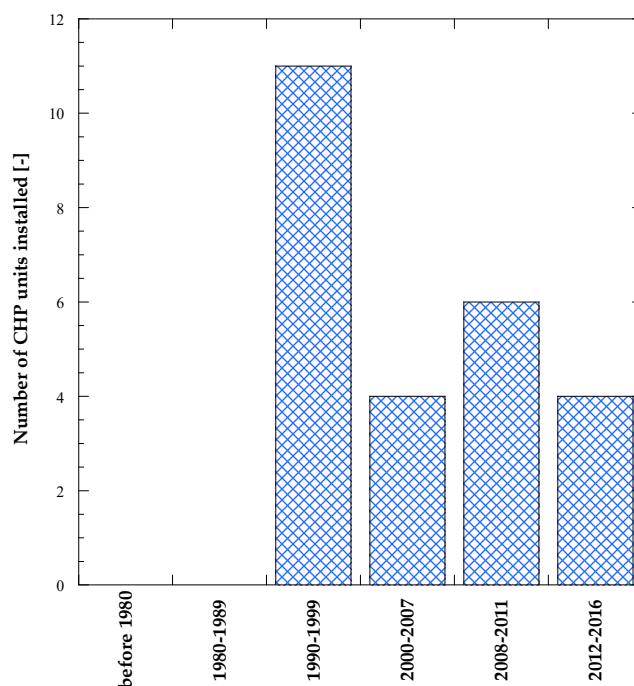

Figure 1. Combined heat and power (CHP) units installed in the period 1980–2016 [12].

In 2019, the ceramic tile industries located in Italy comprised 135 [13], of which 54 were equipped with a spray dryer. Within the latter, 28 were provided with a CHP unit, helping to satisfy both the electrical and thermal request of the production process.

The literature on cogeneration in industrial applications is exhaustive: most relevant examples can be found in [14–25]. In detail, performance assessment and optimal schedul-

ing of a CHP power plant for industrial applications can be found in [14–18]. Description and energy analysis of specific applications of CHP to industrial processes have been reported in [20–24] for the food processing industry, in [21] for cement production, in [25] for the textile industry, and finally in [19] for the chemical and pulp mill industry.

In contrast, studies dealing with the specific application of cogeneration in ceramic tiles factories, according to the authors' knowledge, are limited. Caglayana et al. [26–28] presented an energy, exergy, and sustainability analysis of a CHP gas turbine applied in the ceramic sector. The main results of their studies showed that the utilization of the gas turbine (GT) unit could provide 0.1115 m^3/s and 0.0732 m^3/s of natural gas savings for the ground and wall tile dryers, respectively. Moreover, their results highlight that the most efficient components are the air compressor and combustion chamber, while the minimum energy efficiencies were obtained for the wall tile dryer (8%) and ground tile dryer (8%) components. Yoru et al. [29] presented an energy and exergy analysis on a CHP system installed into a ceramic plant consisting of three GT units. Results claim that the exergy efficiency was inversely proportional to the ambient temperature: the rise of ambient temperature at the compressor inlet adversely affected the efficiency of the system. The energy and exergy efficiencies of the cogeneration system were calculated as 82% and 35%, respectively.

More strategies on how the EU ceramic sector is following energy efficiency policies and environmental concerns can be found in [30–36].

In particular, different technological options to reach the EU 2020 and 2050 greenhouse gas (GHG) emissions objectives were compared in [34] using the LCA methodology on 25 different technological scenarios of the life cycle of porcelain stone tiles. The GHG emissions' objectives, considering only the ceramic tile production stage, can be achieved by modifying the product design (removal of the glaze and reduction of the thickness of the ceramic body) or by electrifying 50% of the thermal processes through renewable sources.

A more efficient and sustainable production appears to be the only option for a long-term prospective of manufacturing industries. Efforts required by the traditional industry should be directed toward implementing measures that concurrently guarantee a global energy savings and a reduction in the environmental impacts.

In the aforementioned context, ENEA launched a two-year research project in collaboration with the University of Bologna, Centro Ceramico, and Confindustria Ceramica with the aim of delineating the current status of cogeneration in the Italian ceramic tile sector. The final purpose of the project is to define the energetic and environmental benefits associated with the application of CHP systems to the ceramics industry. This paper summarizes the results of the first-year research activities, which focused on outlining the average characteristics of the prime movers installed, and quantifying the contribution of CHP thermal energy, supporting the spray dryer section. Starting from the analysis of the energy audits of ceramic companies collected by ENEA, a detailed assessment of the CHP units' specific characteristics was realized by integrating these data with information directly requested from ceramic companies.

The study's outcomes provide for an overview of the current situation, and can be used by industrial developers as guidelines for the selection and design of CHP units as well as by law-making bodies as a reference for energy efficiency programs including incentives policy.

The rest of this manuscript is organized as follows. In Section 2, a synthetic description of the ceramic tile production process is presented, and emphasis is given to the detailed explanation of the spray dryer technology. Thermal integration with the CHP units, contributing to satisfy the heat consumption of the dryer unit, is presented with schematic layouts of the integrated system. The research method, data collection, and energetic performance indexes, ad hoc defined for the purpose of this analysis, are outlined in Section 3. Section 4 presents and discusses the main results of the study. Finally, in Section 5, the conclusions of the study are highlighted along with the future steps of the project.

2. Description of the Ceramic Tile Process

Ceramic tile production plants have been totally revolutionized to improve productivity and decrease energy consumption as a reaction to the energy crisis of 1974 [37].

Ceramic tiles are the result of a process that is strongly influenced by the raw materials and firing temperature: as a function of these two parameters, different types of tiles can be obtained (porcelain tile, monoporosa, single-firing tile, double-firing tile, etc.).

