How can the European ceramic tile industry meet the EU's low-carbon targets? A life cycle perspective

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Abstract

Ceramic tile manufacturing is deemed to be an energy intensive industry, mainly based on combustion processes and, therefore, subject to European policies aiming at reducing greenhouse gas emissions. The “Roadmap for moving to a competitive low-carbon economy in 2050”, approved by the European Commission, calls for sectoral strategies to reduce CO_2 emissions by 20% by 2020 and by 83–87% by 2050, compared to 1990 CO_2 emissions. This study included up to 17 technological alternatives and their combination, resulting in 25 technological scenarios associated to the life cycle of porcelain stoneware tiles. In this regard, a high parametrized LCA model was developed to allow for the required flexibility. The scenario analysis can be used: a) to estimate the degree of technological innovation required; b) to define and to focus strategies and; c) to devise the lines of technological development that need to be implemented in the ceramic tile manufacturing sector in the coming years. The alternatives consisted of endogenous and exogenous sectoral technologies. The technologic alternatives involved changes in product design (thickness and decoration), changes in the manufacturing process (preparation of raw material by dry or wet route, and simultaneous implementation of thermal energy efficiency techniques), and changes in the energy sources (hybrid and/or electric driers, and kilns and decarbonization of the power grid mix). It was clearly proven that the wider the scope of the Life Cycle Assessment study is, the greater eco-innovations are necessary. In all the studied scenarios, the manufacturing stage was always the most significant from the global warming point of view. Finally, regarding the achievability of EU objectives, the results of this study show that the implementation of widespread technologies suffice for fulfilling 2020 targets; nevertheless, only some limited combinations of both widespread and ambitious breakthrough technologies may achieve the 2050 reduction targets.

Keywords: Low-carbon economy; Ceramic tiles; Life cycle assessment; Technological scenarios

1 Introduction

The most important ceramic subsector (in turnover) is the floor and wall ceramic tiles. According to European data, production is around 1304 million m^2, consumption amounts to 964 million m^2 and total sales were close to €9 billion in 2016. (Baraldi, 2017; Cerame Unie, 2017). Spain and Italy are the largest EU ceramic tile producers, together accounting for around 80–90% of European production. (Baraldi, 2017; Cerame Unie, 2017).

Europe produces different types of ceramic tiles. The most common ones are earthenware tiles, glazed stoneware tiles and porcelain stoneware tiles (PST) (ASCER, 2011). Their manufacturing processes are quite similar irrespective of the type of tile, and mainly consist of the reception and storage of raw materials, their granulation, tile forming, drying, glazing and decorating, and firing (EIPPCB, 2007). Some of these stages can be carried out by means of alternative technologies or routes. For instance: raw material milling may be performed through a wet or dry route; tile forming through pressing or extrusion; firing in one or two stages, etc. (Ros-Dosdá et al., 2017). The most popular manufacturing process in Europe (raw material wet milling and single-firing) is schematically illustrated in Fig. 1.

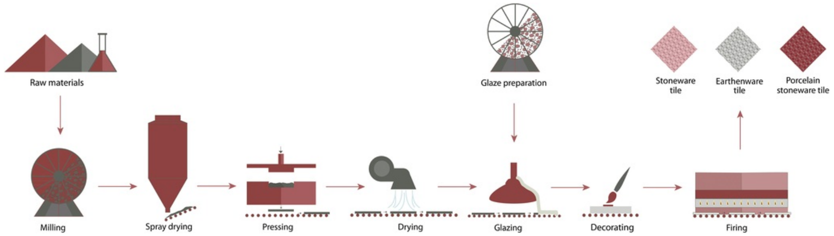

Fig. 1 Schematic illustration of the single-fired ceramic tile manufacturing process.

alt-text: Fig. 1

Ceramic tile manufacturing is an energy-intensive process (30–40 kWh/m^2 for an average specific weight of 22 ± 1 kg/m^2) (Ibáñez-Forés et al., 2011; Mezquita et al., 2017; Monfort et al., 2010; Ros-Dosdá et al., 2017), being thermal energy the most important demand. This energy is mainly obtained by combustion of natural gas, which represents 90% of the overall direct energy consumption. Thermal energy consumption mainly takes place in three process stages: spray drying of ceramic slurries (36%), drying of the formed ceramic tile bodies (9%), and ceramic tile firing (55%) (EIPPCB, 2007; Monfort et al., 2010).

Ceramic tile manufacturers are concerned about the carbon dioxide emissions (Gabaldón-Estevan et al., 2014), since they are subject to control pursuant to the EU Climate Change and Energy Sustainability policies and laws, such as Directive 2003/87/EC, Directive 2009/29/EC, and Directive 2012/27/EU, which establish specific targets on this topic. Additionally, in 2011, the European Commission published the “Roadmap for moving to a competitive low-carbon economy in 2050” and, for the industrial sectors, the objective is to reduce CO_2 emissions from 83% to 87% by 2050 (COM (2011) 112 final).

