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High-temperature heat pump application in the ceramic sector

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Abstract

The decarbonisation of hard-to-abate sectors, particularly energy-intensive industries, represents one of the most technologically challenging objectives of the EU 2050 targets and requires economic assessments involving private investments and public support actions in the form of incentives and tariffs. The ceramic industry is one of the industrial sectors with the highest added value in Europe, particularly in Italy. On the other hand, the transformation processes of the raw material and subsequent manufacturing of ceramic tiles require relatively high temperatures (i.e., up to 200°C for tiles drying, up to 550°C for slip spray-drying, and over 1000°C for tiles firing), for which the availability of competitive technological solutions compared to fossil fuel combustion processes remains limited. In recent years, the development of high-temperature heat pumps (HTHPs), i.e., those for heat sink temperatures above 100°C, has increased significantly. Nonetheless, doubts remain regarding the possibility of effectively integrating HTHPs into industrial processes from both technical and economic perspectives. The article describes the possible HTHP integration pathways in the ceramic tile manufacturing process and identifies which HTHP solutions are technologically feasible, including an assessment of their economic and environmental impacts.

Keywords: High-temperature heat pump; ceramic sector; hard-to-abate; electrification; GHG emission reduction.

1. Introduction

Industrial production processes account for a significant share of overall environmental emissions in Europe due to their impact on greenhouse gases (GHGs), air pollutants, wastewater discharges, and waste generation. The Industrial Emission Directive (IED) aims to achieve a high level of protection for human health and the environment as a whole by reducing harmful and greenhouse gas (GHG) industrial emissions across the EU [1], particularly through the better application of Best Available Techniques (BAT). Increasing energy efficiency and renewable energy in industrial processes is part of the IED, and it is also coherent with the Clean Industrial Deal (CID), launched in February 2025 [2], which outlines actions to turn decarbonisation into a driver of growth for European industries. Then, through the Action Plan for Affordable Energy (APAE) [3], the EU Commission aims to i) speed up the roll-out of clean energy and accelerate electrification, ii) complete the internal energy market with physical interconnections, and iii) use energy more efficiently and cut dependence on imported fossil fuels. In particular, CID and APAE propose measures to enhance every stage of production, with a focus on energy-intensive industries that urgently require support to decarbonise, transition to clean energy, and address high costs, unfair global competition, and complex regulations.

The European industrial sector accounts for approximately one-quarter of the EU28's final energy consumption, with 215 million tonnes of oil equivalent (Mtoe) in 2023 [4]. Meanwhile, waste heat sources are present in all industries, totalling 300 TWh/year in the EU. Figure 1 shows the distribution of EU28's final

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energy consumption in the industrial sector for 2023 (based on data extracted from [4]). The chemical and petrochemical industry ranks first with 20.6% of the whole consumption, while non-metallic minerals (which includes the ceramic industry in the Eurostat classification), pulp and paper, and food and beverage industries are, respectively, at the second (13.9%), third (13.7%) and fourth (12.4%) places.

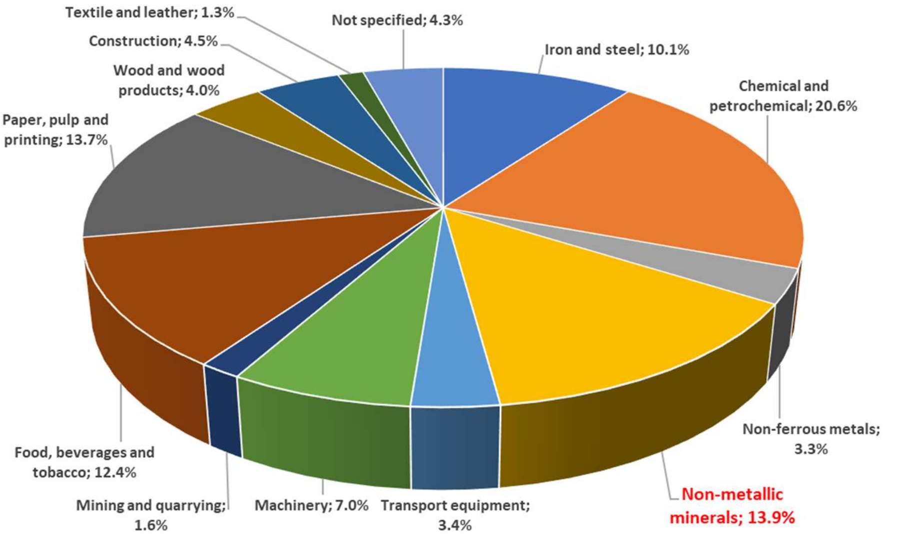

Figure 1. Distribution of final energy consumption in the EU28's industrial sector in 2023 (based on data extracted from [4]). The ceramic sector is classified under the "Non-metallic minerals" category (caption in red).