The production process (Figure 2) generally starts with the storage and the preparation phase of the raw materials, consisting of two main operations: wet grinding and water content adjustment [38]. Wet grinding technology, which uses a continuous or discontinuous drum mill, can reduce particle size, dust pollution, and provides a good homogenization [39]. Subsequently, the aqueous suspension ("slip", with a water content of $\cong$30%) obtained from the wet grinding is dried and transformed into spherical granules by way of the operation called spray drying.
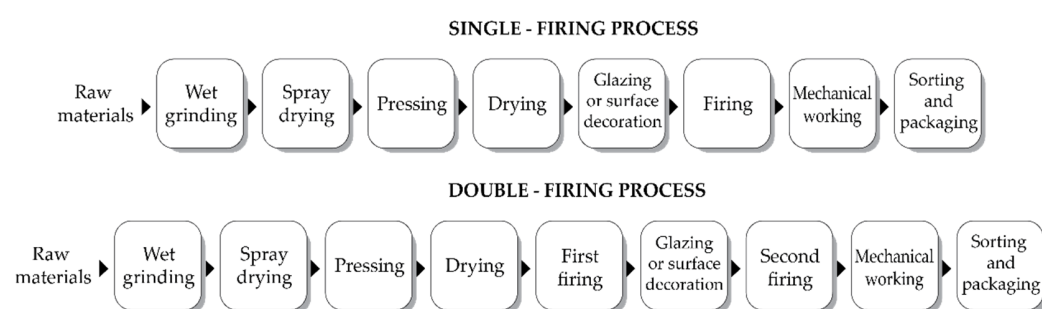
Figure 2. Flow chart of the single and double production process of ceramic tiles.

Spray-dried granules (still containing $\cong$5–6% of water) are then shaped by discontinuous or continuous pressing in order to obtain the tiles, which are further dried to remove the remaining water through a process of surface evaporation and interstitial diffusion, which takes place homogeneously in the vertical or horizontal rapid dryers. After the glazing and decoration phases, currently mainly performed by digital printing, firing takes place in roller kilns 70 $\div$ 100 m long. In kilns, the tiles are exposed to increasing temperature until they reach the maximum temperature zone around 1000–1200 °C, then they are quickly cooled. After cooling, tiles can be treated by several mechanical processes such as cutting, grinding, lapping, and polishing, after which they are sorted and packed.

The production process above described is a single firing process and is mainly used for the production of monoporosa and porcelain tiles.

A double firing process was also adopted in the past. In this case, glazing and decoration occurred after a first firing step at about 1000–1100 °C, which is needed to fire only ceramic tile bodies. The second firing was necessary to fire only the glaze, and it was generally carried out at lower temperature as a function of the type of glaze ($\cong$700 °C).

Tables 1 and 2 summarize the energy consumption according to the phase of the production process and the type of product, respectively.

Table 1. Specific thermal and electrical consumption according to the process phase [40].

| Process Phase	Specific Thermal Consumption [GJ/t]	Specific Electrical Consumption [GJ/t]
Wet grinding	-	0.05–0.35
Spray drying	1.1–2.2	0.01–0.07
Pressing	-	0.05–0.15
Drying	0.3–0.8	0.01–0.04
Firing	1.9–4.8	0.02–0.15

Table 2. Average total specific consumption according to the type of product [40].

Type of Product	Average Total Specific Consumption [GJ/t]
Single-firing tile	5.78–6.37
Double-firing tile	4.67

2.1. The Spray Dryer Technology

The spray dryer apparatus, as shown in Figure 3, essentially consists of a cylindrical chamber, where a heat exchange is promoted between the slip and a hot air flow with a temperature of about 500 °C. The slip is finely sprayed upward via nozzles in the form of droplets, while the hot air is directed tangentially downward to impose a spiral motion. Thanks to the heat exchange process, an immediate evaporation and consequent hardening of the external side of the droplet take place, and simultaneously, the water vapor in the interior leaves the droplet through its rear, which collapses inward, forming the characteristic hollow sphere appearance [38,39].
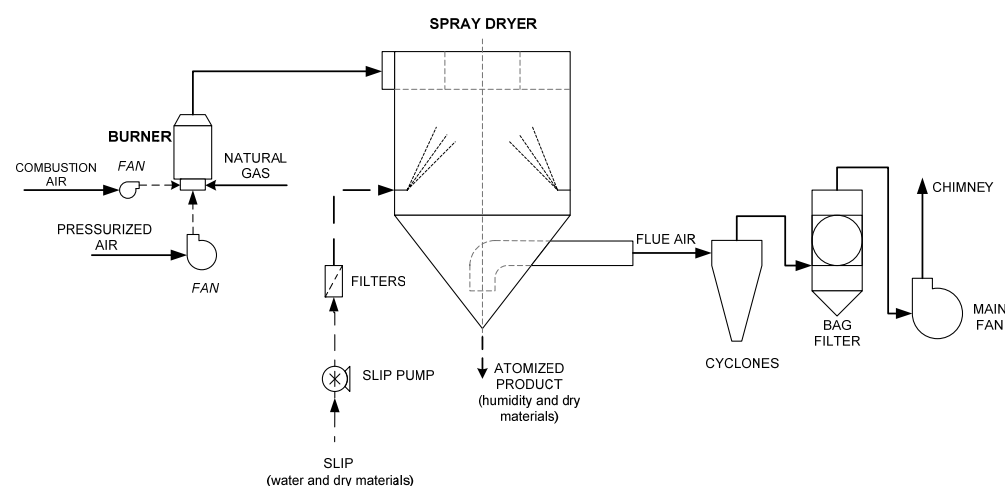
Figure 3. Schematic layout of the spray dryer unit.

The application of spray dryers in the ceramic tile industry has optimized the shaping process, assuring a high degree of compactness in the formed product. Spray-dried powders have a tailored particle size distribution (mainly concentrated in the 125–500 μm range) and a moisture content of ≅5–6%. The spray-dried powder optimally fills the press molds by the spherical shape of the granules, which improves its floatability and compaction. Furthermore, spray drying promotes the agglomeration of fine powders (<125 μm), avoiding de-airing problems during pressing [39].

