# ASSESSMENT OF HORIZONTAL DECARBONISATION TECHNOLOGIES IN THE CERAMIC INDUSTRY

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## ABSTRACT:

This paper presents a general overview of the various horizontal decarbonisation technologies potentially applicable to the ceramic tile industry, without taking into account their economic feasibility, as that depends on multiple factors exogenous to the ceramic industry. The ceramic sector is a heat-intensive industry, depending mainly on the combustion of natural gas and thus a generator of $CO_2$ emissions. It is well known that $CO_2$ is one of the greenhouse gases (GHG) listed by the Inter-governmental Panel on Climate Change (IPCC), so it has been the subject of detailed international monitoring for many years, given its relationship with global warming and therefore Climate Change. In late 2019, the European Commission published the European Green Deal, which is the new strategy to be implemented in the fight against climate change. The main goal is to reduce GHG emissions compared to 1990 levels by up to 50-55% by 2030 and to make Europe the first carbon-neutral continent by 2050. The scope for the technologies currently used in the ceramic tile manufacturing process to reduce their direct emissions is certainly limited. With the ambitious emission reduction targets set at European level, the sector will have to radically alter its manufacturing processes through specific decarbonisation measures (bringing down maximum temperatures, dry milling, etc.) and/or by incorporating horizontal decarbonisation technologies. Among such horizontal decarbonisation technologies that are candidates for contributing to a significant reduction in emissions are the use of alternative fuels, such as hydrogen or biofuels, $CO_2$ capture systems, or electrification of the main heat-generating systems, provided that the electricity comes from a renewable source.

In view of the current level of maturity of some of these horizontal technologies, it is not unrealistic to imagine a demonstration pilot plant coming on stream in the not too far future, which will help to encourage widespread implementation across the industry in the medium term. However, that will only be possible if the institutional and financial support and capital investment necessary are forthcoming to bring about the technological transition that is just around the corner.

## 1 INTRODUCTION

The European Union's new strategy (as laid down in the European Green Deal) indicates that the main target is to drastically reduce GHG emissions by up to 55% by 2030, and to make Europe the first carbon-neutral continent by 2050.

Fulfilment of such ambitious goals can only be achieved with major technological transformations, and among the different options being proposed are the use of alternative fuels, such as biomass, biogas or biomethane, as well as hydrogen, the incorporation of new technologies, such as $CO_2$ capture systems, the integration of renewable energies, or the use of electric dryers and kilns using electricity from renewable sources fed from the grid or generated on-site at the production plant (Figure 1).

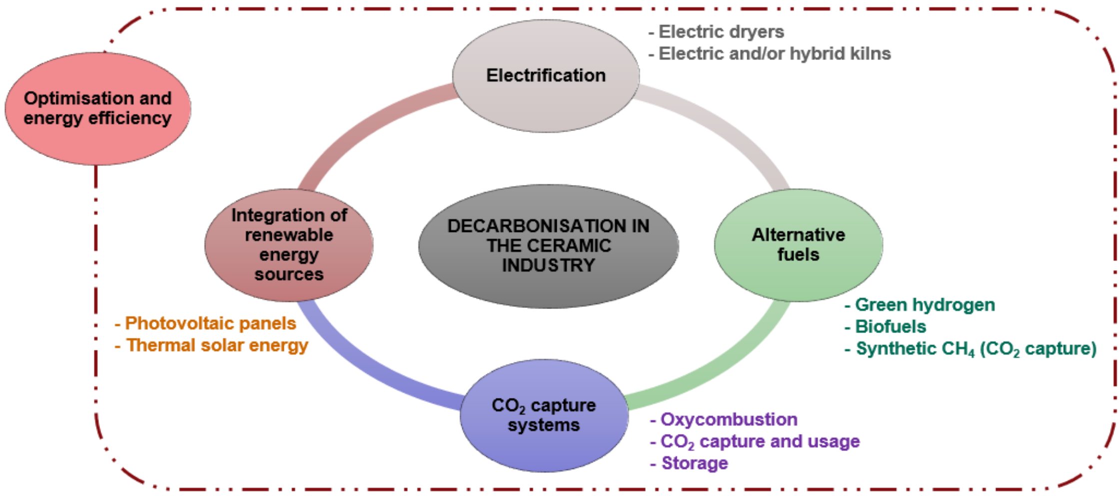


***Figure 1.*** *Decarbonisation technologies potentially applicable to tile manufacturing technology*

Future low-carbon technologies, together with widescale deployment of renewable energies and hydrogen production and transport infrastructures that are already being planned, are expected to enable the ceramic industry to substantially improve its carbon footprint and achieve a carbon-neutral production process over the next few years.

The ceramic industry accounts for a significant part of the power consumed in the region of Valencia and, consequently, it will play an important part in this ecosystem. In consequence, it will no doubt have to align itself with the energy sector in order to adapt its manufacturing process to future energy sources and thus contribute to the energy transition.

