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Evolution of CO2 emissions in the Spanish ceramic tile sector.

Report no. C214297
No. of pages: 20
ASCER - ASOCIACIÓN ESPAÑOLA DE FABRICANTES DE AZULEJOS Y PAVIMENTOS CERÁMICOS
Castellón, 18 November 2021

El Instituto de Tecnología Cerámica está integrado por el Instituto Universitario de Tecnología Cerámica "Agustín Escardino" de la Universitat Jaume I de Castellón y la Asociación de Investigación de las Industrias Cerámicas, AICE, entidad privada de carácter no lucrativo creada por iniciativa de la Generalitat Valenciana, a través del IVACE, en colaboración con las industrias del sector cerámico

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1. Normative and regulatory context

The European Union has evidenced its determination in the fight against the climate change for decades. In fact, on 29 April 1998, the European Community was one of the first to sign the Kyoto Protocol, which entered into force in the European Union in 2002[1] [2], through adoption of policies aimed at mitigating the effects of climate change based on mandatory quantified objectives to limit and reduce greenhouse gases (GHG). The six GHG included in the protocol are as follows: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC), and sulphur hexafluoride (SF_6), carbon dioxide[3] undoubtedly being the most important GHG in terms of anthropogenic absolute emissions. In fact, the emissions of the other GHG are expressed as equivalent carbon dioxide emissions.

Anthropogenic CO_2 emissions are known to originate mostly from fossil fuel combustion, in order to obtain electric power, thermal energy or for transport. For that reason, to reduce their emissions, innumerable initiatives relating to energy generation and use have been promulgated, in particular, for example, the ones aimed at increasing energy efficiency in households and industry[4], fostering the implementation of renewable energy sources[5], facilitating transition of the transport sector towards less fossil fuel use [6], increasing research[7] [8] [9] into new technologies and fuels to minimise energy consumption and resource use, among others.

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[1] Kyoto Protocol to the United Nations Framework Convention on climate change. United Nations, 1998.

[2] Council Decision (2002/358/CE) of 25 April 2002 concerning the approval, on behalf of the European Community, of the Kyoto Protocol to the United Nations Framework Convention on Climate Change and the joint fulfilment of commitments thereunder.

[3] COM(2011) 112. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the committee of the regions. A Roadmap for moving to a competitive low carbon economy in 205. Brussels, March 2011.

[4] Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency.

[5] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.

[6] Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019 amending Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles.

[7] Decision No 1982/2006/EC of the European Parliament and of the Council of 18 December 2006 concerning the Seventh Framework Programme of the European Community for research, technological development and demonstration activities (2007–2013).

[8] Proposal for a Regulation of the European Parliament and of the Council establishing Horizon 2020 – The Framework Programme for Research and Innovation (2014–2020).

[9] Regulation (EU) 2021/695 of the European Parliament and of the Council of 28 April 2021 establishing Horizon Europe – the Framework Programme for Research and Innovation, laying down its rules for participation and dissemination, and repealing Regulations (EU) No 1290/2013 and (EU) No 1291/2013.

Initially, the target set was a global GHG emissions reduction of 40% by 2030[10], relative to the levels of 1990, but in September 2020 it was proposed to increase this to 55%[11], in the frame of the European Green Deal actions[12]. With the adoption by the European Council of the European Climate Law[13], this new emissions reduction target has finally been accepted in 2021.

Among the initiatives implemented by the EU to reduce GHG emissions, of note, because of its importance, is the EU Emissions Trading System (ETS), a cornerstone of the EU's policy to combat climate change. The system works on the principle of 'cap-and-trade'. An absolute limit or 'cap' is set on the total amount of GHG that the entities covered by the system can emit. The cap is lowered over time so that total emissions fall.

This system started operating in 2005. It is the world's first carbon market and remains its largest one.

The European ceramic tile industry is subject to EU ETS rules. This means that each company must annually quantify and report the GHG emissions generated at its facilities, and pay for them, at the price set in the emission rights market, with the entailing rise in costs on the corporate economic balance, as the cost of CO_2 emissions must be added to the energy costs. In addition, it is necessary to add the uncertainty associated with the CO_2 market, owing to the great price swings. Over the last year, the emission rights price has risen by 126%, going from about 23 EUR/t CO_2 in June 2020 to over 60 EUR/t CO_2 in September and October of 2021[14], as may be observed in Figure 1.

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[10] COM/2014/015 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A policy framework for climate and energy in the period from 2020 to 2030.

[11] COM/2020/562 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people.

[12] COM/2019/640 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal.

[13] COM(2020) 563 final. Amended proposal for a Regulation of the European Parliament and of the Council on establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law).