The hot air flow in the spray dryer is usually generated by the combustion of natural gas and ambient air into a burner section (see Figure 3). At this stage, CHP units are usually installed, exploiting the gas turbine and internal combustion engine technologies.

As visible in Figure 3, the flue air stream, before being discharged into the atmosphere, is forced to pass through a gas cleaning section typically composed of cyclones and bag filters for dust removal.

In a large part of Italian installations, energy efficiency solutions are adopted to supply part of the heat required by the spray dryer. The study in [12] reports that over a sample of 71 spray dryers, 18% of them made use of heat recovery from kilns, 44% used CHP units, 4% used both systems, and 34% did not use any solution.

*2.2. Cogeneration System Supporting the Dryer Process*

Gas turbines (GTs) and internal combustion engines (ICEs) are the two CHP technologies currently installed in the ceramic tiles industry [12]. In both types of prime movers,

the electrical energy generated by the CHP unit is used to fully or partially satisfy the electricity demand of the ceramic tile production process. The heat rejected by the prime mover (PM) is used to support the spray dryer process with the direct use of exhaust gases.

Simplified layouts of GTs and ICEs thermally integrated with a spray-dryer are presented in Figures 4 and 5, respectively.
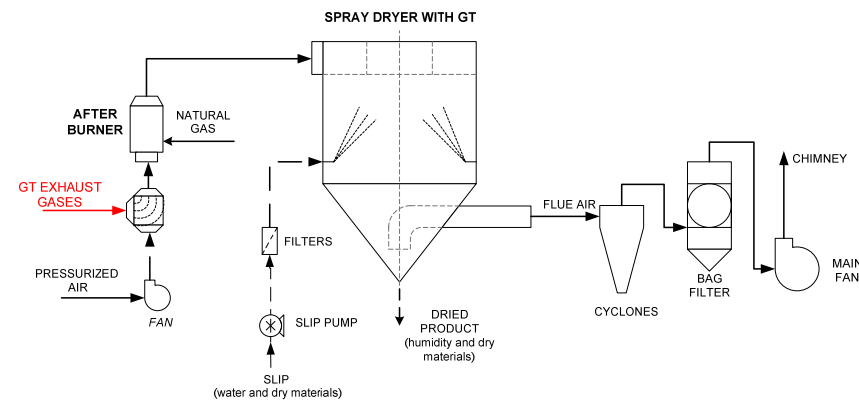
Figure 4. Schematic layout of the thermal integration between the combined heat and power (CHP) gas turbine (GT) unit and spray dryer.
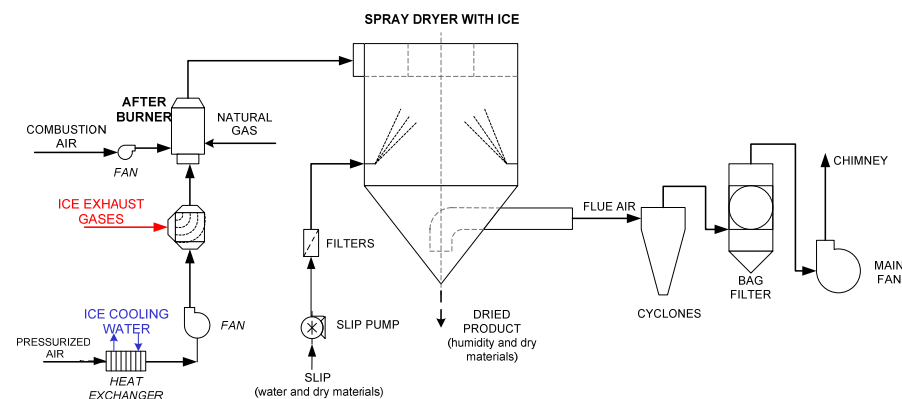
Figure 5. Schematic layout of the thermal integration between the CHP internal combustion engine (ICE) unit and spray dryer.

In both configurations, the CHP units' exhaust gases are heated up until the optimal process operating temperature (i.e., typically in the range 500–600 °C), thanks to an after-burner. The main difference between the arrangements lies in the amount of fresh air that is added into the process. Exploiting exhaust coming from a GT unit allows for the use of a small fraction of fresh air coming from ambient and pressurized by means of a fan ("pressurized air" in Figure 4). The streams are mixed, as in Figure 4, before entering the after-burner. If the mass flow of the exhaust is sufficient to support the drying process, the air mass flow could eventually be unnecessary. Conversely, the direct use of ICEs exhausted gases require a more significant amount of fresh air. Thus, as visible in Figure 5, both streams named "combustion air" and "pressurized air" are used in this configuration. The pressurized air stream is mixed with the ICE exhausted one and post combustion takes place, also introducing the combustion air inside the after-burner component.

This difference between the CHP spray dryer setup was mainly due to two reasons: (i) the different mass flow of GT and ICE exhaust gases discharged for a given electrical size, and (ii) the different concentration of oxygen in the exhaust. For the same electric size of the CHP unit, ICEs are characterized by a lower amount of thermal power discharged with the exhaust, both in terms of mass flow rate and temperature, due to the higher conversion efficiency compared to GTs, and to the fraction of low-temperature heat discharged to the

engine coolant. In addition, GT exhausted gases are typically characterized by an oxygen concentration within 18–19% vol. dry, while the ICE typical oxygen concentration is lower, in between 14–15% vol. dry.

The last difference lies, as indicated in Figure 5, in the possibility of preheating the pressurized air stream exploiting the low-grade heat coming from the ICE water cooling circuit. As visible in Figure 5, a heat exchanger is placed upstream of the fan component to increase the temperature of the pressurized air stream exploiting the engine's cooling water heat. Typical air temperature increase is in the range 40–50 °C.

3. Methodology and Performance Indexes

In the ceramic sector, 197 energy audits carried out from 143 companies were collected by ENEA in December 2019 [4]. A total of 103 EAs from 68 companies referred to the tile ceramic process and have been analyzed to check the CHP presence in the industrial process. The total number of production sites including a CHP system was found equal to be 28.