Energy-intensive industries, such as the ceramics industry, are essential to speeding up energy transition, as they can absorb large volumes of energy free of GHG emissions and thus rapidly push down the production costs of new fuels and make them competitive.

Therefore, over the next few years, R&D&I efforts must be directed at transforming or adapting current manufacturing processes and developing new disruptive technologies that enable decarbonisation targets to be achieved in both the short and long term.

To address this transition, new solutions from the technical and non-technical point of view are needed, together with greater collaboration between companies from different energy-intensive sectors, as the main technological challenges are similar across all process industries.

In addition, the Spanish ceramics industry competes on a global playing field and its competitiveness must be protected throughout the transition. This transformation calls for unprecedented levels of change. New technologies are likely to have a higher cost, so their roll-out may entail a risk of lower corporate competitiveness compared to other producer countries that do not have the same $CO_2$ costs as the E.U., which in turn may increase the risk of companies relocating. These risks should be averted by means of an effective policy framework or by boosting innovation and the scaling of technologies, thereby reducing the inherent cost.

This paper offers an overview of the alternative technologies either already available or in the development stage that may help the ceramic industry to decarbonise in the coming years.

## 2 THE CERAMIC TILE MANUFACTURING PROCESS

The ceramic tile manufacturing process involves three main stages in which $CO_2$ is emitted. These stages are the spray-drying of raw material slurries, the drying of unfired bodies, and firing. For that reason, this paper focuses on those three types of process, which are the ones that will have to be adapted to ensure the future manufacturing process is carbon neutral.

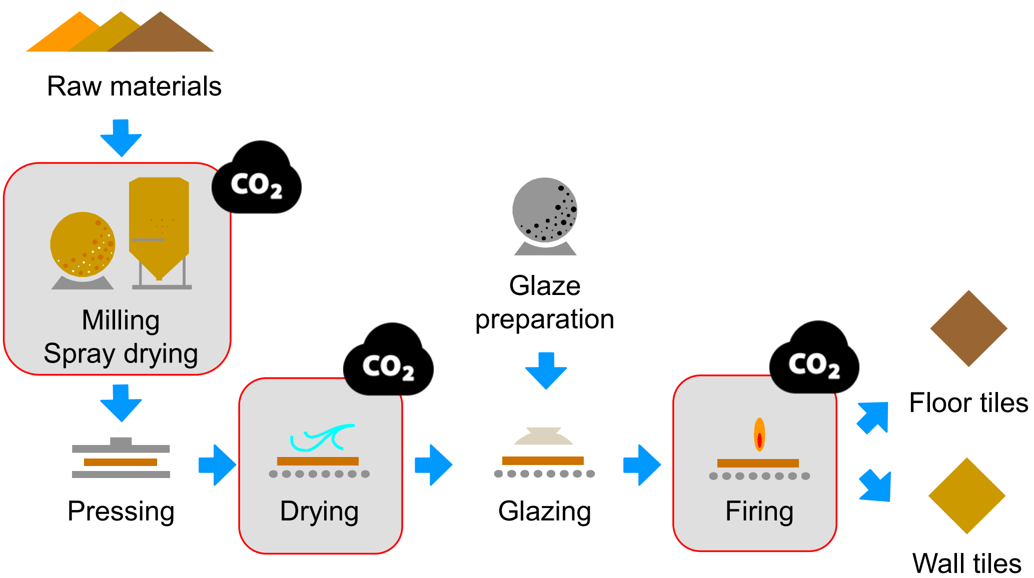


***Figure 2.*** *Tile manufacturing process*

These three stages of the manufacturing process all call for inputs of heat energy, which comes from the combustion of natural gas. The characteristics of each system in terms of energy and $CO_2$ emissions are described below.

## 2.1 SPRAY DRYERS

In the case of spray dryers, drying gases need to reach temperatures of between 450º and 600ºC to dry the slurry and obtain granulated spray-dried powder.

Evaporation capacities in spray dryers range widely from 1,200 l/h to 20,000 l/h for the largest spray dryers. The output of spray-dried granules from a spray dryer varies greatly and depends on both the size and design of the dryer and the characteristics of the slurries. Within the evaporation capacity range mentioned above, spray-dried granule production ranges from 5,000 kg/h to over 50,000 kg/h.

The heat requirements in a spray-dryer process are very high, since it calls for a continual stream of high-temperature gas. Average **specific consumption** in the spray-drying process is **476 kWh/t** dry spray-dried powder (based on the UHV of natural gas) with the plant running at a steady pace.

In general, between 60-70% of the energy fed into a spray-dryer is used to dry the slurry. The rest is lost mainly in stack exhaust gases or, to a lesser extent, on surfaces in the plant, and in the spray-dried powder.