Since solutions are sector specific, the EU recommends that each industrial sector prepare a specific roadmap in order to identify the best available techniques (BAT) to reach the mentioned objectives. The European ceramic industry has prepared, through Cerame-Unie, its own roadmap. The document considers alternative energy sources and current and future production of technologies (Cerame Unie, 2012), and urges to consider the complete lifecycle of ceramics, arguing that the contribution of durable products to resource and energy efficiency can only be appreciated with a holistic approach, including its durability and impact over the use phase.

Several studies on how to improve the energy efficiency in the manufacturing sector of ceramic tiles have been published (Mezquita et al., 2014a, 2014b; Shu et al., 2012a, 2012b) as well as Life Cycle Assessment (LCA) studies that identify hotspots and make proposals for improvement (Almeida et al., 2016; Bovea et al., 2010; Ibáñez-Forés et al., 2013).

Previous studies (Cerame Unie, 2012; ~~Gabaldon-Estevan et al.,2014,~~_ (Gabaldon-Estevan et al., 2014)2016) show that these objectives for the European ceramic sector are extremely demanding, and unreachable with current technologies and policies. Therefore, its application implies implementing breakthrough technology to dramatically reduce carbon dioxide emissions. Moreover, Bocken et al., 2014 stated that fundamental changes, such as an integrated approach that goes beyond eco-efficiency initiatives and rethinking the way that businesses work are required to deliver long-term sustainability to reach the scenario for 2050, including new perceptions of values and new business models aligned in a route to a sustainable and circular economy.

On the other hand, several studies have been published with the aim of evaluating long term CO_2 emissions in several industrial sectors (Ajanovic, 2013; García-Gusano et al., 2015; Griffin et al., 2017; Selvakkumaran et al., 2014; Xu et al., 2014). However, none of them assess the CO_2 emissions from a life-cycle perspective. If this life-cycle perspective is not applied, for example, it may erroneously be concluded that the installation of electric kilns and driers would suffice to reach the established industrial targets on CO_2 emissions. Therefore, a holistic approach, such as the one provided by a life cycle perspective, is necessary to avoid environmental loads shifting to exogenous entities. This is especially important in the case of energy studies. In fact, some authors (Streimikiene and Šivickas, 2008) have identified contradictory impacts in the implementation of changes required to meet EU Directives targeting specific sustainable objectives. Consequently, assessment from a life cycle perspective is essential to find a trade-off and to avoid environmental burden shifting. Indeed, many studies consider that the LCA methodology is the most appropriate for scientific basis to assist decision-making processes in the development of truly effective environmental policies and strategies (Tan and Culaba, 2002). LCA is a standardized and widely used methodology and is accepted for analyzing the interactions of a technological system with the environment (Guinée et al., 2002; Klöpffer and Grahl, 2009; Tan and Culaba, 2002).

In this regard, the aim of this study is to compare different technological options to reach the EU 2020 and 2050 Greenhouse Gas (GHG) emissions objectives, applying an attributional LCA approach.

To this end, the current study was developed using real and verified data obtained by the authors from the Spanish ceramic tile industry (Ros-Dosdá et al., 2017), which is considered to be sufficiently representative of the European ceramic tile industry, (it accounts for around 50% of the European production) (Baraldi, 2017). From the global warming point of view, there are major similarities, such as the process technologies, product manufactured, legal framework based on European Directives, etc. (Gabaldon-Estevan et al., 2016). Nevertheless, there are differences to be considered in other countries, such as the degree of cogeneration systems implementation (Confindustria Ceramica, 2018; Pardo, 2018) or the raw material origin. The study is focused on PST, since it is the type of ceramic tile with the greatest commercial and innovation interest due to its high technical, functional and aesthetic versatility (ASCER, 2011; Sánchez et al., 2010).

2 Research method

2.1 Goal definition

On the account of the introduction above, the aim of this study was to determine whether and how it is possible to achieve the emission reduction objectives set by the European Commission through a roadmap for moving to (and surviving in) a competitive low carbon economy in 2020 and 2050, using the LCA methodology on different technological scenarios of the PST life cycle.

When performing LCA, several standards (EN 15804:2012+A1:2013; ISO 14040:2006; ISO 14044:2006) and the ILCD handbook (Wolf et al., 2010) recommendations were followed. The EeBGuide was consulted as well (Lasvaux et al., 2014). In addition, scenario analyses were used: a) to estimate the degree of technological innovation required; b) to define and to outline the strategies and; c) to devise the lines of technological development which need to be implemented in the ceramic tile manufacturing sector in the coming years.

2.2 System definition and functional unit

The analyses considered the entire life cycle, i.e. from cradle to grave, although other scopes were used in the discussion of results. Life cycle modules were those used in CEN/TC 350 standards. The system boundary included the raw materials supplied for the body and glaze manufacturing, the raw materials transport means and distances, and each stage of the ceramic tile manufacturing process. Once the tiles are packaged, they are worldwide distributed; then, the tiles are duly unpacked for installation with fast-setting mortars. In this paper, a residential scenario was considered with a lifespan of 50 years. Afterwards, 70% of the removed tiles are deemed to be recovered as a filler, and 30% landfilled.

The Functional Unit (FU) was defined as “covering 1 m^2 of household floor surface for 50 years with an average PST”. The characteristics of an average fired PST were defined as: water absorption <0.5%; 23.2 kg/m^2 weight; and 10.4 mm thickness with 0.76 kg/m^2 of glazes (Ros-Dosdá et al., 2017).