Starting from the analysis EA collected by ENEA, a detailed assessment of the CHP units' specific characteristics was realized by integrating those data with information directly requested from the ceramic companies. For this purpose, a questionnaire was sent to all the ceramic tile industries equipped with CHP units and located in the tile district, containing the following specific macro-requests:

- type and model of the CHP unit installed;
- annual consumption of natural gas feeding the CHP unit and annual generated electricity;
- annual operating hours of the CHP unit;
- annual consumption of natural gas feeding the after-burner section;
- annual amount of slip input to the dryer section and dried products generated;
- annual operating hours of the dryer unit; and
- annual electricity consumption of the ceramic tile production process.

In response to that, this study analyzed the annual operating data collected from ten CHP installations. The energetic analysis of the dryer process and of the CHP system was accomplished by introducing the following ad hoc-defined performance indexes:

CHP natural gas primary energy input, $Q_{in,CHP}$, calculated as the product of annual natural gas volume flow input to the CHP unit and lower heating value, assumed equal to 8250 kcal/Sm^3.

CHP average electric efficiency, $\overline{\eta_e}$, defined as the ratio between annual generated electrical energy, E_{CHP}, and primary energy input, $Q_{in,CHP}$.

Ratio of produced to consumed electrical energy, δ. This index helps to assess the design and the main target of the CHP unit. A value of δ equal to 1 means that all the energy generated by the CHP unit is used to satisfy the electricity consumption required by the production process. Values higher or lower than 1 mean, respectively, that a surplus or a deficit of electricity occurs compared to the production process needs.

Thermal energy discharged by the CHP unit, $Q_{gas,CHP}$. This variable accounts for the thermal energy discharged with PM exhaust gases, available to the thermal user. It has been evaluated, indirectly, based on following equations, according to the definition reported in [41]:

For the gas turbine:

$$Q_{gas,CHP} = Q_{in,CHP} \cdot \eta_1 - \frac{E_{CHP}}{\eta_2 \cdot \eta_3 \cdot \eta_4} \tag{1}$$

For the internal combustion engine:

$$Q_{gas,CHP} = Q_{in,CHP} \cdot \eta_1 \cdot k_5 - \frac{E_{CHP}}{\eta_2 \cdot \eta_3 \cdot \eta_4} \tag{2}$$

where $\eta_1, \eta_2,\ \eta_3$, and η_4 in Equations (1) and (2) represent, respectively, the combustion chamber, auxiliaries, electric conversion, and gear box efficiencies. Conversion efficiency values have been assumed equal to the ones reported in Table 3. Coefficient k_5, only included in Equation (2), accounts for the fraction of discharged thermal energy (i.e., primary energy not converted into electricity) available in the high temperature heat circuit (i.e., with exhaust gases). The value of coefficient k_5, dependent on the ICE model, was assumed according to the manufacturers' specifications. Assumed values were in the range 0.74–0.78.

Table 3. Assumed value of conversion efficiencies [41].

η_1 [-]	η_2 [-]	η_3 [-]	η_4 [-]
0.9900	0.9800	0.9625	0.9850

To quantify the real amount of heat input to the spray dryer with PM exhaust gases, the quantity $Q_{gas,CHP}$ was corrected with a factor representing the ratio between the annual operating hours of the spray dryer unit and annual operating hours of the CHP system.

Thermal energy input to the dryer with natural gas, $Q_{in,SP}$, calculated as the product of annual natural gas volume flow input to the after-burner and lower heating value equal to 8250 kcal/Sm^3.

Total heat consumption of the dryer, Q_{TOT}. This variable accounts for the total heat input to the spray dryer component obtained by adding the two main thermal contributions $Q_{in,SP}$ and $Q_{gas,CHP}$. It must be pointed out that the heat requested to heat up and vaporize the water content in the slip represents the main contribution (typical values are in the range 70–80%) to the total process need. Minor contributions are represented by the heat necessary to heat up the combustion and/or the pressurized air streams, the heat absorbed by the solid matter, and the heat dissipated through the dryer walls as the process is not adiabatic.

Fraction of total heat consumption of the spray dryer covered with CHP discharged heat, Λ.

$$\Lambda = \frac{Q_{TOT}}{Q_{gas,CHP}} \tag{3}$$

Spray dryer specific consumption, C_s. This parameter is calculated as the ratio between Q_{TOT} and annual amount of evaporated water, $\dot{m}_{H2O}$, according to Equation (4):

$$C_s = \frac{Q_{TOT}}{\dot{m}_{H2O}} \tag{4}$$

The parameter C_s defines the amount of thermal energy requested by the process for unit mass of evaporated water, and it is normally expressed in kcal/kg H_2O. Alternatively, the specific consumption can also be expressed with reference to kg of dried product produced.

4. Energy Analysis Results and Discussion

This section is organized as follows. The first sub-section shows the results related to the CHP units, whereas the second sub-section describes the results related to the spray dryer as the thermal user.