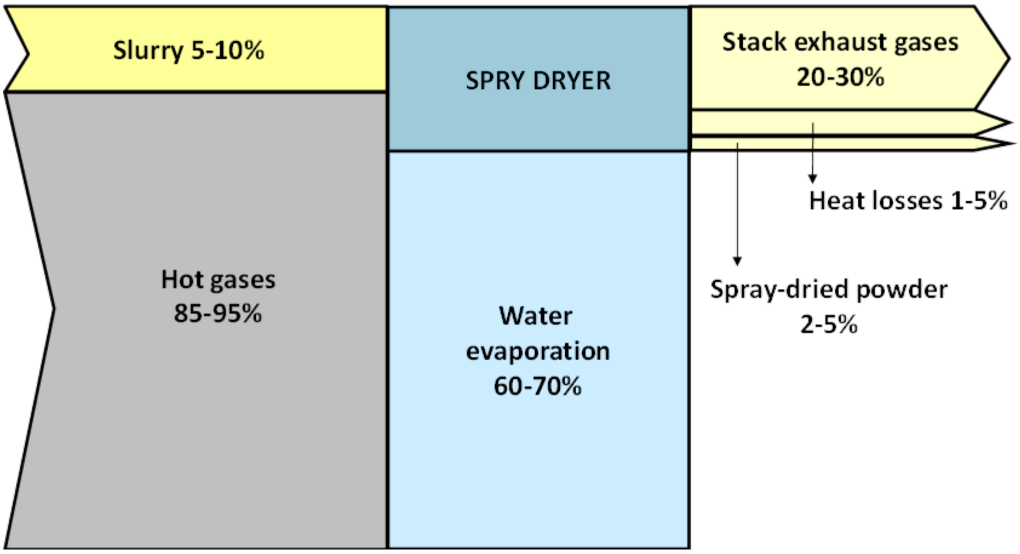


***Figure 3.*** *Sankey diagram of a spray dryer.Standard range of values in each stream. Source: ITC-AICE.*

As far as $CO_2$ emissions are concerned, it is estimated that a spray dryer emits over **86 kg $CO_2$/t dry solid.** Therefore, considering an average production figure of 22 t dry solid per hour, a spray dryer can emit about **48 t $CO_2$/day**, but the $CO_2$ is diluted in the gas exhaust stream in a proportion of between **1-2%.**

## 2.2 TILE DRYERS

The granulated powder obtained from spray dryers contains between 5% and 7% water to facilitate the next stage, where it is formed by pressing. After the tiles have been pressed, they need to go through a drying process, for two reasons: to eliminate moisture (thus increasing their mechanical strength), and to increase their temperature (to ensure the next stages of glazing and decorating perform properly).

Pressed tiles can be dried in vertical or horizontal dryers, in which a stream of hot gases, usually produced by the combustion of natural gas, is fed in direct contact with the pressed tiles to evaporate the water they contain. It is therefore a process of drying by forced hot gas convection and the temperature of the gases is around 200ºC.

In both types of dryers, hot air can be recovered from cogeneration plants or from other systems that have waste heat, such as kilns. Total heat supply to the dryer is the sum of the heat energy recovered and the heat energy supplied by the combustion of natural gas and consumed in the dryer.

The energy balances calculated for dryers indicate that between 30-35% of the energy supplied is used to dry the tiles. Usually, the energy used to heat the tiles accounts for between 15-20% of all the energy supplied to the dryer, and therefore overall efficiency in drying stands at between 45% and 55%, i.e., approximately half of the energy supplied to the dryer is used and the other half is lost.

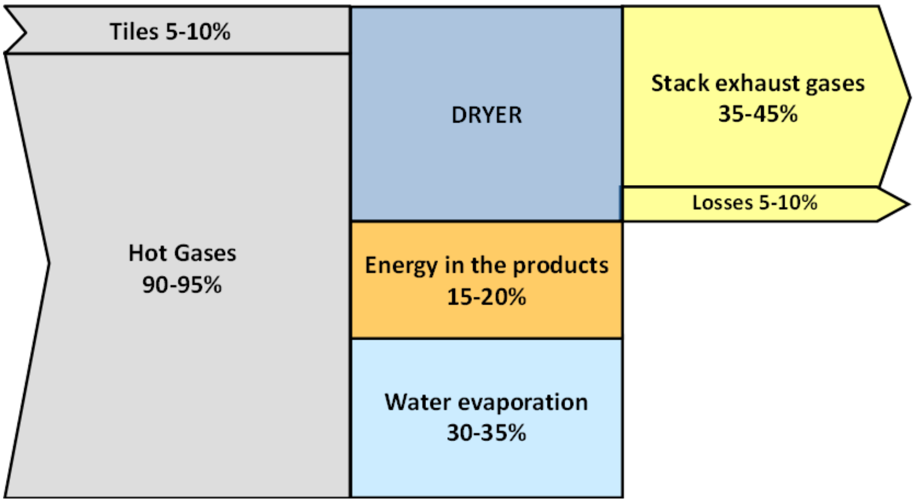


***Figure 4.*** *Sankey diagram of a tile dryer. Source: ITC-AICE.*

Average heat energy consumption is around **125 kWh/t dry solid** (based on the UHV of natural gas) with the plant running at a steady pace. No significant differences in energy consumption have been found between vertical and horizontal dryers, or per type of processed product.