2.3 Baseline scenario and latest scenario

The study was built on a compilation of environmental information from 26 Spanish companies to obtain 14 Environmental Product Declarations (EPD) of PST. Therefore, inventory data, which corresponded to the period 2010–2015, were verified by independent third parties. The study includes companies from the whole value chain: elaborated raw material producers (both spray-dried granulated and glazes) and ceramic tile manufacturers. Moreover, some generic data, such as the type of means of transport or the type of waste management processes, were taken from a Spanish sectoral LCA study, carried out in 2007–2009 (Ros-Dosdá et al., 2017).

In order to define the reference scenario, i.e. 1990, inputs and outputs of energy (thermal and electrical) for that year were taken from sectoral historical data (Celades et al., 2012), as they constitute more than 80% of the GHG emitted throughout the manufacturing process of the PST (Almeida et al., 2016; Benveniste et al., 2011; Bovea et al., 2010; Ibáñez-Forés et al., 2011; Ros-Dosdá et al., 2017). Table 1 compares the PST manufacturing energy data of 1990 and 2010–2015.

Table 1 Main changes in the energy data inventory from 1990 to 2010–15.

alt-text: Table 1

PST manufacturing process	1990	2010–2015
INPUTS		
Electrical energy taken from the grid (MJ/m^2)	19.21	16.50
Thermal energy from natural gas (MJ/m^2)	108.0	128.3[a]
OUTPUTS		
Electrical energy sold to the grid (MJ/m^2)	0	14.6

[a] Including natural gas to feed the combined heat and power cogeneration system (CS) installed in the spray drier.

2.4 Limitations

No reference to the technical or economic viability of the proposals is discussed in this paper. In fact, the authors recognize that, in some cases, the development and implementation of the breakthrough technology will still be required (e.g. 100% of renewable energy used in kilns and driers), and they are aware that some studies (Wesselling et al., 2017) claimed that the integration of breakthrough innovations in traditional industries (as the studied ones) is typically slower than in high-tech industries for different reasons, such as the need for long-term investments, low risk managerial decisions or lack of market incentives. Nevertheless, the results of this study provide an idea of the level of theoretical demand set by the European Union and the technological trends to fulfil the required targets.

2.5 Selection of environmental impact categories

The life cycle impact assessment was carried out applying the CML 2001 impact assessment method (Guinée et al., 2002), as suggested in EN 15804:2012+A1:2013, updated to 2015. Although special attention was given to the Global Warming Potential (GWP), other environmental categories were also analyzed under the CML 2001 method (Guinée et al., 2002), as shown in Table 2, to study potential environmental burden shifting.

Table 2 Environmental impact categories.

alt-text: Table 2

Impact category	Acronym	Units
Abiotic Depletion - elements	ADP-elements	kg Sb Equivalent
Abiotic Depletion - fossil fuels	ADP-fossil	MJ
Acidification Potential	AP	kg SO_2 Equivalent
Eutrophication Potential	EP	kg PO_4^{3-} Equivalent
Global Warming Potential (100 years)	GWP	kg CO_2 Equivalent
Ozone Layer Depletion Potential (steady state)	ODP	kg R11 Equivalent
Photochemical Ozone Creation Potential	POCP	kg C_2H_4 Equivalent

2.6 LCA model

The LCA model was developed in GaBi software (PE International, 2008b; Thinkstep, 2016b) and the bundled professional databases PE International 2008a, Thinkstep 2016a and ELCD 3.2 (JRC-IES, 2015). in order to obtain the background data. A total of 194 variables were parameterized to allow for the scenario analyses. Some parameters served to define the technological route when multiple alternatives were possible (e.g. dry milling vs. wet milling) and some others were used to input process values (e.g. thermal energy needed in the firing stage). The latter parameters could be grouped into different categories: consumption of raw and auxiliary materials; water and energy consumption; emissions to air; waste generated; distances and types of transport between the different life cycle stages; etc. Table 3 presents a summary of the different parameter categories applied in this study.

Table 3 (For a better reading, replace this table with the attached one)Parameters included in the LCA model.

alt-text: Table 3

Parameters to define the technological route		
Processes	**Technological route**	**Features**
Body raw materials preparation	**a)** Wet milling **b)** Dry milling	It is possible to define an application rate for each route

Forming	**a)** Pressing **b)** Extrusion	
Waste management	**a)** Incineration **b)** Recycling c) Disposal	
Firing	**a)** Single firing **b)** Double firing	One of the possible routes must be chosen
Use scenario	**a)** Residential use **b)** Commercial use **c)** Sanitary use	

Parameters to define the process values (quantification of inputs/outputs)

Type of parameters	**Life cycle processes**	**Features**
Types and quantities of raw materials	• Body composition • Glaze composition	Mineralogical composition
Types and distances in transports	• Raw materials to the granulates factory • Granulates to the tile factory • Glazes to the tile factory • Packaging to the tile factory and to the glazes factory • Auxiliary materials: – to the tile factory – to the installation site – to the building • Tiles to the buildings	Type of vehicle (truck, trailer, cargo), load capacity