### 4.1. Combined Heat and Power (CHP) Energetic Results

The preferred choice in terms of CHP prime mover is the internal combustion engine, with seven out of ten installations. Figure 6 shows the design electric power of the CHP prime movers plotted against the average annual mass flow rate of evaporated water. Blue squares in the figure represent the ICE units while the red circles represent GT units. The electric size of the installed CHP units was between 3.4 MW and 4.9 MW with an average value equal to 4 MW.
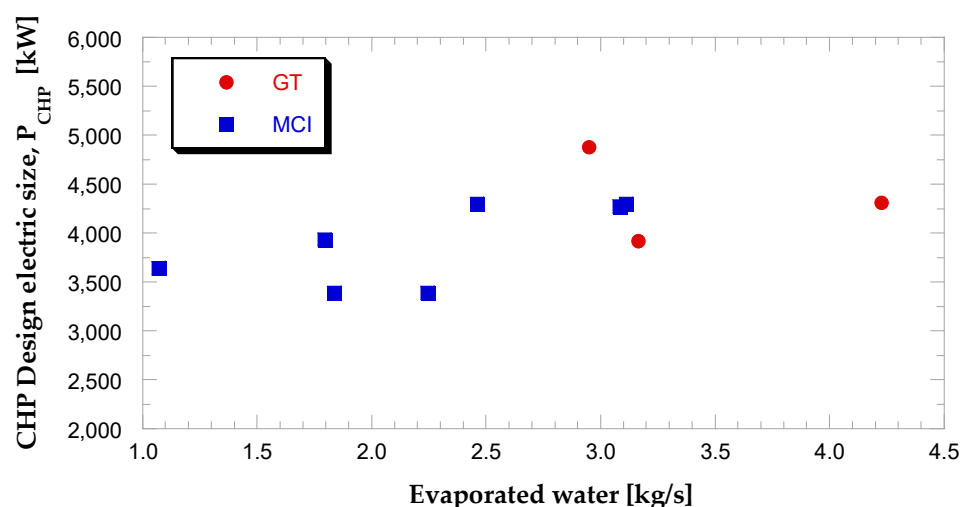
Figure 6. Design electric power size of the CHP units installed versus evaporated water average mass flow rate.

Gas turbines seem to be the preferred choice only when the size of the spray dryer technology is high (i.e., with average water mass flow rate higher than 2.50 kg/s), while ICEs are preferred with low evaporative capacity.

Figure 7 shows the electric efficiency values of installed CHP units plotted versus design electric size. ICE units are characterized by higher efficiency values, in the range 42–44%, compared to GTs whose values hardly exceed 30%. This outcome is also confirmed by the data reported in Figure 8, where the primary energy consumption of CHP units is plotted versus annual operating hours. Annual primary energy consumptions are in the range between 3210^6 and 10210^6 kWh/y, significantly higher for gas turbines compared to combustion engines for similar values of operating hours. Five CHP units reached operating hour values above 7000 h/y, three were between 6000 and 7000 h/y, while the remaining two were in operation for about half the time during the entire year (i.e., operating hours between 4200–4800 h/y).
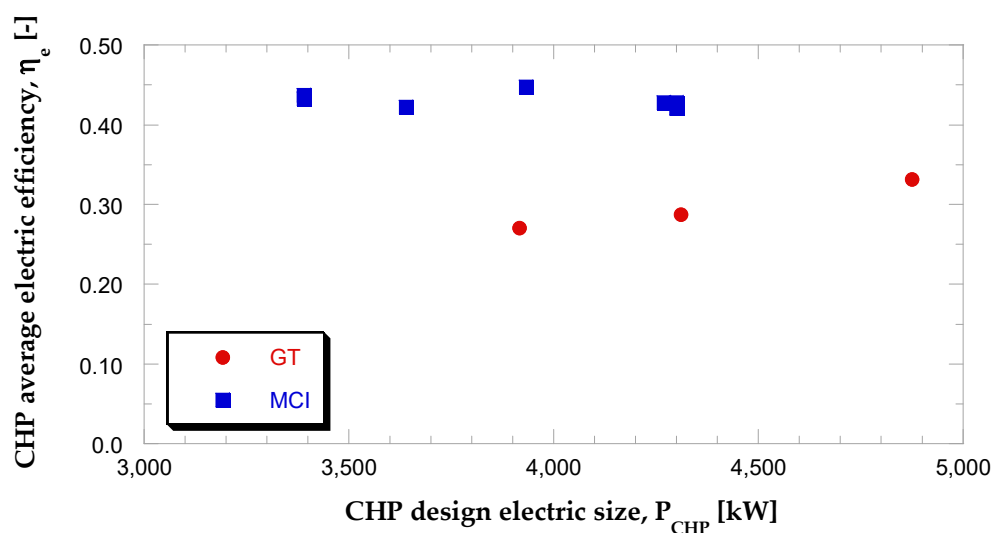
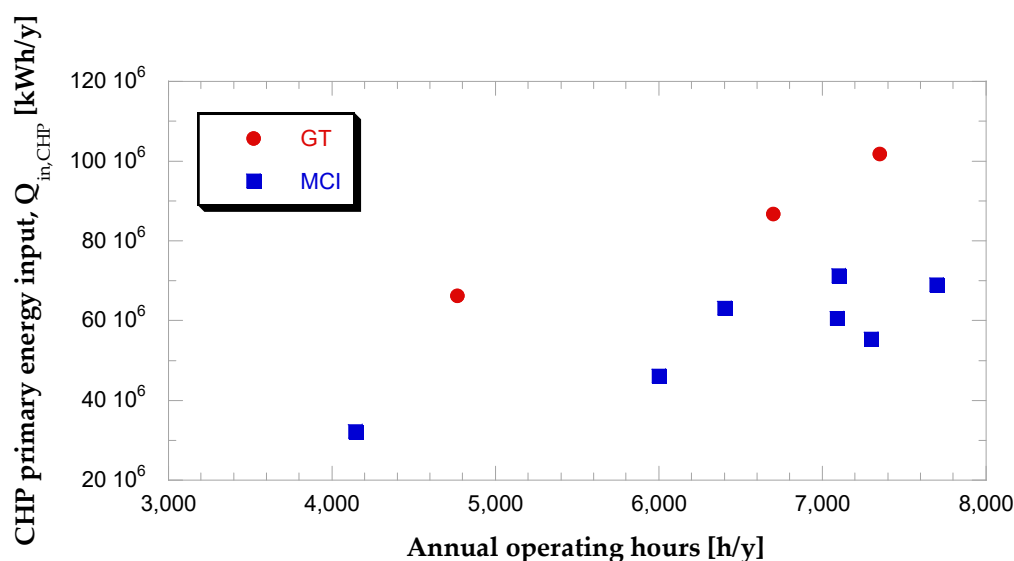**Figure 7.** CHP average electric efficiency versus design electric size.