Industrial process heat accounts for more than two-thirds of total energy consumption in industry, and over one-third of this process heat demand is at relatively low temperatures (i.e., below 200°C) [5]. Furthermore, a good match with the waste heat potential is found in the industrial sector [5,6]. The so-called "heat upgrade technologies", such as traditional heat pumps, mechanical vapour recompression heat pumps, absorption heat pumps and absorption heat transformers, allow low-temperature heat (i.e., ambient heat, waste heat or renewable heat) to be upgraded to higher temperatures [7]. Heat upgrade technologies are promising solutions for enhancing the efficiency of industrial processes and reducing GHG and polluting emissions. In traditional heat pumps, the recovered heat vaporises the working fluid in the evaporator, which is compressed to a higher temperature by electrical power. The working fluid is condensed and expanded in a valve, and then the cycle repeats [8]. In mechanical vapour recompression (MVR) heat pumps, the pressure and, consequently, the temperature of waste gases are increased by a compressor, thereby allowing the heat to be reused. The most common type of vapour compressed by MVR is steam. MVR heat pumps are widely used in specific industrial applications, such as evaporator and distillation installations, seawater desalination and industrial wastewater treatment plants [9,10]. Absorption heat pumps (AHPs) and heat transformers (AHTs) are thermally activated heat upgrading technologies in which the compression of the working fluid is achieved in a solution circuit consisting of a generator, an expansion valve, a solution pump and an absorber. The difference between AHP and AHT is that in an AHT, thermal energy required to vaporise the working fluid in the evaporator is supplied at a higher temperature than that of the heat required for separating the working fluid pair in the generator. In the Sustainable Development Scenario of [11], both electrically and thermally driven heat pumps are considered a potentially economically viable solution for heat supply at temperature ranges of up to 400°C. However, according to both IEA HPT Annexes 35 [12] and 58 [13], the commercially available heat pumps are limited to supply temperatures below 100°C, while the availability of systems capable of higher supply temperatures or high-temperature heat pumps (HTHPs) is limited. In particular, the integration of HTHPs into existing processes still needs to be demonstrated at a relevant scale in the medium temperature range (90-150°C) to improve market confidence [14].

The EU ceramics industry generates an annual production value of around €30 billion, accounting for approximately 25% of global production, and employs over 200,000 direct jobs throughout the EU [15]. The major producing countries in the EU are Italy, Germany, Spain, France, the UK, Portugal and Austria. Production is also strong in the Czech Republic, Poland, and Hungary, all of which have growing and dynamic ceramic sectors that traditionally export to other EU countries. The EU ceramic industry is a world leader in producing value-added and high-quality ceramic products manufactured by flexible and innovative companies, the majority of which are SMEs. Over the last decade, the market landscape has undergone significant changes with the emergence of low-cost products from new competitors in emerging and developing countries. Producing ceramics is an energy-intensive process. Total emissions from the European ceramic industry amount to 19 million tonnes of CO_2 annually, which is roughly 1% of Europe's total industrial emissions covered by the EU Emissions Trading System (ETS). Around 90% of emissions come from three sectors: bricks and roof tiles, wall and floor tiles and refractories. On the other hand, being mostly composed of SMEs and small emitters, ceramic installations represent 10% of all industrial installations under the ETS [16]. The European ceramic sector has reduced its total emissions by around 33% since 1990 and by more than 45% since its emissions and production peak in the 2000s, primarily by optimising processes, increasing production efficiency, and implementing fuel substitution. However, the most significant reduction in carbon emissions occurred in the 1980s when ceramics almost entirely switched from "heavy" fossil fuels (i.e., coal and kerosene) to natural gas. The European Ceramic Industry Association has developed an emissions reduction model that combines a range of measures to achieve a gradual reduction in emissions, aiming to reach carbon neutrality by 2050 [16], including higher energy efficiency and the introduction of emerging and breakthrough technologies, such as HTHPs. While there is potential for a high impact of HTHPs in the ceramic industry [17,18,19], several barriers (including regulatory ones to implementation, low fossil-fuel prices, adaptation to the industry processes, high investment cost, lack of knowledge and trust) hinder a wider adoption of HTHPs. The first step for the market uptake of HTHPs in the ceramic industry is the preliminary techno-economic evaluation of the HTHP integration in existing facilities. Nevertheless, literature about HTHP application in the ceramic industry is limited [20].