As far as $CO_2$ emissions go, it is estimated that a dryer emits over **21 kg $CO_2$/t dry solid.** Therefore, taking an average production rate of 7 t dry solid per hour, a dryer can emit about **1 t $CO_2$/day,** but that $CO_2$ is highly diluted in the gas outlet stream, at a percentage rate of around **1%.**

### 2.3 SINGLE-DECK ROLLER KILNS

After glazing and decorating, the pressed ceramic body is fired mostly in single-deck roller kilns. Firing temperature and the duration of the cycle depend on the size of the tiles, the kiln's rated output, the nature of the body and the coating, etc., but generally, the firing cycle lasts between 40 and 70 minutes, with a maximum firing temperature of between 1,100ºC and 1,200ºC.

The energy consumed during firing is mainly heat energy, produced by the combustion of natural gas in high-speed burners.

In addition to emissions from the combustion of natural gas, one must also take into account the reactions that occur during the firing stage. From the viewpoint of GHG emissions, the decomposition reaction of the carbonates present in the slurries is especially relevant because it is highly endothermic and generates $CO_2$ as a reaction by-product.

Studying the energy balance of a kiln shows that less than 20% of the energy supplied is used to carry out the transformations of the ceramic material that take place during firing. The rest of the energy is mainly lost through the kiln exhaust stack (between 40-60%), so recovering part of that energy either in the actual kiln or in some other stage of the process allows for greater energy usage in the kiln and thus improves overall energy efficiency.

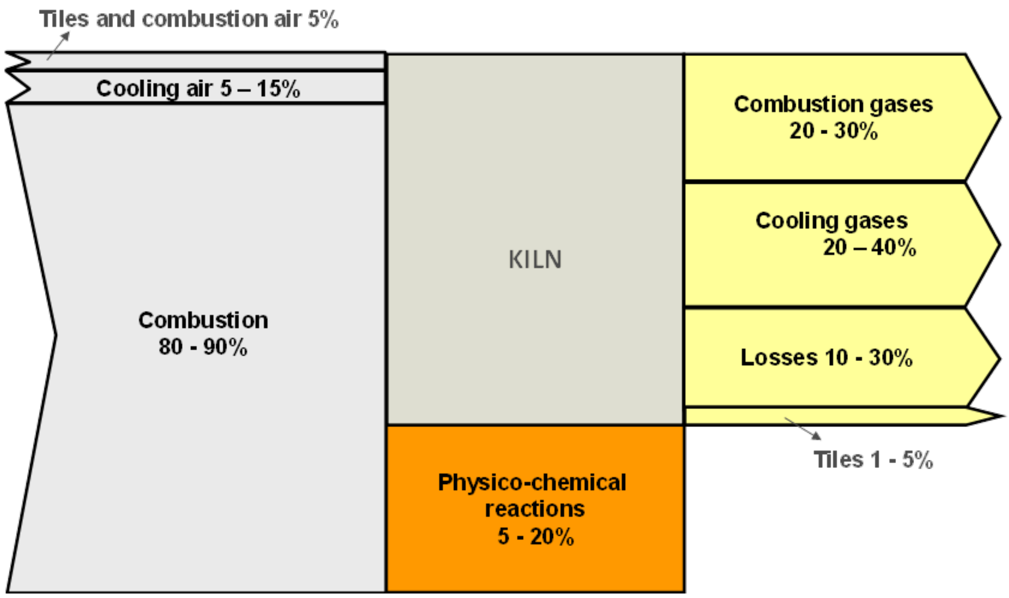


***Figure 5.*** *Thermal energy balance in a kiln. Range of standard values for each stream. Source: ITC-AICE.*

The average thermal energy consumption of a kiln can generally be estimated at **793 kWh/t fired material,** or **15.5 kWh/m²** (based on the UHV of natural gas), when running at a steady pace.

Therefore, a ceramic tile firing kiln producing **glazed stoneware and/or porcelain stoneware** emits over **150 kg $CO_2$/t fired tile,** while for **porous compositions,** emissions stand at around **220 kg $CO_2$/t fired tile.** Therefore, for a kiln with an average production of 4.5 t fired tile/h, daily associated emissions would range between **16 and 24 t $CO_2$/day.**

table 1 shows the characteristics of the gas stream from the exhaust stack of a roller kiln. It is important to remember the composition of this gas stream varies, as it contains both the products from the combustion of natural gas and from the chemical reactions that take place in the tiles. The main pollutants present in varying amounts are usually compounds of fluorine, chlorine or boron, nitrogen oxides, sulphur oxides, volatile organic compounds, and particles.

| Parameters | Value |
|---|---|
| Temperature (ºC) | 190 - 230 |
| Stack mean flowrate (Nm$^3$/h) | 11,000 – 15,000 |
| **$CO_2$ content (%)** | **3 – 5** |

***Table 1.*** *Characteristics of the exhaust gas stream from a kiln*

## 3 HORIZONTAL TECHNOLOGIES FOR DECARBONISING THE CERAMIC SECTOR

The table hereunder lists the various technical options available, identified from a comprehensive review of the literature, surveys, Delphi study with a group of experts, conferences, and work meetings with companies and business associations, etc.