Energy consumption	• Granulate production • Glaze production • Tile production	Thermal and electrical energy
Water consumption	• Granulate production • Glaze production • Tile production • Tile installation	Source of water: tap water; groundwater; recycled water
Quantity and type of emissions to the air	• Granulate production • Glaze production • Tile production	Channeled emissions (cold and hot)
Quantity and quality of waste water	• Granulate production • Glaze production • Tile production	Destination, pollutants and management processes
Solid waste	• Granulate production • Glaze production • Tile production • Tile installation • Tile maintenance • End-of-life	Hazardous and non-hazardous wastes Destination and management processes

This high parameterization of the model made programming more difficult at the beginning, but it gave much more flexibility to build scenarios in the long run. The modelling applied a modular approach, i.e. each process was modelled separately to facilitate the definition of process routes and technological and managerial options, providing high flexibility in the scenario simulation process.

2.7 Technological alternatives

A literature review of the technological alternatives and innovation trends allowed us to identify a set of the technologies which are the most likely to be applied in the horizon 2020 and 2050. They may be classified as: widespread (ready to be implemented) or breakthrough (further research is needed) and exogenous (outside the scope of the ceramic tile industry) or endogenous (sector specific) technologies. In Table 4, the characteristics of each technological alternative are summarized, as well as the reference source used to identify these technological alternatives and their representative values for energy and material.

Table 4 **(For a better reading, replace this table with the attached one)** Summary of technological alternatives. (Table 4 is very wide, better to edit horizontally, using the width of two columns)

alt-text: Table 4

Technological alternatives		Options		References sources
		Reference	Description	
Product design	Quantity of glaze	GL100	Current average amount of glaze decorative materials. For PST is estimated as 0.76 kg/m^2 solid, with 33% frit content	ASCER 2011; Nicoletti et al., 2002; Ros Dosdá et al., 2017
		GL50	Reduction in the amount of glaze in 50%	
		GL0	No glaze coating or decoration is applied	
	Thickness of the tile	TH100	Current PST average thickness. 10.4 mm, weighing 24.2 kg/m^2 unfired	ASCER 2011; Da Silva et al., 2014a, 2014b; Girao et al., 2009; Pini et al., 2014; Raimondo, 2010; Ros Dosdá et al., 2017
		TH50	Reduction of 50% of PST thickness, thus reducing its mass.	
Manufacturing process	Body raw material preparation process	WCS	Wet milling of body raw materials using cogeneration systems	Mezquita et al., 2017; Bonucchi, 2012; Melchiades et al., 2010; Schianchi, 2012; Shu et al., 2012a, 2012b
		DRY	Dry milling of body raw materials	
	Energy efficiency technologies in driers and kilns	CTT	Current Thermal Technology scenario in driers and kilns	Almeida et al., 2016; Bovea et al., 2010; Ibáñez-Forés et al., 2013; Mezquita et al., 2014a, 2014b
		WDS	Simultaneous implementation of widespread technologies to increase the overall efficiency up to 45% (driers + kilns)	
Energy sources	Electric energy source	SGM90 SGM15 SGM20 SGM50	Electricity from the Spanish Power Grid Mix (SGM) of different years (1990, 2015, 2020, 2050)	Cerame Unie 2012; Capros et al., 2013; Gabaldón-Estevan et al., 2014, 2016; REE, 2016
		REN50	Electricity in 2050 came from a mix of 100% renewable sources	
	Thermal energy source	NG100	Combustion: 100% natural gas	Cerame Unie 2012; Ros Dosdá et al., 2017
		NG50	Hybrid: 50% natural gas +50% electric sources	
		NG0	Electric: 100% electric sources	

A sensitivity analysis was carried out to identify the most critical parameters from the point of view of global warming. This material is attached as supplementary information.

2.8 Technological scenarios

From the combination of the different technological alternatives identified in the previous chapter, a total of 25 technological scenarios were formulated. Inventory data for each scenario was adapted from the average PST inventory (Ros-Dosdá et al., 2017) to the technological alternatives applied in each case.

In Table 5, the scenarios are listed from A to Z, showing the different technological alternatives chosen from the ones listed in the columns, grouped in three major classes: product design, manufacturing processes, and energy sources. In the scenario simulation, it should be considered that reference scenario A compiles technological alternatives which are the most likely to be applied in 1990, taken as a baseline by the Kyoto protocol and EU Directives, and scenario C represents the most likely technological situation in the ceramic tile industry in 2015.