To address the literature gap regarding the application of HTHP in the ceramic industry, this paper presents the design of alternative options to integrate an HTHP system that supplies heat up to 180°C to ceramic tile dryers. For each case, the design is optimised to guarantee i) the use of sustainable working fluids and ii) the highest COP. Environmental and economic impact assessments are performed to evaluate CO_2 savings, the net present value, and the payback time of the proposed solution. The sustainability impact of techno-economic parameters on the environmental and economic performances is estimated through a sensitivity analysis.

2. Case study description

The case study is based on a ceramic tile manufacturing plant located in Imola (Italy) with a production capacity of up to 6.5 million square meters per year of porcelain stoneware tiles. The ceramic tile manufacturing process is a complex activity that involves several stages (Figure 2), ranging from the treatment and preparation of raw materials to the production of finished products. In the case of the plant under investigation, all these processes are realised on the same site.

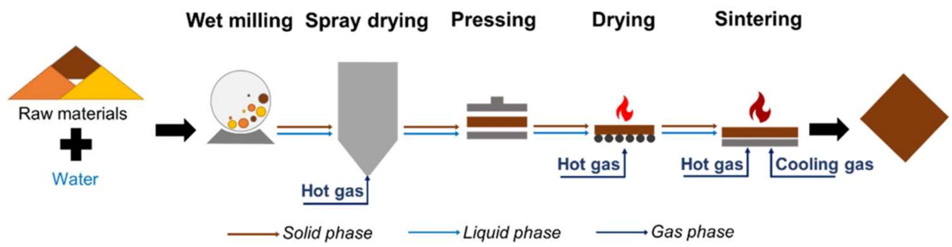

Figure 2. Synthetic process flow diagram of ceramic tile manufacturing.

The raw materials are composed of clays, plastic clays, feldspars, and sands, primarily feldspathic. The raw materials are typically mixed with a fraction of production scraps using a wheel loader and discharged into two weighing hoppers, which enable control over the mix formulation. In the grinding stage, the raw materials are further mixed and milled. In the plant, the grinding is a wet milling in which the raw materials are milled using ball mills together with water to produce a slurry (also called "slip" or "*barbottina*", in Italian), which is an aqueous suspension of the finely ground raw materials with approximately 32-33% water content. The screening residue is recycled, while the grinding water is generally supplemented with wastewater from other processing stages. The water is preheated up to 70-75°C using waste heat from a combined heat and power (CHP) plant. Colourants can be added at this stage, loaded directly into the mills. The slip is stored in large underground tanks and subsequently atomised using a spray dryer (also called "atomiser"). The slip is fed at high pressure (up to 30-35 bar) through nebulising nozzles into the atomiser, where it encounters a stream of hot air at a temperature of around 500-550°C. The hot air stream is generated by natural gas burners and/or through the recovery of heat from the flue gas of the CHP unit. The atomisation aims to achieve an almost instantaneous evaporation of the water content in the slip, thus allowing the production of hollow fine particles (100-600 μm equivalent diameter) with a rounded shape suitable for pressing. The residual humidity of the atomised slip powder is about 5-6%. The atomised slip exits at a temperature of around 50°C, and it is usually stored in large silos close to the spray dryer. In the pressing stage, the atomised slip is compacted to contain shrinkage and greatly reduces porosity in the fired product, while improving the material's roughness and mechanical characteristics upon firing. A cutting machine imparts the required dimensions to the pressed material, based on the format desired by the final product. The following stage is the drying of ceramic tiles. Dryers are used to remove residual moisture from the tiles and achieve the target humidity of 0.3% before firing. There are two possible dryer configurations, i.e. vertical and horizontal. The drying process is achieved by recovering waste heat from the kiln and is integrated with natural gas burners. The temperature inside the dryers is around 160-200°C. Once dried, the tile, if necessary, is subjected to a surface glazing treatment where ceramic or vitreous materials are applied to give it colour and wear resistance. The firing (or sintering) process is the last thermal treatment stage to which the ceramic tiles are subjected. The firing is realised in a methane-fueled roller kiln. The kiln can be divided into subsequent sections: i) preheating, in which the dried tiles entering the kiln are heated up to 600°C, thus reaching the desired moisture content and preventing thermal shocks before entering the firing or sintering section. The firing section formalises and completely changes the properties of the green part to the grey part of the tiles, removes any pores and binds together constituents of ceramic tiles. Moreover, the firing process improves the strength and reduces the fragility of tiles. The temperatures are as high as 1215°C. Once the firing is completed, the tiles need to be cooled for further process stages. The cooling phase is divided into two stages: a rapid cooling down to 600°C, and a slow cooling from below 600°C to ambient temperature. The majority of the heat content in the flue gas is recovered for air preheating, and therefore, the flue gas temperature at the kiln chimneys is approximately 120°C. Table 1 summarises the capacity and characteristics of the equipment installed in the ceramic tile manufacturing plant under analysis.