[14] https://www.sendeco2.com/es/precios-co2

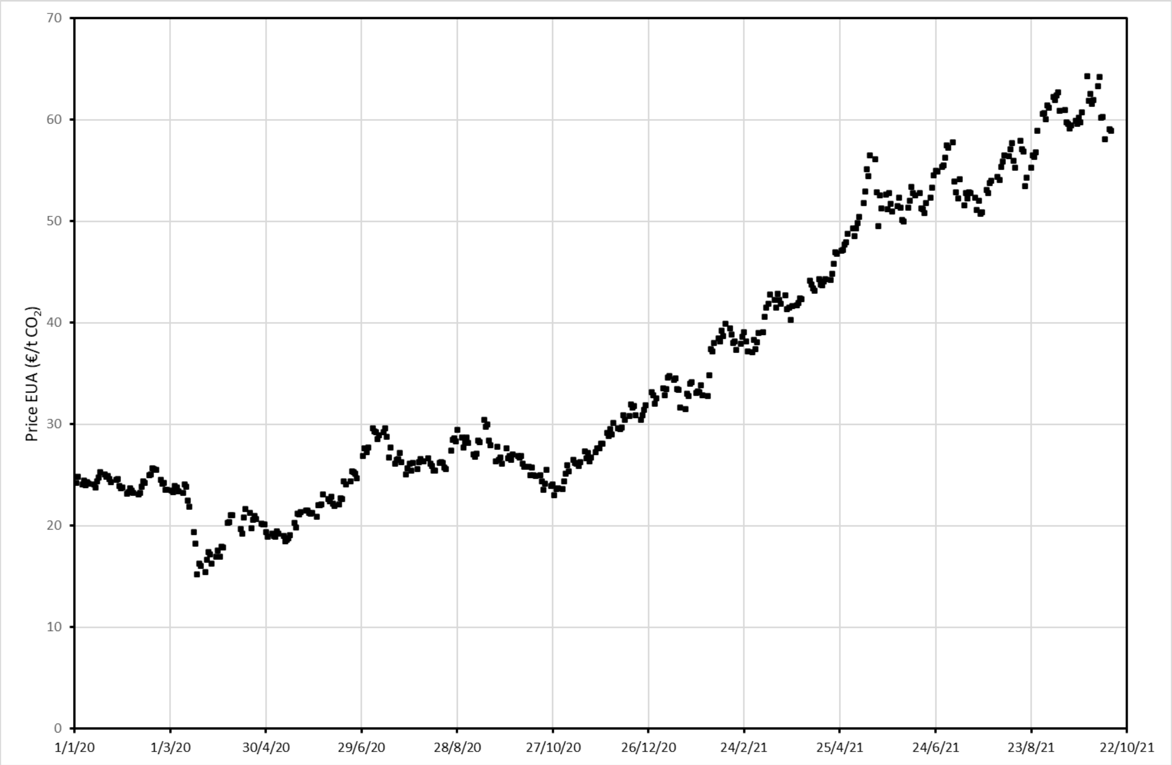

Figure 1. Evolution of the CO_2 emissions price (EUA) in 2020 and 2021.

To avoid company delocalisation to countries with lower environmental pressures, the European Commission[13] established the possibility that the sectors most at risk of relocating their production outside Europe (known as 'sectors at risk of carbon leakage') could receive a free allocation of emission rights as part of their needs. The ceramic tile sector meets the criteria for being deemed a sector at significant risk of carbon leakage[15], given its important export share and the high costs of CO_2 that it must bear in its accounts.

However, the free emissions allocation to the ceramic tile sector does not cover the actual emissions, so that the cost of the emissions not met by this mechanism becomes an additional direct cost for sector companies.

Specifically, the emissions shortfall in 2020 was about 450 000 t CO_2 for the Spanish ceramic sector, entailing an estimated additional cost of €11.3 million. Although the evolution depends on many factors, a significant increase in costs relating to GHG emissions is expected in the next few years[16].

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[15] https://ec.europa.eu/clima/policies/ets/allowances/leakage_en#tab-0-1

[16] P. Ruf; M. Mazzoni. El mercado europeo del CO_2: el impacto de los altos precios del CO_2 en las utilities y las industrias. ICIS, 2019.

2. Evolution of sector emissions

The evolution of sector emissions can be addressed at the level of overall emissions (t CO_2/year) or specific emissions (t CO_2/m^2). In addition, if a life cycle assessment perspective is adopted, the GHG emissions associated with the extraction and supply of raw materials, product distribution, packaging, etc. should also be considered.

The scope of this report is restricted to direct emissions, as insufficient information is available to consider the emissions of other life cycle stages of a historical nature. In addition, tile manufacturing companies can only influence the emissions that are directly generated in their production process.

Direct CO_2 emissions in the ceramic sector originate from natural gas combustion, used in spray-drying, drying and firing processes, and in the decomposition of carbonates found in some ceramic compositions during the firing stage. About 90% of the emissions stem from natural gas combustion, and the remaining 10% come from thermal decomposition of the carbonates found in ceramic tile body compositions[17].

This technical report analyses the evolution of direct specific emissions (kg CO_2/m^2), as they are the best indicator of the impact that successive technology improvements have had on sector GHG emissions. Information is also set out on the annual overall emissions and their historical evolution, which are directly related to the sector’s level of production.

The evolution of total emissions in the ceramic sector is shown in Figure 2, together with sector production. In general, it may indeed be observed that, except for the last period of the 1980s, absolute emissions of CO_2 in the Spanish ceramic tile sector have exhibited an almost linear dependence on total production made.

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[17] Monfort, E.; Mezquita, A.; Granel, R.; Vaquer, E.; Escrig, A.; Miralles, A.; Zaera, Análisis de consumos energéticos y emisiones de dióxido de carbono en la fabricación de baldosas cerámicas. V. Boletín de la Sociedad Española de Cerámica y Vidrio. 49 (4) (2010) 303-310.

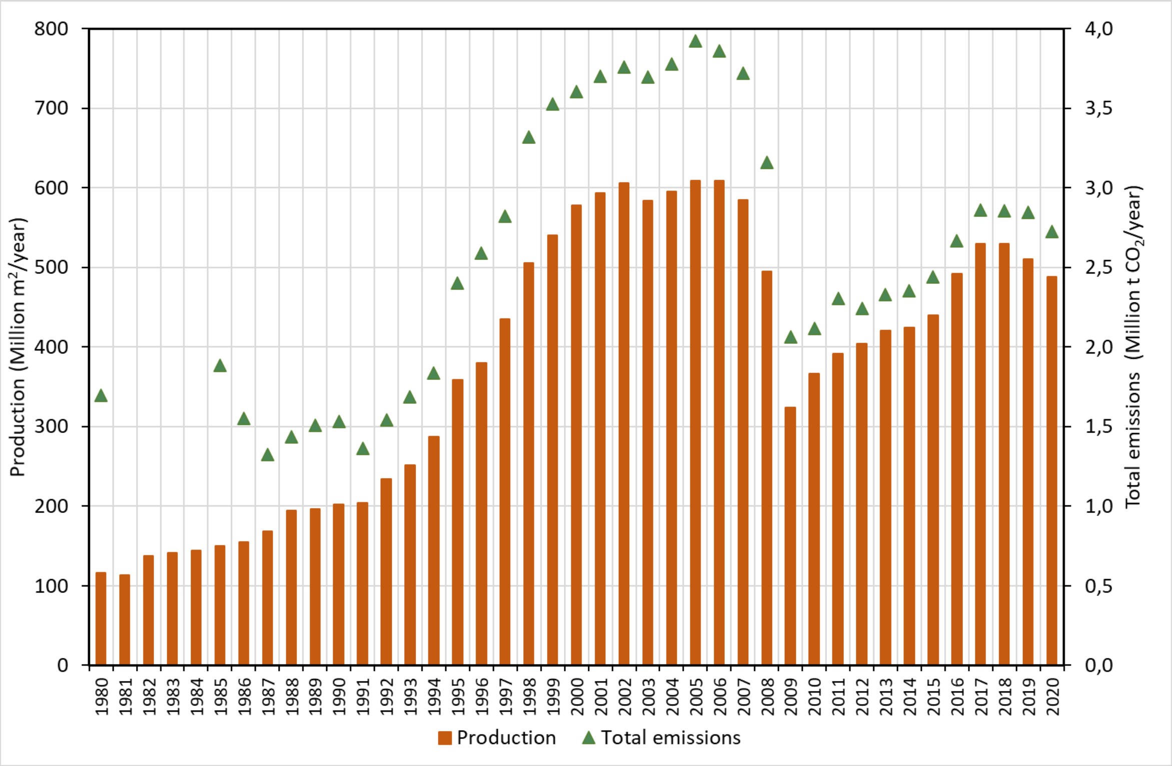

Figure 2. Evolution of absolute emissions of CO_2 and production of the Spanish ceramic tile sector.