Table 5 (For a better reading, replace this table with the attached one)Simulated technological scenarios (made up of a combination of technological alternatives).

alt-text: Table 5

Scenarios	Technological Alternatives					
	Product design		Manufacturing processes		Energy sources	
	Glaze	Thickness	Milling	Driers & Kilns	Electric energy source	Thermal energy source

	GL100	GL50	GL0	TH100	TH50	WCS	DRY	CTT	WDS	SGM90	SGM15	SGM20	SGM50	REN50	NG100	NG50	NG0
A (baseline)	X			X		X		X		X					X		
C (2015)	X			X		X		X			X				X		
D	X			X		X			X		X				X		
E	X			X		X			X			X			X		
F	X			X		X			X				X		X		
G	X			X			X		X			X			X		
H	X			X			X		X				X		X		
I	X			X		X			X			X				X	
J	X			X		X			X				X			X	
K	X			X			X		X			X				X	
L	X			X			X		X				X			X	
M	X			X		X			X					X		X	
N	X			X			X		X					X		X	
O	X			X			X		X			X					X
P	X			X			X		X				X				X
Q	X			X		X			X					X			X
R			X		X	X			X			X			X		
S			X		X	X			X				X		X		
T		X			X	X			X					X		X	
U			X		X	X			X					X		X	
V		X			X	X			X					X			X
W			X		X	X			X					X			X
X			X		X	X			X					X			X
Y		X			X		X		X					X			X
Z			X		X		X		X					X			X

3 Results and discussion

The emissions of CO_2 equivalent (CO_2eq.) associated to all technological alternatives and constructed technological scenarios in the lifecycle of PST were quantified and analyzed with the support of GaBi Analyst (Thinkstep, 2016b). It should be noted that the same distribution destinations, maintenance operations and end-of-life management were considered in all technological alternatives and scenarios. Furthermore, other environmental impact categories were evaluated to identify possible burden shifting. In the figures, both the potential CO_2eq. emitted in 1990 (A, baseline scenario) and the reduction considered by the EU objective for 2020 and 2050 are especially highlighted.

The sensitivity analysis performed assessed the influence of inventory data related to technology alternatives on the Global Warming Potential impact category. The results showed that the parameters related to the use of energy (directly or indirectly) were the most critical ones; these parameters included the consumption of thermal and electrical energy, cogeneration systems and the thickness of the tiles, but also the quantity of glazes and frits. The results of the sensitivity analysis are presented as supplementary information.

3.1 Potential reduction by technological alternatives

3.1.1 Product design alternatives

In the product design, two major factors were considered: quantity of glaze (GL100/GL50/GL0) and thickness of the tile (TH100/TH50). Regarding decoration materials, the extraction and transport of raw materials and the manufacturing of 1 kg of solid glaze with 33% of frit content applied on PST involved the emission of 0.8 kg CO_2eq. In this regard, it should be pointed out that the frit is the glaze component with a higher carbon footprint, since its manufacturing process includes the fusion of the raw materials at around 1500 °C (Gómez-Tena et al., 2009). Consequently, the reduction in the amount of glaze or frit content would entail an almost proportional reduction of CO_2eq. emissions.

On the other hand, lightening the tile by reducing the thickness of the ceramic body is possible as long as the technical and functional performance of the final product are not compromised (da Silva et al., 2014a; Girao et al., 2009). Fig. 2 (left) shows a potential reduction of 36% of CO_2eq. emissions corresponding to a 50% thickness reduction (C-TH50) when compared to the latest scenario (C-TH100). This high dependence was due to the influence of thickness along the life cycle through the reduction of raw materials extraction, transportation, energy demand, etc. (da Silva et al., 2014a; Pini et al., 2014; Ros-Dosdá et al., 2017). No burden shifting in other impact categories were identified, as shown in Fig. 2 (right) where both technological alternatives are compared with relative values in 7 environmental impact categories. Indeed, the only impact category that exhibited a non-proportional reduction was the ADP element category, which is much more influenced by glaze components than by body thickness.

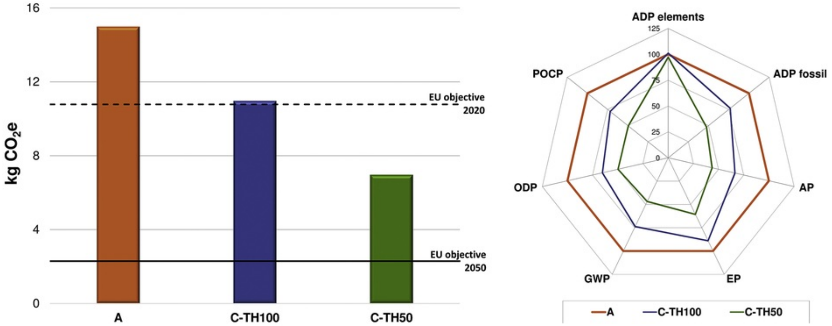

Fig. 2 Effect of the thickness reduction on the associated CO_2eq. emissions of PST life cycle (left) and relative contribution in each impact category (right).

alt-text: Fig. 2

3.1.2 Manufacturing process alternatives

Two main process alternatives were analyzed: body raw materials preparation process (WCS/DRY) and energy efficiency technologies implemented in driers and kilns (CTT/WDS).

In the European ceramic tile industry, body raw materials are commonly prepared following a wet route (EIPPCB, 2007), because it facilitates the production of higher quality ceramic tiles in larger sizes. However, some studies claim that the new dry route developments may allow similar results to be obtained in a more sustainable way (Bonucchi, 2012; Mezquita et al., 2017; Shu et al., 2012a, 2012b). Nevertheless, these studies have not taken a life cycle approach. Consequently, a specific analysis has been included in this work. To perform the comparison in this section, three alternatives were considered: wet route (WET); wet route using combined heat and power cogeneration systems (WCS); and dry route (DRY).