Figure 8. CHP natural gas primary energy consumption versus annual operating hours.

In Figure 9, the generated electrical energy is compared to the electricity demand of the facility. The black continuous line represents a value of δ equal to one (i.e., the case of self-consumption of the whole CHP generated electrical energy). As observed, the value of δ was higher than one in all of the analyzed cases. In particular, in six installations, the surplus of electricity was marginal (i.e., δ between 1.03 and 1.08), suggesting that the design and the load regulation strategy of the CHP units were targeted to meet the request of the facility. In the remaining cases, a modest surplus of electricity was generated (δ between 1.10 and 1.25). Only one case showed a significant amount of electricity generated compared to self-consumption (δ equal to 1.39).
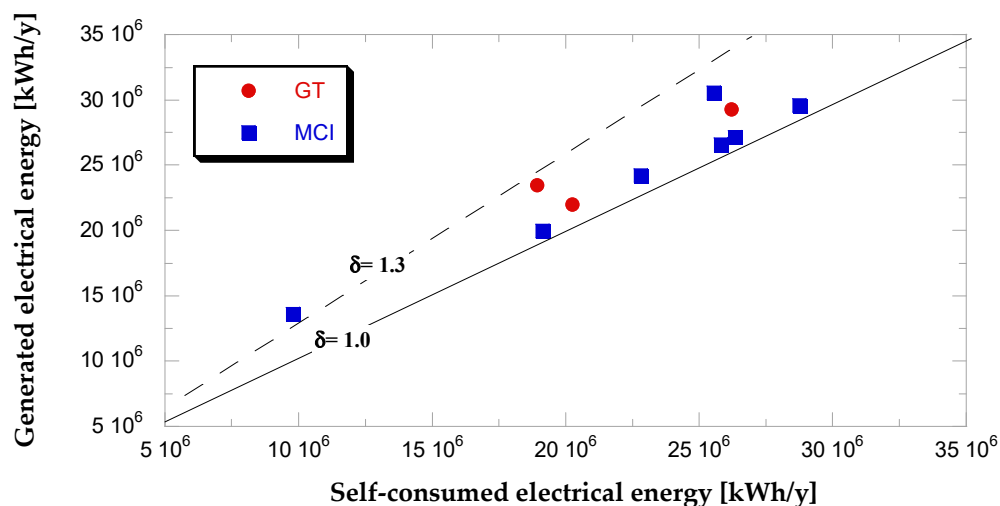

Figure 9. CHP generated electrical energy versus the electricity demand of the facility.

4.2. Energetic Results of CHP-Spray Dryer Integrated System

The total heat consumptions of the spray dryer units are plotted in Figure 10 as the function of annual evaporation capacity. As expected, an increase in thermal energy required for the drying process was observed as the evaporative capacity increased. The obtained trend was almost linear with values of Q_{TOT} in the range $15 \cdot 10^6$–$75 \cdot 10^6$ kWh/y.
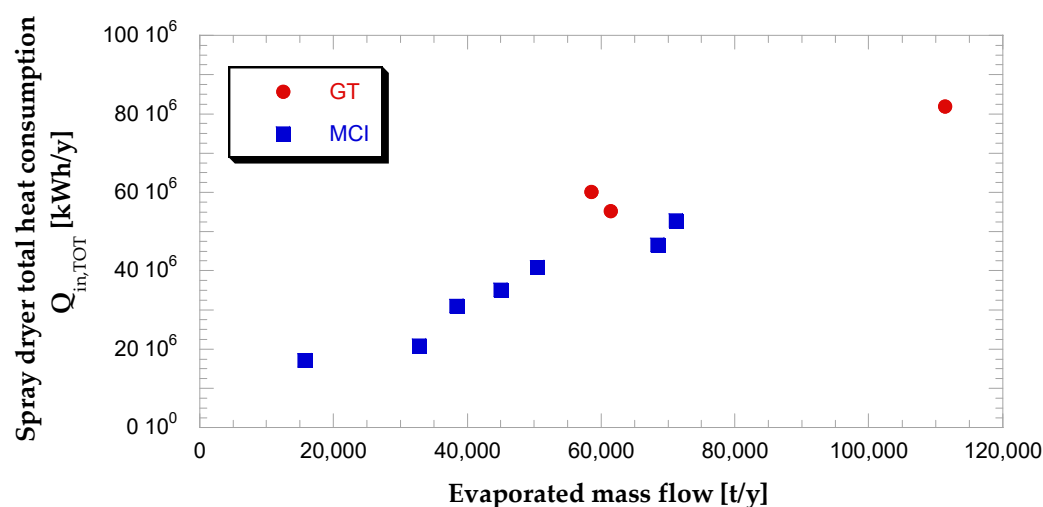
Figure 10. Total heat consumption of the spray dryer plotted against evaporated mass flow.