At the end of the 1980s, the fuel used in drying and firing processes changed from fuel oil or gas oil to natural gas, which in turn led to technological changes in the process that significantly raised overall energy efficiency in the production process. That is why, during that period, increased production was not accompanied by a rise in total emissions.

It may be observed that, after widespread implementation of the new technologies, the higher the amount of tile made, the greater was the energy consumption, as no radical changes occurred in manufacturing technology from an energy viewpoint.

However, the impact on process overall energy efficiency resulting from the changes made in production technologies and from the energy saving actions implemented in the process can be more clearly observed on analysing CO_2 specific emissions.

The evolution of CO_2 specific emissions over the last 40 years is shown in Figure 3. The data reveal an important drop in the specific emissions from the beginning of the 1980s to 1990. From then on, the emissions continuously kept falling, but at a slower pace. This evolution was determined by the technological changes adopted in the production process, as well as by the different energy saving actions that were implemented.

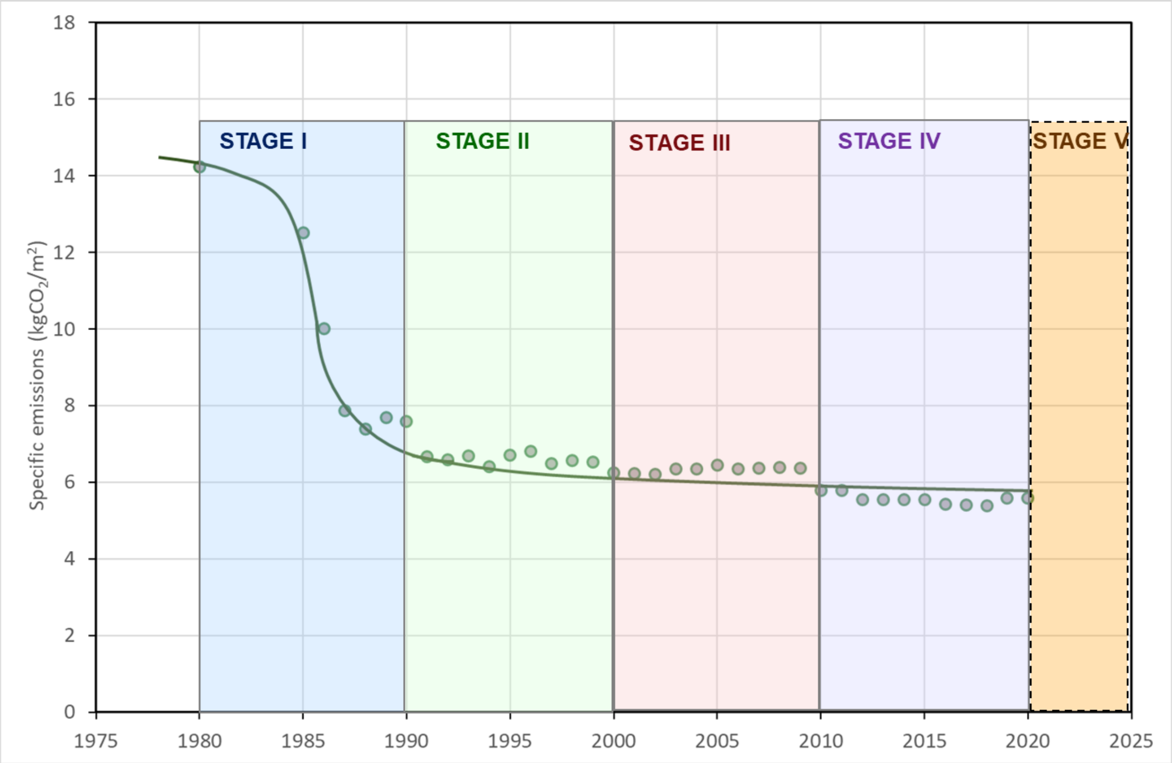

Figure 3. Evolution of specific emissions of CO_2 and production of the Spanish ceramic tile sector.

The main technological changes and energy saving actions implemented in each decade considered, and their impact on the emissions per unit product made, are explained in greater detail below.

2.1. Stage I: From 1980 to 1990. Technological revolution.

Ceramic tile manufacture in Spain, as an industrial economic activity, dates back to the beginning of the 20th century. The first kilns were kilns with batch chambers, and the fuel used was firewood (biomass) from areas near the factories. The firing cycles lasted several days, and there was hardly any way of controlling the firing conditions, so that end-product quality was quite low[18].

In the middle of the 20th century, electricity began to become available for industry, which allowed implementation of material handling systems in the kilns, and development commenced of continuous kilns (of the tunnel or channel type). In addition, liquid fuels obtained from petroleum, mainly fuel oil, were introduced, replacing biomass. The products made were, for the most part, porous earthenware tiles, manufactured by double firing: the tile body was fired in the first firing, and the glaze in the second firing. Processing took place in muffle kilns, without any direct contact between the gases and the tiles, to avoid tile defects caused by unburnt fuel particles generated in combustion.

The arrival of natural gas by gas pipeline in the ceramic industrial area in the 1980s led to a radical change in ceramic tile manufacturing technology, particularly in regard to the firing stage: single-deck roller kilns were developed, featuring direct contact between the gases and the tiles and not requiring

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[18] Joan Feliu Franch. La cerámica arquitectónica de Onda en el siglo XIX. Ph.D. dissertation. UJI, 1998.

the material to be piled up, thus significantly shortening firing cycles (firing cycles went from 30–70 hours to 40–60 minutes), thus increasing productivity of the facilities.

The new natural gas kilns made it easier to control process variables, as they had automatic regulation systems, which allowed widespread development of the single-fire manufacturing process. This was initially introduced for making vitrified products (used mainly as flooring), which developed notably with this technology, and single firing was subsequently used for fabricating porous products. One of the product firings therefore also began to be suppressed, with the entailing fuel saving per unit product made.