The WCS is very popular in the Spanish ceramic tile industry. A combined heat and power cogeneration system (CS) installed in the spray-drier allows for the simultaneous production of electric and thermal energy with high efficiency, but it entails more natural gas consumption than the thermal process itself (Caglayan and Caliskan, 2018; Mezquita et al., 2017; Monfort at al., 2010). The surplus of electricity cogenerated was usually sent to the power grid. To analyze this co-product from a life-cycle perspective, an expansion of the system was applied instead of an allocation method, due to the lack of data and high level of uncertainties to represent the physical causalities of this process (Azapagic and Clift, 1999) and the difficulty to apply economic allocation since only the electricity which is sold to the grid has an economic value. Then, it was considered that only flexible technologies of the SGM would be displaced by the system (Weidema, 2000).

Fig. 3 (left) shows a comparison of CO_2eq. emissions associated to the preparation of body raw materials following different routes and considering the implementation of CS. Fig. 3 (right) shows the relative contribution to other environmental impact categories and provides the evidence that potential transferring of environmental loads occurs when these processes were assessed from a life cycle perspective. Thus, the achievement of a slightly reduction of 2% of CO_2eq. with the total implementation of DRY milling instead of the WCS would imply increasing the emissions of acidification substances and photochemical oxidants by 9% and 12%, respectively.

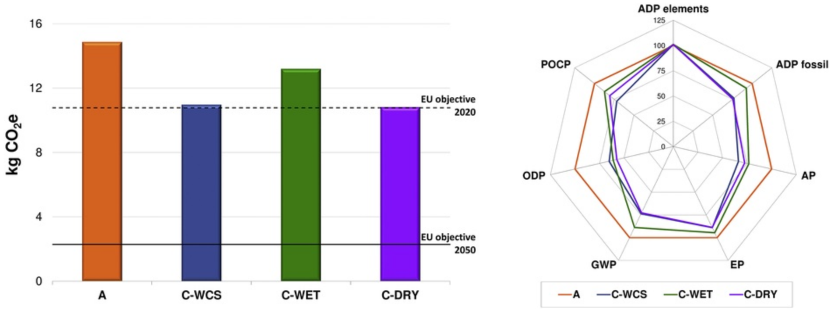

Fig. 3 Effect of the preparation of raw material on the associated CO_2eq. emissions of PST life cycle (left) and relative contribution in each impact category (right).

alt-text: Fig. 3

Regarding the energy efficiency technologies in thermal processes (driers and kilns), Fig. 4 reveals that the current scenario (scenario C) with an average thermal efficiency of 15%, almost fulfils the EU's objectives for 2020. Mezquita et al., 2014a, 2014b showed that the simultaneous implementation of the available widespread technologies allows for a maximum thermal efficiency of around 45% to be achieved (scenario D). Fig. 4 indicates that this does not suffice to attain the EU's objectives for 2050; therefore, these outcomes suggest that the combination of widespread and breakthrough technologies will be needed.

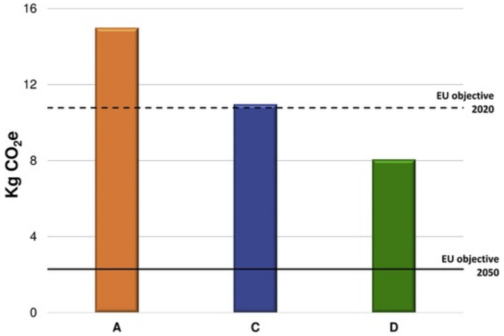

Fig. 4 Effect of the energy efficiency of thermal processes on the associated CO_2eq. emissions of PST life cycle.

alt-text: Fig. 4

3.1.3 Energy source alternatives

The effect of the evolution of the Spanish power grid mix (SGM) until 2050 was based on Capros et al., 2013 who forecasted, in a study for the European Commission, the power and transport evolution with considerations regarding to market, economics, industry structure, demography and energy/environmental policies and regulations. The relation between the evolution of the SGM and its GHG emissions was obtained by programming the different mixes using the GaBi software (Thinkstep, 2016b).

Fig. 5 shows the environmental performance of the PST life cycle over the years, considering both that the technology implementation and design of the product remains as in scenario C (2015), and that the SGM evolves according to the forecast made by Capros et al. (2013). Moreover, an additional alternative is presented in this figure: scenario C with a 100% renewable scenario in the SGM for 2050 (C-REN50). The figure also shows the content of energetic renewable sources and the GHG reduction targets set by the EU. REN50 was built on the percentage of renewable sources foreseen for 2050 and calculating an extrapolation to cover 100%, thereby maintaining the proportions of the different technologies. REN50 was composed then by 54% wind power, 24% solar power, 15% hydropower, 6.5% biomass and 0.5% geothermal and other renewable energies.