Table 1. Characteristics of the main equipment installed in the ceramic tile manufacturing plant under analysis.

Equipment	Number	Capacity
Wet mills	6	Total capacity of 46,000 kg/h of slip
CHP plant	1	6 MWel + 5 MWth
Spray dryer	1	9000 kg/h of water
Press	5	Total capacity of 55,000 square meters per day of ceramic tiles
Horizontal dryer	2	Total capacity of 8,000 kg/h of ceramic tiles
Vertical dryer	2	Total capacity of 8,000 kg/h of ceramic tiles
Kiln	2	Total 10 ton/h ceramic tiles production

3. HTHP integration into ceramic tiles manufacturing processes

Since the focus of the paper is on HTHP integration in the ceramic tile manufacturing, finding a suitable application for HTHP requires an analysis of the existing heat demand for each process and the related temperature. There are some limitations to the following analysis, as the availability of data related to current natural gas (and electricity) consumption does not allow for direct measurement of each equipment. Another limitation is the availability of aggregated data, which is only provided on a monthly basis, regarding ceramic tile production. Finally, the air (or flue gas) flow rates are not measured, whereas temperature and humidity are typically monitored at several stages of the entire manufacturing process. To design a strategy for energy reduction, it is essential to determine the state of energy consumption by analysing key performance indicators of the different processes with accuracy through the implementation of monitoring tools and energy management systems [21].

Table 2 provides a summary of the temperature levels reached in the main processes that require heat. It is evident that HTHP can be applied only in the drying process; in fact, water and slip pre-heating in the milling and atomising stages, respectively, can benefit from low-grade waste heat recovery from other thermal processes. Meanwhile, air heating in the spray dryer and the kiln requires temperatures that are not achievable with the current HTHPs. Figure 3 shows a schematic of the mass and energy balance of a dryer. Since the natural gas measurement of each dryer is unknown, the whole consumption of the operating dryers is divided by two in the analysis, thus hypothesising an average behaviour of each piece of equipment. According to the dryer manufacturer's information, the mass balance incorporates hot flue gas recirculation and mixing before discharge through the chimney, allowing for heat recovery and reduced natural gas consumption.

Table 2. Temperature levels of heat demand for the main thermal processes.

Process	Fluid	Temperature level	Heat source
Wet mills	Water	70-75°C	Waste heat from the CHP plant
Spray dryer	Air	500-550°C	Waste heat from the CHP plant and natural gas burners
	Slip	50-60°C	Waste heat from the CHP plant
Dryer	Air	160-200°C	Natural gas burners and waste heat from the kiln
Kiln	Air	600-1200°C	Natural gas burners

Figure 3. Schematisation of the mass and energy balance of a dryer.

Two different configurations have been designed and analysed, using the process flue gas as a heat source. Flue gas condensation is avoided by maintaining the flue gas temperature above the dew point, thereby preventing corrosion risks. In the first configuration (#1), the HTHP is integrated for hybridisation of the drying process and supports the pre-heating of combustion air; in this initial configuration, the target condensation temperature is set at 140°C. In the second configuration (#2), a cascade HTHP is proposed, aiming to cover all the heat demand of the dryer, thus being ideally independent from natural gas consumption and 100% electrified. Different refrigerants have been evaluated using the Honeywell Genetron Properties 1.4.2 Suite [22]. R601a emerged as the most effective in terms of thermodynamic cycle performance for configuration #1 and for the high-temperature (HT) section of the cascade heat pump in configuration #2. For the low-temperature (LT) section of the cascade heat pump, the selected refrigerant is R600a. Nevertheless, it is worth mentioning that both iso-pentane (R601a) and iso-butane (R600a) are highly flammable and would require careful installation and management due to safety concerns [23]. Table 3 summarises the two configurations analysed in the following chapter.