The ceramic sector quickly adopted these technological changes, to the extent that, just one decade after the arrival of natural gas in the industrial area, practically all the kilns were already using natural gas as fuel, and over 60% of tile production was already being made with a single firing.

This technological upgrading not only affected the kilns, but there were innovations in practically every process stage, enabling greater control of the entire manufacturing process. This had major consequences, in particular, enhanced end-product quality and a significant decrease in process energy consumption, and hence in direct CO_2 emissions.

Figure 3 shows how, during the adoption period of the above technological innovations up to 1990, though sector production increased year by year (see Figure 2), the emissions per unit product made fell, due to the greater energy efficiency achieved with the new firing technologies.

Specific emissions of CO_2 dropped by 46% from 1980 to 1990, going from 14,2 kg CO_2/m^2 to 7,6 kg CO_2/m^2.

Note that 1990 is the reference year used to calculate the emissions reduction targets. In the case of the ceramic tile sector, as mentioned previously, in 1990 direct emissions of CO_2 from the process had already decreased by almost 50% compared with the values of the early 1980s.

2.2. Stage II: From 1990 to 2000. Consolidation of new technologies.

During the 1990s, as the natural gas grid developed, the sector completed its upgrading to the new technologies and, from then on, efforts to reduce energy consumption in the manufacturing process focused on improving the recently implemented new firing technology. Companies strove to increase insight into the influence of process variables on energy consumption[19,20] and to improve production rates and production management, in addition to firing process control, minimising defects in the end product, both in floor and wall tiles [21].

All these efforts gave rise to a gradual drop in specific emissions of CO_2, from 7,6 kg CO_2/m^2 at the beginning of the 1990s to 6,2 kg CO_2/m^2 in 2000.

The technological upgrading of the sector towards single firing processes required radical modification of the tile body raw materials preparation process. Indeed, dry milling of the raw materials used to make the ceramic bodies, which had till then been the most widely used preparation method, made way for wet milling, followed by spray drying of the suspension, in order to obtain particle granulates with appropriate size distribution, shape, and flowability for fabricating tile bodies

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[19] Escardino, A.; Jarque, J.C.; Moreno, A.; De la Torre, J. Secado de materiales cerámicos (I). Consideraciones generales. Isotermas de equilibrio. Técnica Cerámica, 185, 452–462, 1990.

[20] Mallol, G.; Monfort, E.; Jarque, J.C. Optimización de las condiciones de operación de un horno monoestrato. Cerámica Información, 202, 6–13, 1994.

[21] Moreno, A; Mallol, G.; Llorens, D.; Enrique, J.E.; Ferrer, C.; Portolés, J. Estudio de los gradientes transversales de temperatura en un horno monoestrato en diferentes condiciones de operación. Cerámica Información, 229, 29–36, 1997.

with improved performance features[22]. The incorporation of the spray-drying stage with a relatively high energy consumption might have been expected to increase specific emissions but, thanks to the advantages that it provided in the firing stage and to the widespread implementation of roller kilns, it was able to maintain and even to continue reducing the overall specific emissions of CO_2 in the process.

Cogeneration systems simultaneously produce mechanical energy, which is used to generate electricity, and thermal energy, contained in the exhaust gases, from a single primary energy source. The cogeneration systems implemented in the sector are natural gas turbines, whose exhaust gases are used as drying gases in the spray dryers, as they are clean gases, with a high oxygen content and temperature close to that required by the process, in the range between 450ºC and 600ºC. In addition, the electricity produced allows companies to generate part of the electricity needed in the production process, ensuring supply and avoiding power outages in the electrical grid. The cogenerated power surpluses are fed into the general electrical grid, generating an economic benefit for the facility, as well as benefits for the national electric system stemming from the distributed generation (decrease in grid losses, primary energy saving, lower CO_2 emissions, etc.).

The first cogeneration facilities date back to the end of the 1980s, but it was in the 1990s that a greater number of cogeneration systems were installed in the sector. It is estimated that, in 2020, the installed total power was about 232 MW.

The cogeneration implemented in the ceramic sector is deemed to be highly efficient, in view of the high degree of exhaust gas energy recovery in the production process, which allows companies to meet the 10% minimum level of primary energy saving laid down by European regulations. For this reason, individually generating heat for the spray dryer, in addition to the electricity, consumes more primary energy and produces more emissions than generating it simultaneously with a cogeneration system, owing to the lower efficiency of thermal power stations for electricity production, compared to the efficiency of cogeneration systems.

On an overall countrywide level, the use of cogeneration systems in industry enables CO_2 emissions associated with the energy supply to be reduced, while at the site of the cogeneration facilities the emissions increase. For this reason, in calculating the emissions associated with ceramic tile manufacture, the emissions produced in the process and the emissions associated with electricity production in the cogeneration systems are considered.

However, as noted previously, the implementation of cogeneration systems, as observed in Figure 3, did not impede the continuous drop in specific emissions.

2.3. Stage III: From 2000 to 2010. Increase in production capacity.

This period may be deemed, principally, a period of expansion for the sector. With the new technologies already widely implemented, and a greater understanding of the process variables, the sector’s production capacity increased noticeably. This is the historical period in which the greatest production was achieved, exceeding 600 million m^2 annually for several years.

In 2003, the first directive on emissions trading entered into force[23], affecting the ceramic sector, albeit not fully. The emissions that were controlled in the first allocation plans (PNA 2005-2007 and PNA 2008-2012) accounted for about 40% of sector emissions, which is why the impact in the sector

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[22] Negre, F.; Jarque, J.C.; Felíu, C.; Enrique, J.E. Estudio de la operación de secado por atomización de polvos cerámicos a escala industrial, su control y automatización. Cerámica Información, 216, 12-17, 1996.

[23] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC.

during these first years of emissions trading was partial. This period helped businesses become better acquainted with EU ETS rules[24].

However, the efforts of the sector to continue reducing natural gas consumption continued, via implementation of saving actions aimed at optimising the process variables most closely related to energy consumption and on improving production management. Among the energy saving actions that were generally carried out, the following may be noted: increasing ceramic suspension density, optimising oxygen content in the combustion chamber to avoid defects in the end product (black core, shades, etc.), gas recovery from the cooling stack in the dryer located at the kiln entry, among others[25].