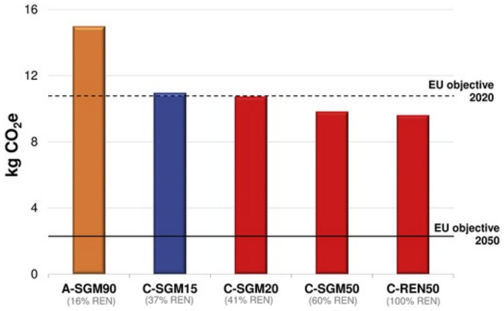

Fig. 5 Effect of the SGM on the associated CO_2eq. emissions of PST life cycle.

alt-text: Fig. 5

In Fig. 5, a very slight decrease in CO_2eq. emissions can be observed; consequently, it may be concluded that the accomplishment of the EU target in 2050 relying solely on the evolution of the SGM (exogenous factor) was not realistically affordable, supporting Gabaldón-Estevan et al., 2016.

Fig. 6 shows the CO_2eq. emissions associated with the life cycle of the scenario C when electric driers and kilns were used in the manufacturing process. An increase in emissions was detected due to the nature of the SGM. Fig. 6 evidences that SGM 2015 has a bigger carbon footprint than natural gas, i.e. 0.09 and 0.07 kg CO_2eq./MJ, respectively and, therefore, from the global warming impact point of view, it does not make sense to devote efforts to develop electrification technologies, if electricity from renewable energy sources is not assured. It means that ceramic industry "*per se*" cannot meet the EU CO_2 emissions objectives, if exogenous technologies are not implemented in reducing the SGM carbon footprint. The implementation of renewable sources at sector or plant scale does not seem to be sufficient to supply the required energy, hence this option has not been considered in this study.

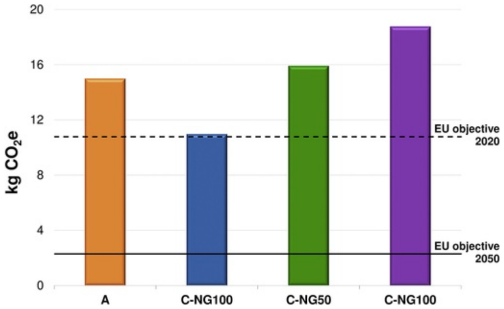

Fig. 6 Effect of the thermal process electrification on the associated CO_2eq. emissions of PST life cycle.

alt-text: Fig. 6

3.2 Potential reduction by technological scenarios

This section presents the results of the LCA of 25 technological scenarios. These 25 technological scenarios were obtained by the combination of those previous technological alternatives (see Table 5) which delivered substantial improvements in reducing CO_2eq. emissions.

Fig. 7 depicts the results of CO_2eq. emissions of each PST technological scenario, differentiating each module of the life cycle of PST, from the raw material supply (stage A1) to the end-of-life (stage C4). In Fig. 8 a gate-to-gate scope (life cycle stage A3) is shown. In each scope, the CO_2eq. emissions of the reference scenario and the correspondent EU objective reductions for 2020 and 2050 are marked.

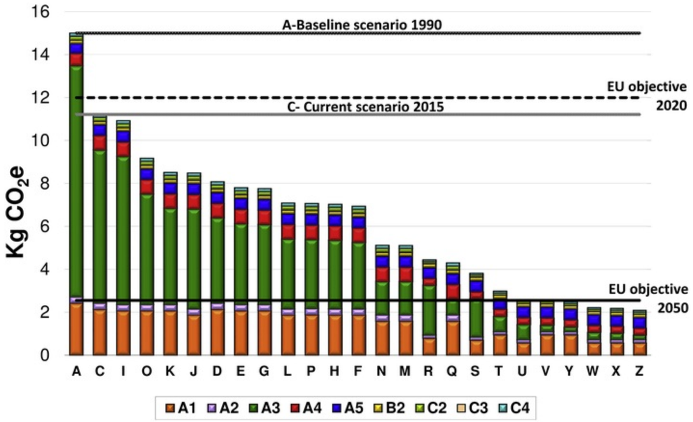

Fig. 7 **CO_2eq. emissions of PST technological scenarios and the contribution of each lifecycle module. Cradle to grave scope.** A1 raw materials supply; A2 transport; A3 manufacturing; A4 transport; A5 installation; B2 maintenance; C2 transport; C3 waste processing; C4 disposal. Codification used in EN 15804.

alt-text: Fig. 7

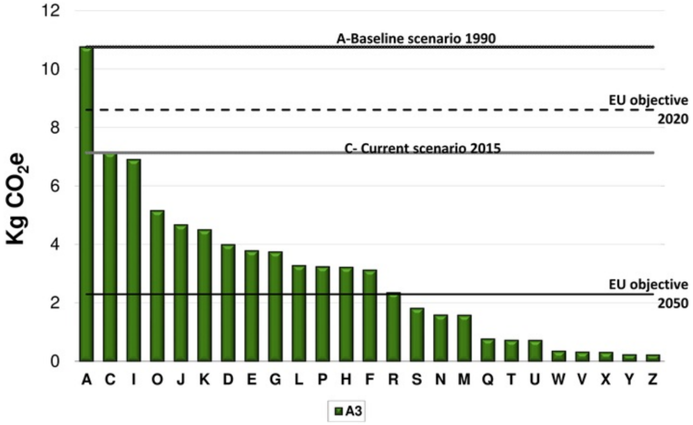

Fig. 8 CO_2eq. emissions of PST technological scenarios with a gate to gate scope.

alt-text: Fig. 8

Fig. 7 shows that, according to the proposed simulation, the CO_2eq. emissions associated with A1 and A2 stages (extraction and transport of raw materials, respectively) are mostly affected by the body thickness (tile weight), being the latter much less significant in absolute value. In this regard, it should be pointed out that the effect of the thickness on the emissions beyond the manufacturing process, from A4 (tile distribution) to C4 (end-of-life), also shows slight differences in absolute values among the studied scenarios. Even some of them (specifically A5 and B2, installation and maintenance respectively) are practically independent of the studied technological scenarios.