Contributions of CHP thermal energy, $Q_{gas,CHP}$, and natural gas energy input, $Q_{in,SP}$, to the dryer's heat consumption are shown in Figures 11 and 12, respectively. GTs showed a higher value of $Q_{gas,CHP}$ (between $40 \cdot 10^6$–$60 \cdot 10^6$ kWh/y) compared to the ICEs, thus confirming that their limited electrical efficiency values (see results in Figure 8) had a positive effect on the amount of discharged heat. Percentage values of Λ for GT units, as shown in Figure 13, were between 67% and 77%. In contrast, in the case of ICEs, the contribution of thermal energy discharged with exhaust was limited ($Q_{gas,CHP}$, in between $8 \cdot 10^6$ and $14 \cdot 10^6$ kWh/y), resulting in Λ values between 30 and 45%. It must be highlighted that the value of Λ seems to be dependent only on the technology used as the CHP prime mover, not being influenced by the size of the spray dryers (i.e., amount of evaporated water).
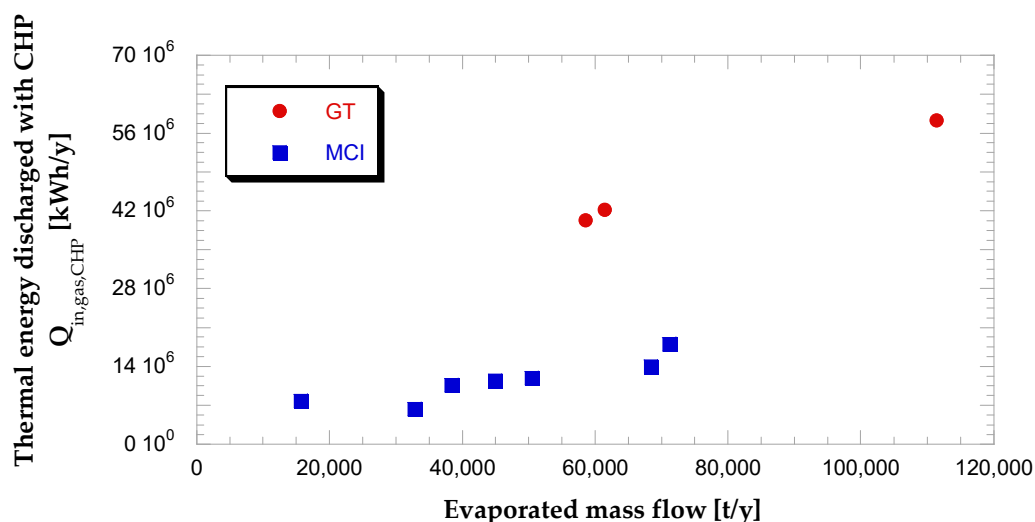

Figure 11. Thermal energy discharged with CHP and input to spray dryer versus the evaporated mass flow.
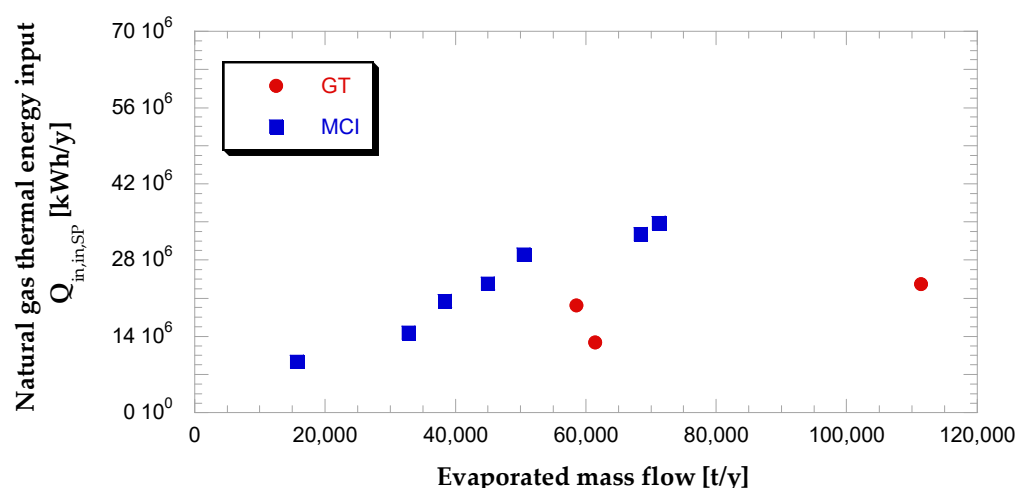
Figure 12. Thermal energy input to spray dryer with natural gas versus evaporated mass flow.
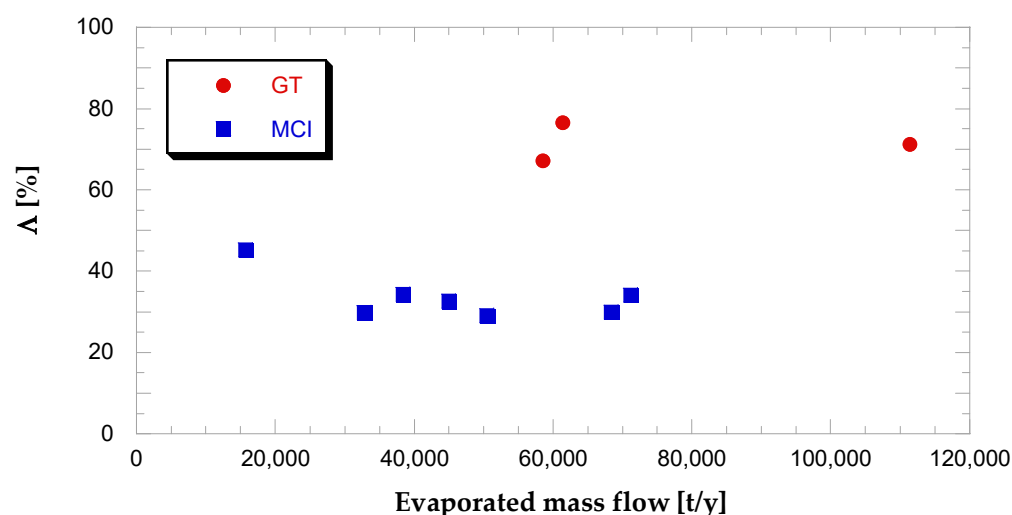

Figure 13. Percentage of total heat consumption of the spray dryer covered with CHP discharged heat versus evaporated mass flow.

Based on the presented results, it can be asserted that for a given prime mover's size, the choice of ICE guarantees the maximum generation of electricity, while the GT allows for the minimization of the consumption of natural gas required to support the spray dryer thermal process. It must be pointed out that other factors such as the engines' flexibility, maintenance costs, specific emission values, etc., can of course affect the choice of the prime mover technology to be installed.

Finally, the spray dryers' specific consumption is presented in Figure 14, referred to as the mass of evaporated water (Figure 14a,b) and to the mass of dried product.

The obtained values were in the range of 600–900 kcal/kg_{H2O} and 250–420 kcal/kg_{dried}, in line with values reported in [37]. Average values were equal to 710 kcal/kg_{H2O} and 305 kcal/kg_{dried}.