This period was thus characterised by greater process control and regulation, and by a gradual increase in porcelain tile manufacture, porcelain tile being a product with lower process emissions, but which required longer firing cycles. The specific emissions of CO_2 continued to fall, but at a slower pace, given the maturity already attained by the technology and the considerable knowledge of the process acquired by qualified technicians in the sector.

2.4. Stage IV: From 2010 to 2020. Continuous technological innovation.

As indicated above, CO_2 emissions in the ceramic sector come from combustion of natural gas, used in drying and firing processes, and in carbonate decomposition in some ceramic compositions during the firing stage. About 90% of the emissions originate from natural gas combustion, while the remaining 10% stem from thermal decomposition of carbonates in the tile body composition[26].

Therefore, since the widespread implementation of single-deck kilns and single-firing cycles, efforts to reduce emissions have mainly focused on cutting back natural gas consumption in the manufacturing process, both in drying processes and in the firing stage[27].

The greater understanding of the technology[28] and the increase in the specific weight of energy costs on production costs have led ceramic tile manufacturers to continue pursuing implementation of energy saving actions, thus reaching current specific emissions (2020) at 5,6 kg CO_2/m^2. This involves a 60% decrease in specific emissions compared to those of 1980 and a 26% drop compared to the values of 1990.

The main actions generally implemented in Spanish ceramic sector companies during the period considered and their impact on the specific emissions of CO_2 are summed up in Figure 4.

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[24] Application of Law 1/2005 overall and sector analysis year 2012. Ministry of Agriculture, Food and Environment. Secretariat of State for Environment. Spanish Office for Climate Change (OECC). 2013.

[25] Monfort, E.; Mezquita, A.; Mallol, G.; Granel. R.; Vaquer. E. Guía de ahorro energético en el sector de baldosas cerámicas de la Comunidad Valenciana. Ed.: Valencia. Agencia Valenciana de la Energía-AVEN. Depósito Legal: V-2078-2011.

[26] Monfort, E.; Mosque, A.; Bulk, R.; Vaquer, E.; Escrig, A.; Miralles, A.; Zaera, Análisis de consumos energéticos y emisiones de dióxido de carbono en la fabricación de baldosas cerámicas. V. Boletín de la Sociedad Española de Cerámica y Vidrio. 49 (4) (2010) 303–310.

[27] Monfort, E.; Mezquita, A.; Vaquer, E.; Mallol, G. Gabaldón, D. La evolución energética del sector español de baldosas cerámicas. Boletín de la Sociedad Española de Cerámica y Vidrio, 53 (3) (2014), pages 111–120.

[28] Mezquita, A; Monfort, E.; Boix, J.; Mallol, G Energy saving in ceramic tile kilns: Cooling gas heat recovery. Applied Thermal Engineering, Vol. 65 (1–2) (2014), pages 102–110.

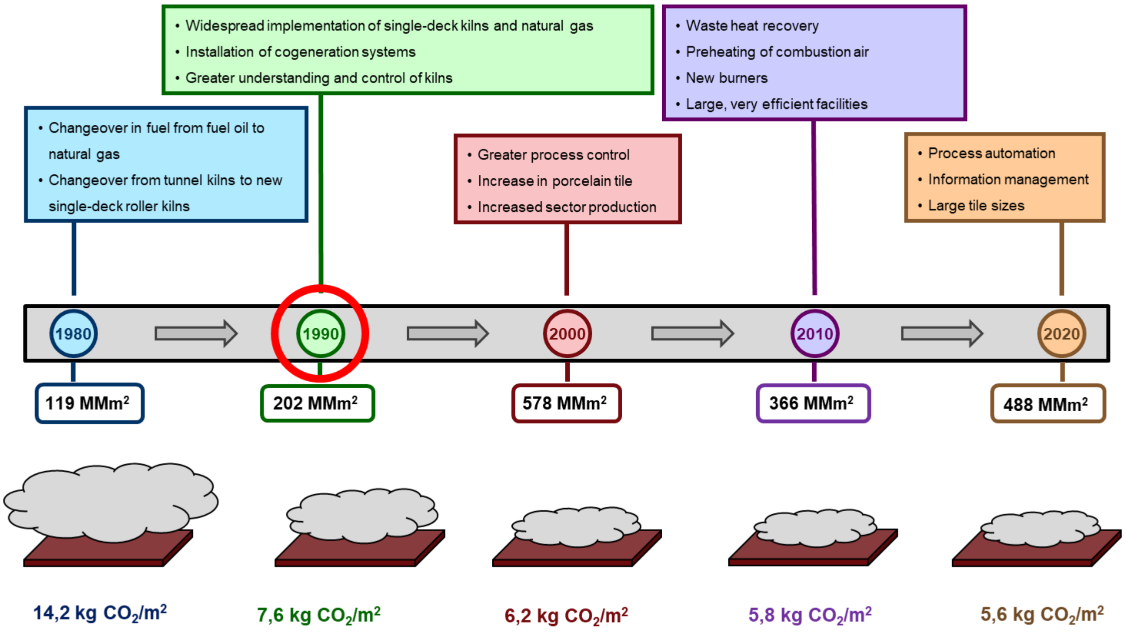

Figure 4. Timeline of the impact of the main actions on specific emissions of CO_2.

Particularly of note among the main energy saving and CO_2 emissions reduction measures widely carried out in the ceramic tile sector over the last decade are waste heat recovery from kiln stacks for use in dryers of newly formed tile, higher combustion air temperature, replacement of conventional burners with high-efficiency burners, as well as all the improvements implemented by ceramic machinery manufacturers in their kilns and dryers to reduce gas consumption.

2.4.1. Waste heat recovery

Various studies[29] [30] indicate that about 50% of the heat input is lost through kiln stacks in tile firing. Two waste heat recovery options have been extensively implemented in the sector: heat recovery with air and heat recovery with an intermediate fluid, namely thermal oil.

In the first case, gases from the cooling stack in tile body dryers or in spray dryers are directly used. In some facilities, waste heat from the flue gas stack is also directly used. Flue gas stack gases contain pollutants that do not allow direct use in dryers, so that recovery is always carried out indirectly, using a gas/air heat exchanger, in which ambient air is heated for use, together with cooling stack gases, in tile body dryers or in spray dryers.

A combustion gas/air heat exchanger, installed in the flue gas stack of a tile firing kiln is shown in Figure 5.