Table 3. The two configurations analysed for HTHP integration in the ceramic tile dryer.

#	Refrigerant	Type	Heat source	Target condensation
1	R601a	Single HP	Dryer flue gas	140°C
2	R601a (HT) and R600a (LT)	Cascade HP	Dryer flue gas	180°C

4. Feasibility study and preliminary techno-economic and environmental assessment

Figure 4 presents the process flow diagram (PFD) of configuration #1, as shown in Table 3, along with the corresponding mass and energy balances. The same analysis has been carried out for configuration #2, and the results are summarised in Table 4.

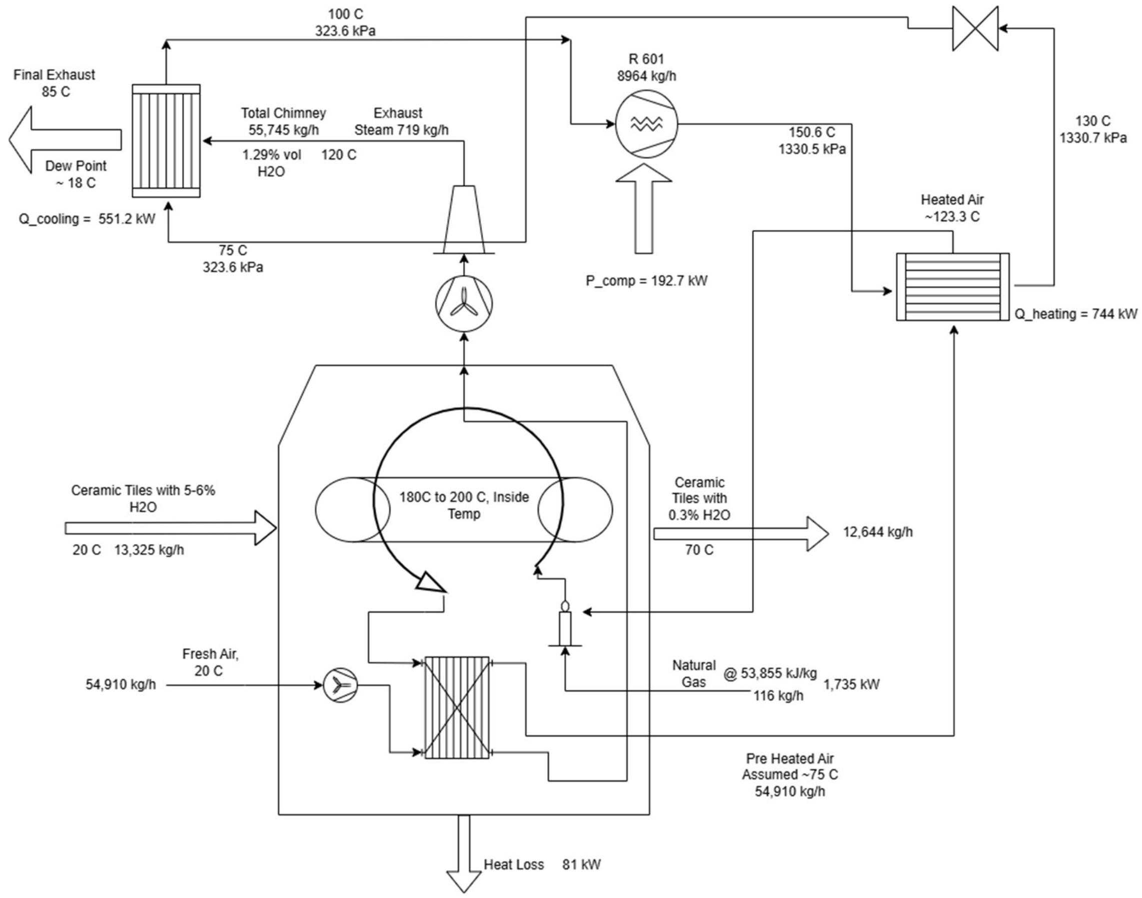

Figure 4. Schematisation of the mass and energy balance of the configuration #1.

Table 4. Operating conditions of the two configurations for HTHP integration in the ceramic tile dryer.