(**a**)

(**b**)
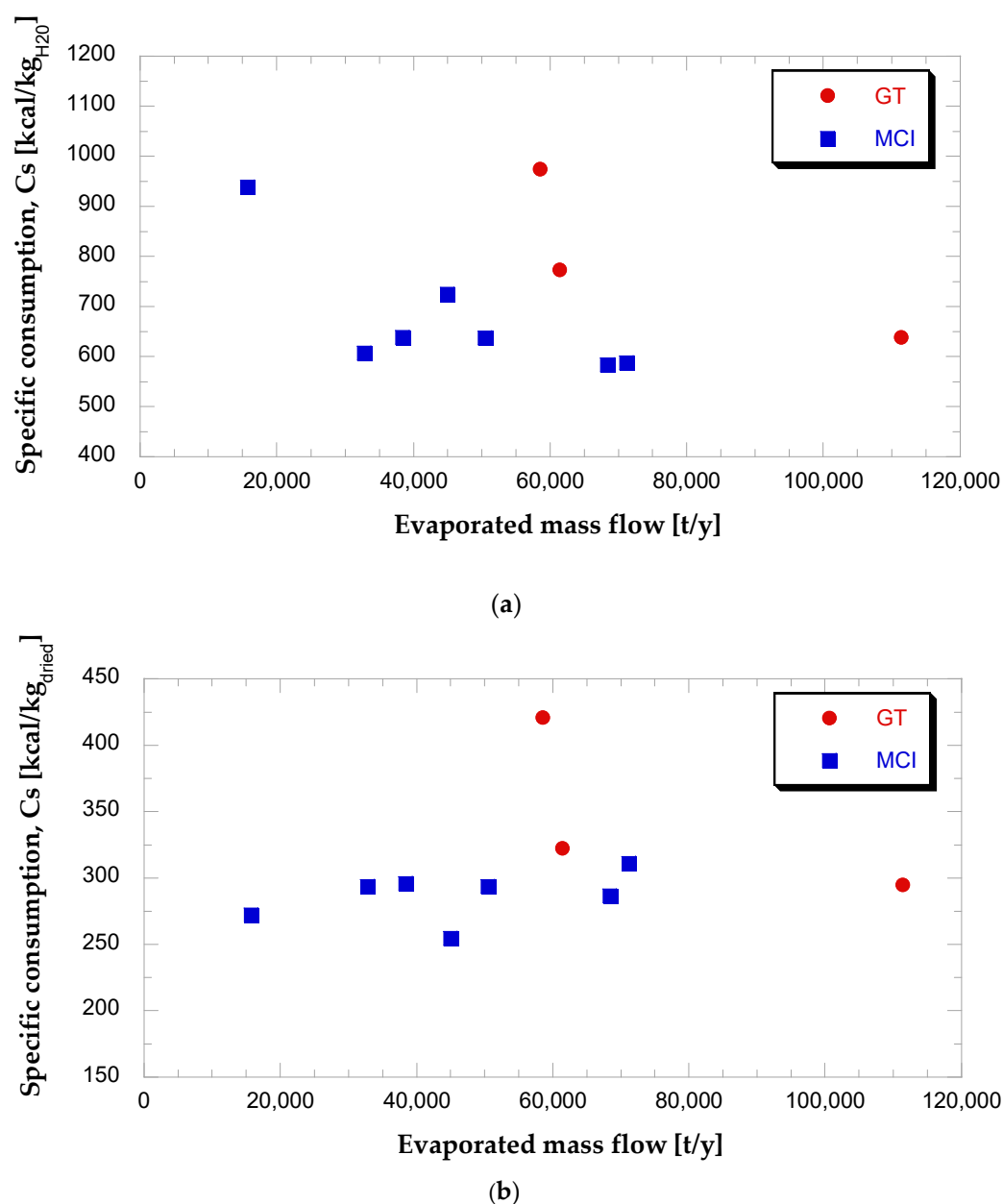
Figure 14. Spray dryer thermal specific consumption based on evaporated mass flow (**a**) and dried product (**b**).

5. Conclusions

In this study, the preliminary results of a two-year research project named "Energy efficiency of industrial products and processes", aimed at evaluating the benefits of cogeneration (CHP) applied to the ceramic tile industry, are presented.

Then findings demonstrate how the use of CHP technology can contribute to pursue the energy savings targets intended within the energy efficiency policy measures. Installed CHP units are used to generate onsite electricity, while thermal energy discharged with exhaust gases is directly used to supply the spray dryer, thus reducing the consumption of natural gas.

Obtained results of the study showed that:

- The electric size of the installed CHP units was between 3.4 MW and 4.9 MW, with an average value equal to 4 MW.
- CHP installed prime movers are internal combustion engine and gas turbines.

- Internal combustion engines are often the preferred choice, due to higher conversion efficiency values in electricity production (found in the range 42-44%).
- In contrast, GTs seem to be the preferred choice only when the size of the spray dryer unit is high (i.e., with evaporated mass flow rate higher than 2.5 kg/s) and the target is to minimize the consumption of natural gas input to the dryer.
- The total specific consumption of the spray dryer process was quantified in the range 600–950 kcal/kg_{H2O} or 250–420 kcal/kg of dried product, in line with values reported in the specific literature.
- The percentage of specific consumption covered with CHP thermal energy is strictly dependent on the type of prime mover installed: lower values, in the range 30–45%, are characteristic of combustion engines, whereas the use of gas turbines can contribute up to 77% of the process's total consumption.

The results aim to provide an overview of the current CHP installations in the Italian ceramic tile sector and could also be used as guidelines in the selection and design of CHP units to industrial developers.

Future steps of the research activity will be focused on thermodynamic modeling of the integrated system for a detailed representation of the thermal fluxes involved. Moreover, a methodology will be defined to assess the reduction of the environmental impact related to the use of a cogeneration unit in the ceramic tile industry.

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