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[29] Mezquita, A; Monfort, E.; Boix, J.; Mallol, G. Análisis energético y exergético del proceso de cocción de composiciones cerámicas. S. Ferrer. Ph.D. dissertation, UJI 2015.

[30] Mezquita, A; Monfort, E.; Boix, J.; Mallol, G. Energy saving in ceramic tile kilns: Cooling gas heat recovery. Applied Thermal Engineering, Vol. 65 (1-2) (2014), pages 102–110.

Figure 5. Flue gas/air heat exchanger installed in a kiln (Courtesy of Poppi Clementino, s.p.a.)

It is estimated, from information provided by companies that install these heat recovery systems, that waste heat recovery systems with air have been implemented in about 30% of the kilns (some 50 facilities) in the ceramic sector, using the recovered heat both in tile body dryers and in spray dryers, in which there is no cogeneration system or the cogeneration facility fails to meet the spray dryer's entire thermal consumption demand. The saving from these waste heat recovery facilities ranges from 201 to 223 GWh/year in energy, which constitutes an average decrease in emissions of the order of 42.820 t CO_2/year.

In the second case mentioned, waste heat recovery from the flue gas stack as well as from the cooling stack is carried out indirectly by heating a thermal oil in gas/oil heat exchangers located in the stacks. The oil is pumped to the tile body dryers, where it releases its sensible heat to the drying gases in heat exchangers installed in the dryers. The drying gases are heated, thus reducing natural gas consumption in the dryer burners. The oil returns to the kiln stacks, circulating in a closed circuit where it is continuously heated and cooled, enabling continuous waste heat recovery[31].

Figure 6 shows a scheme of a facility featuring waste heat recovery with thermal oil.

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[31] Mezquita, A.; Monfort, E.; Vaquer, E.; Ferrer, S.; A.; Arnal, M.A.; Toledo, J.; Cuesta, M.A. Optimización energética en la fabricación de baldosas cerámicas mediante el uso de aceite térmico. Boletín de la Sociedad Española de Cerámica y Vidrio, 51 (4) (2012), pages 183–190.

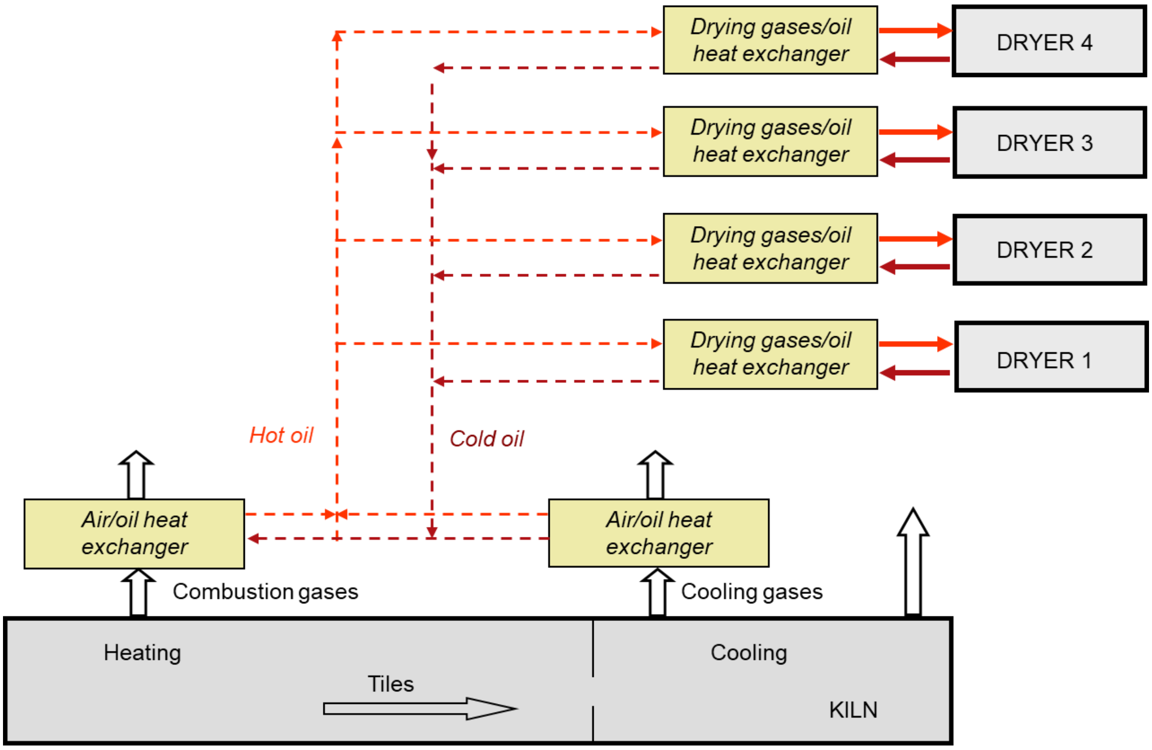

Figure 6. Scheme of a heat recovery facility with thermal oil.

In the ceramic tile manufacturing sector it is estimated, from information provided by suppliers, that there are about 20 kilns in which this heat recovery technology has been implemented, yielding an estimated natural gas saving of 105 to 116 GWh/year, and an average decrease of 22.220 t CO_2/year.

In accordance with the available data, in 2021, systems for waste heat recovery to the dryers had been implemented, overall, in about 40% of the kilns in the sector, the resulting natural gas saving being 306–339 GWh/year, which is equivalent to an average decrease in specific emissions of 0,14 kg CO_2/m^2.

2.4.2. Increase in combustion air temperature

One of the most widespread energy saving measures in the sector has involved preheating combustion air. Initially, single-deck kilns ran with air at ambient temperature for natural gas combustion, but better knowledge and control of combustion by ceramic technicians, in addition to the interest in taking maximum advantage of cooling stack waste heat, led to using hot air in the burners, with the ensuing natural gas saving.

In the first gas kilns, this improvement in kiln energy efficiency was implemented after they had started running but, over time, it became one of the characteristics that kiln manufacturers implemented at the request of their customers and then, by default in practically every kiln. The average saving in natural gas in a kiln, on preheating combustion air to temperatures of the order of 200ºC, ranges from 4,5 to 5,5%, so that, extrapolating this to the entire sector, an estimated average total saving in natural gas is obtained of 340 MWh/year, which is equivalent to a reduction in specific emissions of 0,14 kg CO_2/m^2.