#	Condenser inlet	Condenser outlet	Evaporator inlet	Evaporator outlet	Flue gas outlet	Hot air outlet	Sink capacity	COP
1	150.6°C	130.0°C	75.0°C	100.0°C	85.0°C	123.3°C	0.74 MW	3.86
2	192.6°C	110.0°C	15.0°C	31.7°C	75.0°C	180.0°C	2.48 MW	2.25

The comparison between the two configurations is performed by considering two different parameters: the net present value (NPV), measured in Euros, and the payback time (PT), measured in years. The NPV is computed as in Equation 1, where t (years) is time, n (number of years) is the time period considered for the investment evaluation (which will be assumed equal to both depreciation and technical life time of plants for treatment simplicity purpose), i (%) is the discount rate, F_t (Euro) is the net cash flow at year t. The contribution of tax is not taken into account to simplify the economic assessment.

$$NPV = \sum_{t=0}^{n} \frac{F_t}{(1+i)^t} \qquad (1)$$

The net cash flow F_0 at t=0 corresponds to the starting investment: the simplifying hypotheses of full investment payment and plant operation start in the same year (t=0) are also assumed. The net cash flow for period t > 0 was computed taking into account the main costs C_t and revenues R_t components, as highlighted in Equation 2.

$$NPV = -F_0 + \sum_{t=1}^{n} \frac{[R_t \cdot (1+e)^t - C_t \cdot (1+e)^t]}{(1+i)^t} \qquad (2)$$

Revenues R_t include i) natural gas consumption savings in the ceramic tiles drying process due to HTHP integration, and ii) CO2 emission certificate savings. On the other hand, costs C_t account for i) electricity consumption from the grid operator, and ii) operation and maintenance costs of the HTHP integration. To simplify the analysis, it is assumed that all the required electricity is purchased from the grid as renewable certified energy, thus maximising the CO_2 emission reduction. Equation 3 and Equation 4 define, respectively, how R_t and C_t have been computed: E_{th} is the heat demand covered by the HTHP (MWh/year), c_{ng} is the cost of natural gas (€/MWh), COP is the efficiency of the HTHP (%), η_{th} is the natural gas burner efficiency (%), c_{el} is the renewable electricity purchasing price (€/MWh), t_{CO2} is the yearly saving of equivalent CO_2 emission (ton of eq CO_2/year), c_{CO2} is the trading emission cost of CO_2 (€/t_{CO2}), $C_{O\&M}$ is the operation and maintenance cost of the HTHP integration. The yearly natural gas savings V_{ng} (Nm^3/year) can be computed as in Equation 5.

$$R_t = E_{th} \cdot c_{ng} \cdot \frac{1}{\eta_{th}} + t_{CO_2} \cdot c_{CO_2} \quad (3)$$

$$C_t = E_{th} \cdot c_{el} \cdot \frac{1}{COP} + C_{\mathrm{O\&M}} \quad (4)$$

$$V_{ng} = E_{th} \cdot \frac{1}{\eta_{th}} \cdot \frac{1{,}000 \cdot 3{,}600}{LHV} \cdot \frac{273.15}{298.15} \quad (5)$$

Figure 5 shows the NPV based on the values included in Table 5 for the two different configurations. The first configuration is the only one with a positive NPV at the end of the HTHP lifetime (approximately €186,000) and a PBT of 15 years. In the second configuration, a clear NPV decreasing trend is highlighted. The key parameter playing a difference in the comparison is the COP of HTHP integration. The COP of configuration #1 is almost 70% higher compared to the second one, thus resulting in almost half the electricity consumption per kWh of natural gas saved. Nevertheless, the impact of the first configuration is limited if compared to the second configuration: in fact, while through the first configuration a cumulated reduction of 21,833 tons of CO_2 can be reached over the 20 years of operation, the second configuration offers a chance of full decarbonisation of the drying process, with a cumulated reduction of CO_2 emission up to 73,171 tons.