The options considered were sorted into five categories, in view of the specific needs of the ceramic tile manufacturing process. The table 2 summarizes the horizontal technologies analysed for decarbonising the ceramic tile manufacturing process.

| TECHNOLOGIES | | Analysed options |
|---|---|---|
| **1** | **Improved energy efficiency** | Better combustion control<br>Minimisation of heat losses<br>Optimised waste heat recovery |
| **2** | **Use of alternative fuels** | Biomass<br>Biogas<br>Biomethane |
| **3** | **Integration of renewable hydrogen** | Use as fuel<br>Used to generate electric power |
| **4** | **$CO_2$ capture and usage** | $CO_2$ capture and management of its potential usage |
| **5** | **Electrification of heat generation** | Technologies based on electric heating |

***Table 2.*** *Horizontal technologies analysed for decarbonising the ceramic tile manufacturing process*

In addition to horizontal technologies (which may be common across sectors with high-temperature processes, such as the manufacture of other ceramic products, glass, iron & steel, cement, etc.), other specific options were identified that could have a significant impact for the ceramic tile sector, but which were not included and therefore lie beyond the scope and objectives proposed herein.

## 3.1 IMPROVED ENERGY EFFICIENCY

### 3.1.1 BETTER COMBUSTION CONTROL

In the ceramic tile manufacturing process, monitoring of natural gas combustion at industrial plants employs the test-error-correction method based on gas temperature, since no control systems are available that allow for reliable estimation of the actual flows of natural gas and air fed to each burner.

Kilns account for 60% of natural gas consumption in the ceramics manufacturing process, so that any adjustment of process variables that leads to lower consumption of natural gas will have a significant economic and environmental impact.

Consequently, any steps taken in this regard should aim - simultaneously and with the required accuracy - to characterise gas and air flows, the basic variables required to determine how the combustion process performs.

Such knowledge would explain how combustion evolves in the different stages of the thermal firing cycle, thus enabling the amounts of natural gas and air to be optimised, taking into account the internal circulation of gases in the kiln, in order to minimise energy consumption without impairing the quality of the end product.

Such actions, which today are practically inexistent in our sector, should be the basis for improving industrial heat processes to enable progress in combustion control and a reduction in energy consumption.

Studies carried out in previous years have shown that:

- The amount of air fed to burners has a significant influence on natural gas consumption in the kiln. From the point of view of energy savings and efficiency, combustion needs to be carried out with the least possible amount of air and with the conditions in the kiln atmosphere (oxygen content) stable at the right settings to ensure the quality of the product is not affected.

- Reducing average excess air in the kiln by 20% (from 40% to 20%) leads to a saving in natural gas of over 3% and thus to significant economising for companies.

- Normally, the amount of air fed to burners varies between the different areas in the kiln, so that consumption must be fine-tuned by adjustments adapted to each area of the kiln in accordance with the reactions that take place in the product and the setpoint temperature.

- A lower combustion air flowrate leads to a reduction in the stream of flue gases exiting the kiln through the exhaust stack, which means that one of the main losses of energy from the kiln is diminished.

### 3.1.2 MINIMISATION OF HEAT LOSS THROUGH KILN WALLS

Between 10% and 20% of the heat energy supplied to fire ceramic tiles is dissipated through the walls and ceiling, as well as along fan, piping and other surfaces in the kiln.

The amount of heat lost through the surfaces of a kiln depends on several factors:

- **Kiln design:** Thermal energy losses in a kiln are lower the better its heat insulation.
- **Insulation of openings or apertures:** it is advisable to fit some kind of insulating material, such as glass wool, to cover openings on the surfaces of the kiln (inspection holes, openings at rollers, etc.)
- **Static pressure inside the kiln:** if the static pressure in the firing chambers is too high, degradation of the refractory material used on kiln walls in the firing area accelerates and so energy losses increase.
- **Ambient temperature:** energy losses are greatest in the coldest months of the year.

In general, the hottest zones in the kiln are located in the area with the highest firing temperature, as well as on the deck formed by the rollers.

Should higher-than-normal temperatures be detected on surfaces in the kiln, it is possible in this type of system to replace the refractory material in that area to reduce heat losses and thus bring down the consumption of natural gas.

Maintenance operations in kilns are carried out during yearly production shutdowns, when the refractory lining inside the kiln can be repaired and/or replaced, if necessary.

The energy savings achieved by such a measure depend on the number of kiln modules where the refractory has been renewed and a decrease in surface temperatures achieved.