2.4.3. Development of new kiln burners

Greater control of air combustion with natural gas, as well as knowledge of the influence of combustion parameters on the kiln atmosphere and end product, has fostered development of new burners that allow kilns to run at higher temperatures with less excess combustion air due to the greater natural gas and air mix efficiency. Moreover, the latest burner generations enable better heat distribution in the firing chamber. They therefore enhance temperature uniformity in the same zone in the kiln, as burners traditionally had difficulties in maintaining a uniform temperature in the centre zone of the kiln and in the zones near the walls, a problem that was aggravated with the increased width of the kilns designed to process large-sized porcelain tile (a material more sensitive to temperature gradients)[32].

According to information supplied by kiln manufacturers, the estimated average saving in a kiln on installing more efficient new burners ranges from 8 to 12%, depending on the type of burners that are replaced and on the characteristics of the new burners that are installed. According to these sources, in 2021, it is estimated that the oldest burners have been replaced with new more efficient burners in about 80% of the sector kilns. On the basis of these premises, it is estimated that the burner changeover has led to an overall natural gas saving of about 543 GWh/year, which is equivalent to a decrease in specific emissions of 0,23 kg CO_2/m^2.

Figure 7. Image of a high-efficiency burner. Courtesy of SITI B&T Group.

2.4.4. General innovations in drying and firing facilities

Ceramic machinery manufacturers have ceaselessly improved their products with a view to reducing energy consumption and increasing operations control.

In tile dryers[33] [34], frequency inverters have been implemented in fans to control gas flow rates and reduce heat losses through the stack; moisture gauges have been installed to better control the drying process; and drying operation control has increased by installing more temperature sensors and improving dryer management.

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[32] https://www.ceramicworldweb.it/cww-en/news/tiles/ancorarsquos-new-vulcan-b5-to-be-showcased-at-revestir-2013/

[33] SACMI GROUP: https://sacmi.com/es-ES/ceramics/Azulejos/Secado-industrial-para-ceramica

[34] SITI B&T. https://sitibt.com/secaderos-esp

In the case of kilns[35] [36], in addition to the development of more efficient burners, frequency inverters have been installed in the main gas impeller and extraction fans to increase process control and therefore reduce hot gas exhaust through the stacks; kiln wall and vault insulation has been improved to reduce heat losses through the kiln structure; and an important effort has been made in improving management of production gaps. In addition, the new kilns being installed in the sector are larger, which favours fuel efficiency, resulting in better overall energy performance and lower natural gas consumption per unit product made.

All these measures implemented in dryers and kilns have led thermal energy consumption in the sector, and therefore CO_2 emissions, to decrease as the oldest kilns and dryers were refurbished and new units were installed owing to production extensions, causing an additional overall drop in CO_2 specific emissions of 0,26 kg CO_2/m^2, to reach a current value of 5,6 kg CO_2/m^2.

3. Economic implications

The technological evolution undergone by the Spanish ceramic tile sector has been accompanied by a great capital outlay.

The changeover from tunnel kilns running on fuel oil to natural gas-fuelled single-deck kilns involved not only a technical revolution, but also a major economic outlay. The process was not developed gradually, replacing tunnel kilns as they became obsolete or required renewal, but it was carried out in a short time span of about 6–8 years, so that, in some businesses, the discarded fuel oil kiln had not yet been amortised when it was replaced with a natural gas kiln, with the entailing economic impact on the company.

The investment in a new gas kiln, at the end of the 1980s and beginning of the 1990s, is estimated at about €480,000, taking into account that kiln length at that time was shorter than today's kiln, and the degree of control and automation of the working parameters was low. However, this high investment had a great impact on kiln energy consumption and hence on CO_2 emissions, as noted above. It is estimated that the impact of the investment on reducing emissions was less than 3 EUR/t CO_2, assuming a kiln service life of 25 years.

As knowledge of the new firing technology increased, more efficient kilns were developed, and energy saving actions were implemented. These energy saving actions also involved investments, though their impact on emissions abatement was lower.

It is estimated that, at present, the impact on emissions on replacing a kiln that ends its service life with a new one is about 16–18 EUR/t CO_2, assuming a kiln service life of 25 years.

On the other hand, the impact of the investments in installing heat recovery systems or replacing burners with other, more efficient ones on emissions abatement is 10–15 EUR/t CO_2.

Therefore, at present, the economic effort required to reduce CO_2 emissions is about 5 times higher than in the period of technological change witnessed at the end of the 1980s.

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[35] SITI B&T: https://sitibt.com/hornos-esp

[36] SACMI GROUP: https://sacmi.com/es-ES/ceramics/Azulejos/Hornos-industriales-para-ceramica-y-accesorios

4. Conclusions

The main conclusions drawn from the analysis of CO_2 emissions over the last four decades and from the study of the technological changes and energy saving actions implemented in the Spanish ceramic tile sector are set out below:

- The technological changes implemented in the decade 1980–1990 entailed a significant increase in energy efficiency and a 46% decrease in specific emissions of CO_2. This extremely important drop in CO_2 emissions per unit product took place prior to the reference year for the emissions trading system (1990).
- From 1990 on, when the use of natural gas as fuel and single-deck roller kilns had been widely implemented, energy saving actions and investments to further decrease CO_2 emissions as much as possible were continuously made, leading to a reduction in relation to 1980 of 60%, and in relation to 1990 of 26%.
- In light of the absence of radical changes to the manufacturing technologies from an energy viewpoint, the absolute emissions from 1990 have followed the same trend as that of production, but the increased efficiency has led, over 4 decades, to a continuous decrease in emissions per unit product.
- Technological and production optimisation has reached a point of maturity and excellence to enable the inference that the sector lies within attainable minimum values of CO_2 emissions with the technologies used.
- Greater reductions in CO_2 emissions will only be possible with major technological changes, which are still in a research stage.
- With the technologies and fuels used at present in the ceramics manufacturing process, the margin of reduction in direct emissions of the process is limited, because technologies are involved that have been widely improved and that are deemed Best Available Techniques[37], which is why in some way an asymptotic point has been reached, at which if there are no radical changes in the process, product, or energy sources, improvements are going to be marginal.

By way of summary, the contribution of the different implemented energy saving actions in the abatement of specific emissions of CO_2, in the different periods of time analysed, is set out below.

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[37] Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry. European Commission. 2007.

Table 1. Summary of the evolution of specific emissions of CO_2 (SE) and actions implemented.