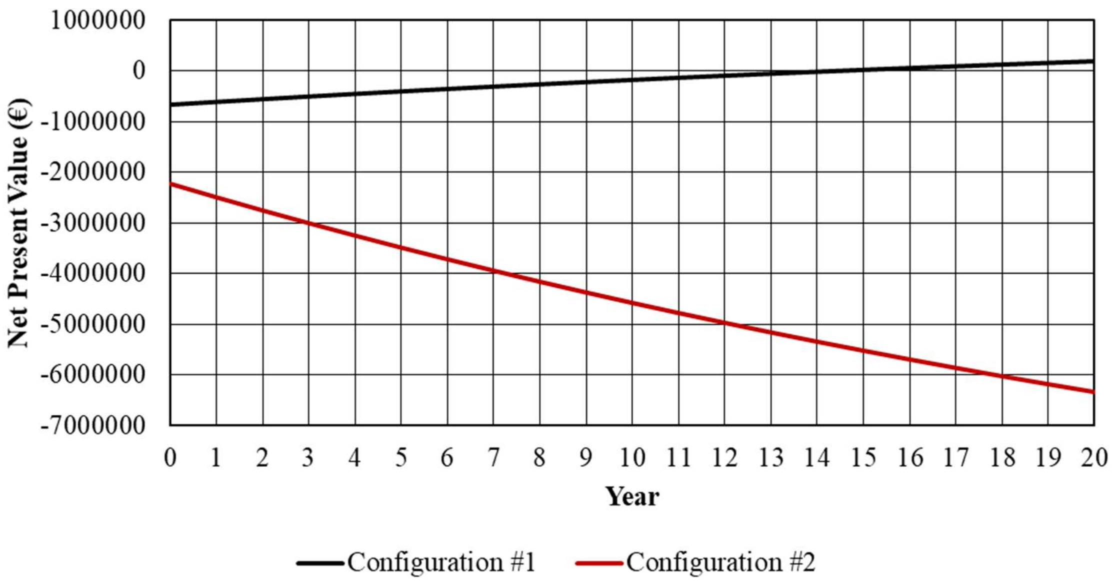

Figure 5. NPV of the three HTHP integration configurations.

Table 5. Assumptions about economic assessment.

Item	Symbol	Value	Comments
HTHP integration cost	F_0	900 €/kW	Cost adapted from [24].
Heat demand	E_{th}	2,317 MWh/year for #1 and #2 7,700 MWh/year for #3	For the operation of the HTHP, 7,000 hours per year have been considered (two months of closure per year).
Natural gas cost	c_{ng}	40 €/MWh	Mean value for Italian industries in 2024.
Renewable electricity cost	c_{el}	150 €/MWh	Mean value for Italian industries in 2024.
Natural gas burner efficiency	η_{th}	90%	Standard value for commercial industrial natural gas burners.
Ton of CO_2 emissions saved per year	t_{CO2}	1,613 ton/year	Computed by considering an emission factor 1.956-ton CO_2 per 1,000 Sm_3 of natural gas.
CO_2 emission trading cost	c_{CO2}	70 €/ton	Mean value for 2024 in Italy.
HTHP O&M costs	$C_{O\&M}$	3% of F_0 per year	Assumed as 3% of HTHP integration cost [24].
Natural gas LHV	LHV	35,880 kJ/m^3	As guaranteed by contract to the pulp and paper industry. The reference conditions are 25°C and 1 bar.
Discount rate	i	5%	
Inflation rate	e	2%	
HTHP lifetime	n	20 years	

Therefore, it is essential to assess the primary parameters, aside from COP, that impact the economic sustainability of HTHP integration, as the environmental ones have been established. In the following analysis, the second configuration will be examined to assess the framework conditions under which the solution offers a positive NPV and a reasonable PBT, as it is the one that can drive the ceramic tile drying process to complete electrification. Figure 6 shows the results of a sensitivity carried out by considering the variation of four economic parameters (HTHP integration cost, natural gas cost, renewable electricity cost, and CO_2 emission trading cost). Since the four economic parameters assessed are linearly influencing the NPV (as defined in Eq. 2), and their variation does not impact the values of other parameters, as assumed by the definitions and values introduced in Table 5, the resulting NPV sensitivity curves are expected to be linear. Natural gas and renewable electricity costs play the primary role in determining the economic sustainability of HTHP integration. In particular, NPV is particularly sensitive to variations in the costs of renewable electricity. For instance, a 50% reduction in renewable electricity costs (while keeping the other parameters constant) generates a 130% increase in NPV, resulting in a positive NPV of €1,994,619 and a PBT of 10 years. In this condition, the electricity-to-natural gas cost ratio reaches a value of 1.9, whereas in the current framework (see Table 5), the ratio is equal to 3.8. Therefore, the economic advantage in HTHP integration is highly influenced by the Country or region in which the installation is planned, and in particular by the local energy prices [25]. Policy makers can use this leverage to favour HTHP integration in hard-to-abate industries: while local policies can have a limited impact on the energy commodities price, fiscal tools can be used to incentivise the use of electricity instead of natural gas (i.e., taxes and levies) [26]. A minor but still relevant role can be played by the CO_2 emission trading cost, which policymakers should use to bridge the gap between natural gas and electricity prices, thereby reducing PBT and the associated investment risk for industries. Nevertheless, the adoption of CO_2 emission trading should be carefully designed to avoid generalised energy cost increases and inflation impact [27]. Finally, the HTHP integration cost (or CAPEX) has a minor impact among the considered parameters. On the other hand, an option to reduce the cost of renewable electricity is to generate it locally (i.e., using photovoltaic panels and batteries for daily or seasonal storage). In this case, the electricity cost may be reduced, but the HTHP integration cost would increase due to the additional expenses for purchasing PV panels, inverters, and batteries, as well as installation costs.