### 3.1.3 OPTIMISED WASTE HEAT RECOVERY

In the ceramic industry, heat energy is used to dry ceramic materials and to bring about the various transformations that take place during their high-temperature firing. Nevertheless, large amounts of waste heat are not recovered, which opens the door to applying new technologies to re-use that heat.

***Developing more efficient heat exchangers*** could increase the amount of heat recovered by enabling heat recovery in streams where at present that is not possible, thus improving overall process efficiency.

In the ceramic tile manufacturing process, the **kiln** is a permanent **source of heat waste.** In many cases, this waste heat, mainly from the gases in the cooling area of the kiln, can be re-used in the same system (for example, to pre-heat combustion air or by directing it to the dryer installed at the inlet to the kiln, thus reducing energy requirements). In some cases, part of this waste heat is re-used in the company's drying section. However, the great potential for re-using heat from flue gases still goes untapped.

Currently, most ceramic tile manufacturing companies do not recover heat from the flue gas stack, due to the complexity of the stream. Furthermore, the flue gas stream is diluted before being exhausted, to ensure that extractor fan is not damaged by the high temperature of the gases.

In practice, several obstacles exist that prevent the use of waste heat:

- **Distance:** if the waste heat sink is too far away, some form of heated conveyance needs to be fitted to transport it and so the heat losses generated during transport push costs up and increase ROI time.
- **Temperature:** Although waste heat is available, often its temperature is too low for other parts of the process. Some of the materials that heat exchangers are built with do not operate with low temperatures, due to condensation and corrosion by the acid components present in process gases.
- **Reluctance to change:** the industrial process has been optimised over years and adding a heat recovery device can be a complicated affair that may affect process parameter settings.

In view of the foregoing, efforts need to be made to develop new heat exchangers that present greater energy efficiency than currently existing ones, and whose design enables greater heat exchange. In addition, heat exchangers made from other types of materials, such as plastic (see Figure 6) should be developed, which would make them apt for use in streams where steel heat exchangers would be corroded by acid condensation, thus enabling low-temperature waste heat recovery.

***Figure 6*** *Example of a polymer heat exchanger*
*(Source: [https://heatmatrixgroup.com/)](https://heatmatrixgroup.com/)*

Digitised maintenance (remote monitoring, continuous corrosion and fouling detection) can help improve the efficiency of new heat exchange systems.

## 3.2 USE OF ALTERNATIVE FUELS

One of the alternative ways of supplying the heat energy required for the ceramic process is to use energy from renewable sources, such as organic matter.

**Biomass** can be used directly as a fuel or as a raw material to obtain combustible gas, following a gasification or fermentation process. Depending on the process used, the gas obtained by treating the biomass has one composition or another.

Therefore, if gasification is used, **synthetic gas** is obtained, which is a mixture of $H_2$, CO, $CO_2$, and $H_2O$ in different proportions, depending on the conditions in which the process takes place. If the biomass is fermented in the absence of $O_2$, a gas, known as **biogas,** rich in $CH_4$ (between 50-70%) is obtained. If that biogas is then purified by eliminating the rest of compounds present, the result is a gas with high $CH_4$ content (around 95%), called **biomethane,** which can be considered energetically equivalent to the industrial natural gas currently supplied by the grid.

At present, no ceramic tile manufacturing plants in Spain use biomass, either directly or indirectly, as an energy source.

It is possible to use biogas as a fuel gas, whereby the most feasible option would be to harness biogas generated from landfills and/or wastewater treatment plants, which need to be located within a maximum radius of about 4km from the point of consumption in order to be economically viable.

In such a scenario, burners have to be highly flexible, able to operate with natural gas, biogas, or a mixture of both, to ensure a stable heat energy supply. This option is already used in some structural ceramics plants, but in the case of the ceramic tile sector, it would first be necessary to analyse the composition of the biogas and determine the implications its use as a fuel would have on the composition of flue gases and its impact on the quality of the end ceramic product and on the refractory surfaces in the kiln, gas extraction systems, etc.

When no landfill is available in the vicinity of the industrial site, the use of biogas becomes more complex since a biomass fermentation plant has to be installed to produce biogas. In addition to the significant capital outlay required for the installation, it is important to ensure the necessary biomass is available in the vicinity of the site, because if it has to be brought in from afar, the cost associated with its transport makes the process more expensive.

Consequently, the best option would be to transform the biogas into biomethane and inject it into the gas grid. Such technology is increasingly being developed and rolled out in several European countries, although its growth is limited by the amount of biomass necessary for production and by generating costs, which remain high.

Furthermore, generating biomethane is a totally foreign concept for the ceramic sector. It is an independent manufacturing process that needs to be undertaken by specialist companies.

In the case of the ceramic tile sector, the most suitable option at present would be to use biomass directly as a fuel for biomass boilers, as a means of providing the heat energy required to dry newly-formed, unfired bodies.