Period	**Specific emissions (kg CO_2/m^2)**	**Main actions implemented**	**Reduction in specific emissions (%)**	
			1980	**1990**
1980–90	14,2	• Fuel changeover to natural gas • Introduction of single-deck kilns	Base	--
1990–20	7,6	• Widespread implementation of single firing and natural gas • Cogeneration systems • Greater understanding and control of the new roller kilns	46	Base
2000–10	6,2	• Greater process control • Increase in porcelain tile • Increased sector production	56	18
2010–20	5,8	• Waste heat recovery • Preheating of combustion air • New high-efficiency burners • Large facilities with high efficiency	59	24
2020–	5,6	• Process automation • Information management • Large tile sizes	61	26

5. Future opportunities for decarbonising the ceramic sector

The GHG emissions reduction targets established at European level are very ambitious, so that, to meet them, the sector will have to radically modify the technologies used in its production process or see itself facing a dramatic drop in global ceramic tile production.

An important decrease in emissions by technological measures will only be possible by using alternative fuels, incorporating new technologies, and making important changes in the manufacturing process.

Among the existing options, to be noted is the use of hydrogen as a direct source of thermal energy by combustion, in the drying and firing processes, specifically so-called green hydrogen. This is hydrogen generated by electrolysis using electricity from a renewable source as energy source. The international community, in particular the EU, is setting high hopes on the possibility of using this fuel to decarbonise some processes that require high operating temperatures. Although it is clearly an alternative of great interest in the long term, technologies are involved whose industrial implementation is in a very early stage of development, and it is going to require development times that are hardly compatible with the proposed European timelines, as it does not display a sufficient degree of technical–economic maturity for mass industrial implementation, at least in the short–middle term.

The main drawback is that it is not a primary energy source, but it needs to be generated and therefore requires electricity consumption, involving power that must come from renewable energy sources for it to be deemed green hydrogen and thus truly to contribute to the general decarbonisation of the economy. The main advantage is that it could be generated in the very plants that consume it, though that would entail major investments in view of the high energy consumption of ceramic companies, and the fact that its combustion only generates water vapour. However, its industrial implementation is considered difficult in the short term, owing to the lack of research in relation to its application in the production process of the ceramic industry, and to the lack of available industrial equipment. On the other hand, the current average price of green hydrogen is of the order of 5 times higher than that of natural gas, which makes it economically unfeasible in the short or middle term. To foster its use through distributed generation, support mechanisms and funding will be needed to make this energy vector feasible in the industry

Other options involve the use of biofuels, such as biomethane obtained from biogas generated from organic wastes. This could be the simplest path towards decarbonisation, as it would not require additional technological adaptations and, on the other hand, it would allow the current natural gas transportation and distribution network to be used. In any event, though it might be an alternative that could allow emissions relating to the use of gas to be reduced and be of great interest for some specific industries, its ability to provide a very significant contribution in the short term is not deemed realistic, owing to its low availability, limited production capacity, and the absence of sufficient political will for deployment on a national level.

One of the possibilities for significantly reducing emissions would be radically changing drying and firing equipment, partly or entirely replacing combustion heating systems with electric heating systems. It is an option that is being studied and developed, and it affords the undoubted advantage that, from a technological viewpoint, very mature alternatives are available, even though the range of commercial industrial equipment that would allow implementation in a general way is limited. This is fundamentally due to the disadvantage of the price of electric energy and of the required power since a great investment in electric infrastructure would be needed to meet the entire sector’s demand. The use of electric facilities would not produce direct emissions of CO_2 into the atmosphere, and it is one of the alternatives being studied at present.

The incorporation of renewable energies into the process itself (photovoltaic generation of electric power, solar generation of thermal energy, biomass, etc.) provides important opportunities and should be maximised as far as possible, but their overall contribution to reducing GHG emissions in the sector is very limited, because of the great energy and temperature demands of the manufacturing process.

On the other hand, CO_2 capture is a technology that affords the clear advantage of not requiring any change to the manufacturing process. However, the low concentration of CO_2 in the output streams, together with the immaturity of capture processes, makes this an economically and technically unfeasible option, at least in the short term.

Therefore, in the next few years, the sector must continue to focus its efforts on improving process control, increasing waste heat recovery, and applying technologies that enable natural gas consumption to be reduced.

At product level, work is ongoing to minimise emissions by developing products with a lower carbonate content to reduce direct process emissions from the product, decreasing the thickness of the products made, lowering firing temperature, etc.

The main advantages and disadvantages of each of the possible decarbonisation technologies deemed applicable to the ceramic sector are summed up in Table 2.

Table 2. Advantages and disadvantages of the possible decarbonisation technologies.

TECHNOLOGY	**ADVANTAGES**	**DISADVANTAGES**
Hydrogen as fuel	▪ Possibility of in-situ generation ▪ Its combustion only generates water vapour ▪ Versatility as energy vector	▪ Is not a primary energy source, requires electricity for its generation ▪ Requires high investments for in-situ generation ▪ The electricity would have to come from renewable sources. Green H_2 ▪ There is no commercial industrial H_2 combustion equipment ▪ There are no previous experiences of the impact on the end product ▪ Requires specific safety measures
Biofuels: biomass/biomethane	▪ Emissions do not count for the ETS ▪ Possibility of using organic waste: industrial symbiosis ▪ Generation of biomethane: would require no change in technology	▪ Difficulties for meeting the sector's total energy demand ▪ Assurance of supply, availability in the environment, and cost of biofuel
Electrification	▪ Generates no direct emissions ▪ Existence of industrial equipment, with limited productions and very specific products. ▪ Ease of process control ▪ Possibility of partially meeting the self-generation demand	▪ Scarce offer of commercial industrial equipment ▪ High price of electricity ▪ Difficulty of meeting energy demand with self-generation
Incorporation of renewables	▪ Generate no direct emissions ▪ Require no major changes in the process	▪ Cannot meet the great energy demand or reach high temperatures ▪ Need for high investments ▪ Very high spatial requirements for solar energy equipment
CO_2 capture	▪ Requires no major changes in the process ▪ Possibility of revalorising carbon captured in other sectors: industrial symbiosis, circular economy	▪ Immature capture processes ▪ Low CO_2 concentrations in sector emissions ▪ Need to incorporate sophisticated gas treatments

Report no. C214297, issued at the request of ASCER - ASOCIACIÓN ESPAÑOLA DE FABRICANTES DE AZULEJOS Y PAVIMENTOS CERÁMICOS, consists of a title page and 20 pages.

Castellón, 18 November 2021

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Sustainability

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