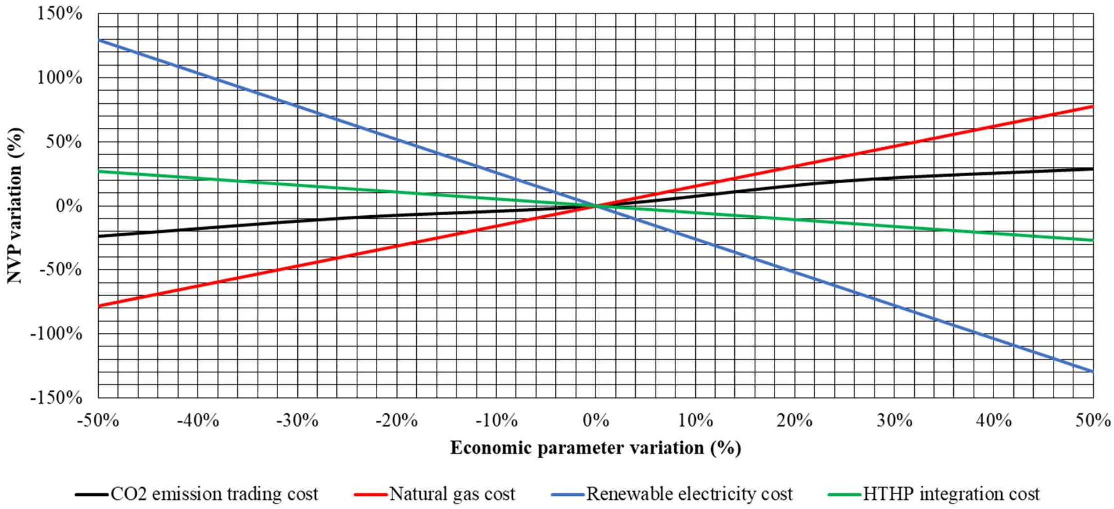

Figure 6. Sensitivity analysis of the main economic parameters' impact on NPV for the HTHP integration configuration #2.

5. Conclusions

The paper analyses the application of HTHPs in a ceramic tile manufacturing company located in Imola (Italy). Specifically, the paper compares two distinct configurations for HTHP integration in the ceramic tile drying process. The temperature lift from the heat source to the heat sink may vary according to the HTHP capacity and the targeted end-user temperature, allowing for a COP between 2.2 and 3.8 by applying state-of-the-art technologies using R601a and R600a as refrigerants. The hypothesis is to feed the HTHP with the renewable electricity purchased by the grid. The HTHP integration in the industrial process produces a more efficient use of the energy. In fact, up to 73,171 tons of CO_2 equivalent emissions can be avoided during the 20-year operation period when the drying process is completely electrified. Nevertheless, the economic sustainability of the HTHP integration is hindered by the high ratio of electricity to natural gas costs. Under current framework conditions, the electrification of about 30% of the energy required for ceramic tile drying can be achieved through HTHP integration, with a 20-year NPV of approximately €186,000 and a PBT of 15 years. Additional investigations are needed to better estimate investment costs through a detailed preliminary design, including the effects of using flammable refrigerants.

An available option for the ceramic company to increase the economic sustainability in HTHP integration is to generate on-site the renewable electricity required for the scope, for example, by installing a photovoltaic plant that includes batteries for energy storage. Nevertheless, this would require a site-specific analysis to assess the existing limitations to local electricity generation in terms of space availability, which will be carried out in the future. Policymakers can also play a significant role. In fact, on one side, they can use taxes and levies to make electrification more attractive in comparison with natural gas use and reduce the electricity-to-natural gas gross cost, while acting on the CO_2 emission trading system, they can further support the adoption of HTHP by covering the market gap between electricity and natural gas cost.

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