Flue gases from biomass are not clean gases, because apart from certain pollutants, such as organic compounds and acidic elements, they also contain amounts of suspended solid particles (small particles of unburnt material) that are exhausted into the atmosphere with the combustion gases.

Therefore, when biomass boilers are used in ceramic tile dryers, the best option to prevent both contamination by unwanted condensation and the deposition of particles on the ceramic tiles inside the dryer is considered to be fitting boilers that use indirect heat.

In such a system, a heat exchanger should be installed, so that the combustion gases from the boiler can heat the drying gases. That way, the combustion gases from the boiler would not come into contact with the ceramic tiles at any time, thus guaranteeing their quality while protecting the integrity of the drying section.

## 3.3 INTEGRATION OF RENEWABLE $H_2$

In theory, hydrogen can be obtained from various compounds, but from an environmental point of view, producing it only makes sense when the energy required to do so comes from renewable sources.

Depending on the origin of the raw materials used, one can distinguish between blue or grey hydrogen, obtained from fossil sources, and green hydrogen that comes from water, using electricity from a renewable source.

In the ceramic industry, hydrogen could be used in processes where natural gas is currently employed, although special attention must be paid to the difference in characteristics between both fuels.

## Hydrogen as a fuel for generating heat in the ceramic industry

Hydrogen could be used as a fuel to replace natural gas to produce high-temperature heat. Given that hydrogen's heating value is about three times lower than that of natural gas per unit of volume, the volume of hydrogen required to produce the same energy would be three times larger.

The great advantage of the process is that hydrogen combustion **does not produce $CO_2$ emissions,** since the only combustion product is water vapour, although it should be noted that its combustion with air can produce NOx, the emission of which is bound by legal limits. Indeed, the formation of NOx during the combustion of hydrogen may become a critical factor if such technology is installed.

Natural gas can be completely replaced with hydrogen or just partially, i.e., using mixtures of natural gas and hydrogen. The latter calls for fewer process changes but with obviously fewer environmental benefits. On the basis of the information collected, full substitution can only be implemented with significant changes to industrial equipment and operating procedures, given hydrogen's special characteristics.

In this sense, from the technical point of view, using hydrogen as a fuel in industrial processes is still an under-developed technology, in which hydrogen burners of the size and power needed by the ceramic industry are yet to be designed, and further research is required to ascertain the influence such a change of fuel would have on the physical and chemical reactions in processed materials, on the construction materials in industrial equipment, on process variables, and on atmospheric emissions.

Likewise, special attention needs to be given to the quality of the end product, because when firing ceramic tiles, end product quality is greatly influenced by the shape and characteristics of the flames.

A priori, the effects of increasing the amount of water vapour generated are difficult to predict and further experimental research is needed to assess the matter.

## Use of fuel cells in the ceramic industry

In addition to using hydrogen in combustion processes, it can also be used to generate electric power (and heat) by means of fuel cells. Fuel cells are electro-chemical devices capable of directly transforming chemical energy into electric power and heat via an electrochemical process.

This electrochemical transformation directly uses the free energy available in the fuel at operating temperature and is therefore not limited by the Carnot cycle, allowing for yields higher than those found in conventional combustion processes to be achieved.

Fuel cells could be used in the ceramic industry in the form of co-generation (CHP) systems, as they generate heat and power at the same time.

The electricity generated could meet the electrical demands of the ceramic tile manufacturing plant or even operate electric vehicles and forklifts, while the residual heat could be used in spray drying and/or pressed tile dryers.

However, the potential use of energy available in the form of heat (i.e., useful heat) depends on the temperature at which it is generated, which in turn depends on the type of technology used. Therefore, the type of fuel cell to use depends on the needs to be covered, although it is even possible to combine the use of fuel cells with a gas turbine.

In the ceramic industry, spray-dryers need heat delivered at a temperature of over 500ºC. To dry ceramic tiles, the temperature required is above 200ºC. Once such heat requirements have been met, if any surplus heat is still available, it could be used for air-conditioning in warehouses and other buildings on site, such as offices and laboratories.

In the specific case of the ceramic industry, high-temperature fuel cells are the ones that best adapt to this type of combined heat & power generation. The leading high-temperature cells are MCFCs - molten-carbonate fuel cells (650ºC) - and SOFCs - solid oxide fuel cells (1000ºC). However, employing these types of cells calls for further development and implementations, since currently they are still extremely expensive.

### 3.4 $CO_2$ CAPTURE AND USAGE

The capture, storage and use of carbon dioxide is a process that consists of separating $CO_2$ from industrial emissions and transporting it to a point of storage or trans-formation.

Current technologies for carbon dioxide capture can be classified into three groups:

- **Pre-combustion:** in this case, the fuel is transformed into a gaseous mixture of $H_2$ and $CO_2$. The $H_2$ is separated and can be used as fuel, while the $CO_2$ is compressed and stored.
- **Oxy-fuel combustion:** This involves combusting the fuel in the presence of pure oxygen instead of air, which increases the concentration of $CO_2$ in the effluent gas and facilitates its final separation before storage.
- **Post-combustion:** it consists of separating the $CO_2$ diluted in the rest of the components of combustion gases produced by burning a fossil fuel with air. This technology is applicable in existing installations.

Given the characteristics of the ceramic tile manufacturing process, the most favourable capture technique applicable to the industry is **post-combustion.**

The main issue is that, at any stage in the manufacturing process, $CO_2$ is diluted in the flue gas exhaust stream, with a high flow rate and practically at atmospheric pressure.

| Parameter | Value | | |
|---|---|---|---|
| | Spray dryer | Dryer | Kiln |
| Temperature (ºC) | 90 | 120 | 210 |
| Stack mean flowrate ($Nm^3/h$) | 70,000 | 4,000 | 12,000 |
| **$CO_2$ content (%)** | **1.0 – 2.0** | **0.5 – 1.0** | **3.0 – 5.0** |

***Table 3.*** *Characteristics of gases in different stacks in the ceramic process*

As the above table shows, carbon dioxide in the gas streams from the tile manufacturing process is highly diluted, with a maximum value of just 5% in the combustion gas exhaust stack from the kiln.

In view of the results shown above and taking into account the temperature and flowrates of the gases to be treated, each company needs to carry out an individual assessment to determine which capture system most optimally fits the specific characteristics of its streams.

At present, there are several alternative $CO_2$ capture techniques, but in practice, their roll-out on an industrial scale is still very scarce, barely a handful of cases in the energy and chemical industries, so for the moment, they do not appear to be sufficiently well-developed for their immediate implementation in the ceramic industry. However, on the positive side, it should be noted that a number of projects dealing with this matter are currently ongoing in various sectors.

### 3.5 ELECTRIFICATION OF HIGH-TEMPERATURE HEAT GENERATION

In regard to the ceramic tile manufacturing process, two stages have been considered for electrification, namely, the drying of formed tiles and firing. The spray-drying stage was not included in our assessment, since its energy efficiency is very high when combined with CHP systems, and furthermore, the electric heating of large air flows is extremely inefficient.

In the case of **ceramics drying,** electrification can be carried out by:

- Using **high temperature heat pumps:** this would allow for part of the consumption to be switched from gas to electricity.
- **Drying using microwave**, **infrared or electrical heating.** In any of these cases, dryers would have to be redesigned, since the technology to supply heat would change as combustion would be eliminated.

In the case of **ceramics firing,** electrification can be carried out by **firing with electric element heating.** In this case, the concept of a kiln that exists today has to be changed completely.

The current state of **electrification for ceramic tile firing kilns** is explained below, as electric ceramic tile firing seems to be one of the most relevant technological alternatives that would enable the ambitious emission reduction targets set by the European Commission to be achieved.

It should be noted that on a commercial level, ceramic tile kilns already exist that use electricity instead of natural gas as an energy source, although they are designed for experimental testing and, therefore, the production levels they can produce are severely limited.

Furthermore, these types of kilns still have much room for improvement and need to be optimised in many respects. Earlier studies have shown that these kilns are not energetically optimised: in continuous production, they do not reach the programmed temperature, so one has to adjust the power rating to improve material heating, while the tile cooling stage is also not optimal and needs to be redesigned.

Likewise, one of the key questions in regard to their further development lies in the price of electricity, which can be considered the most critical factor determining their viability and usage.

In view of the characteristics of the process, it is clear that **electric heating with elements** would be the most obvious choice for firing ceramic tiles.

That technology involves **indirect** heating by electric elements, so the tiles are only heated by radiation, convection or a combination of both, from the elements arranged in their vicinity.

**Electric heating element kilns** have a higher cost compared to combustion kilns in many industrial applications, so their use in industry in general and in the ceramic industry in particular is rare, except in high-temperature applications or when firing in controlled atmospheres is required, etc.

Some advantages and breakthroughs of these kilns are as follows:

- Electric element kilns at a reasonable cost currently reach working temperatures of **1600-1800ºC**, which covers the full range of standard industrial kiln applications.
- In addition, with tube elements and thick plating, **specific power rates of 50-60 kW/m²** of wall, ceiling and floor can be reached, which compete and even exceed the heating temperatures designed to be achieved with natural gas and radiant tubes.
- Improved environmental conditions in the vicinity of the kiln and outside the plant. Absence of combustion gases.
- Greater safety, because the problems that arise in an electric system are minimal and the risk of explosion due to a failure in the combustion system is averted.
- Great accuracy and repeatability in continuous kiln processes, somewhat higher than in flame kilns, especially when temperature is adjusted by means of thyristors.
- Improved flexibility of operation under different work regimes.

Although commercially ceramic tile kilns using electric power instead of natural gas as an energy source do exist, their use is very limited and further development of the technology is still required to optimize their energy efficiency and be able to displace natural gas combustion kilns. However, another intermediate possibility that should be evaluated is the use of hybrid electric and combustion kilns.

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