The main effect of technological scenarios on CO_2eq. emissions can be clearly observed in stage A3 (manufacturing process). To highlight this, an explicit figure (Fig. 8) with a gate-to-gate scope (i.e. manufacturing stage) has been produced.

For the sake of simplicity, in both Figs. 7 and 8, the CO_2eq. emissions associated with the studied scenarios are presented in a decreasing series of data. This allows for a better comparison with the EU objectives, and how the scope of the LCA influences the emission values. The comparison of Figs. 7 and 8 points out the need to clearly refer the targets and emission values to a specific scope to avoid misunderstandings and unfair comparisons among products and sectors.

3.2.1 Technological scenarios fulfilling EU's targets for 2020 (Merge the paragraphs of this section 3.2.1 into a single paragraph)

Figs. 7 and 8 clearly show that all the simulated technological scenarios fulfilled the EU ‘s targets for 2020, i.e. a 20% reduction in CO_2eq. emissions by 2020 compared to 1990.

The current scenario (scenario C) fulfilled the 2020 targets owing to the technological changes experienced in recent years (Celades et al., 2012), but it was slightly lower than the EU's target, therefore any eco-innovation that could be included would ensure compliance with a greater margin.

The technological scenarios with an electric energy source defined for 2020 according to Capros et al. (2013) (Replace this reference: Capros et al. (2013) with "Capros et al., 2013) are the following ones: E; G; I; K; O; and R.

It is worth noting the results obtained with scenario E, which allowed for a significant reduction of the CO_2eq. emissions with a relatively low innovation effort. This scenario consisted of the simultaneous implementation of the widespread technologies in the drying and firing stages (increasing the thermal energy efficiency), while the rest of the alternatives remained unchanged.

Scenario R, the one with the greatest reductions, using the electric energy sources for 2020 (SGM20) required greater effort and more limitations, because it consisted of manufacturing unglazed lightened tiles (GL0, TH50) with the simultaneous implementation of widespread technologies in the drying and firing stage (WDS), but it was really close to the EU ’targets for 2050, particularly when a gate-to-gate approach was applied.

3.2.2 Technological scenarios fulfilling EU's targets for 2050

Figs. 7 and 8 show that few simulated scenarios fulfilled the EU ‘s targets for 2050, i.e. an 85% reduction in CO_2eq. emissions by 2050 compared to 1990, especially when a cradle-to-grave approach was employed.

Effectively, when reduction targets were applied to the *entire product life cycle*, only four scenarios (W, X, Y, and Z) could fulfil the requirements of the Commission (Fig. 7). The common characteristics of these technological scenarios are: changes in product design (reductions of the thickness of the body (TH50) and reduction to half the quantity of glaze (GL50)); implementation of widespread technologies in thermal energy efficiency (WDS). Furthermore, full electrification of thermal processes (NG0) from renewable sources (REN50) would be jointly needed. It is interesting to point out that the route to prepare the body raw materials did not seem to have a significant effect on the carbon footprint, as explained in 3.1.2.

If the objectives were only focused on the *ceramic tile manufacturing stage* (A3), a less demanding implementation of technological alternatives would be needed to achieve the objectives of the European Commission. The technological scenarios that met the requirements of the roadmap were eleven: M; N; Q; S; T; U; V; W; X; Y; and Z (see Fig. 8). These objectives could be achieved either by modifying the product design (removal of the glaze (GL0) and reduction of the thickness of the ceramic body (TH50)) or by electrifying 50% of the thermal processes (NG50) through renewable sources (REN50). In all these cases, the implementation of widespread technologies in thermal energy efficiency (WDS) was considered.

4 Conclusions

It has been proven that the greater the scope of the LCA study is, the greater eco-innovations are needed. The main environmental advantages appear in the use and end-of-life stages of the PST. This happens thanks to their long lifespan, easy cleaning and maintenance, the inert nature of the end-of-life waste flows, and their simplicity or open loop recycling. It is necessary then to clarify the targets and emission values to a specific scope, in order to avoid misunderstandings and unfair comparisons with products or sectors (wood floorings, carpets, etc.), which may have fewer production impacts but higher ones when it comes to use or disposal.

From the studied technological alternatives, the incorporation of widespread technologies to increase energy efficiency of the thermal processes up to 45% (WDS) and the thickness reduction of the ceramic body (TH50) were the alternatives that implied the higher reductions of CO_2eq. emissions. It has been ensured that none of the alternatives implied burden shifting among the different environmental impact categories. On the other hand, the increase of renewable energies in the SGM entailed relevant improvements.

Neither the electrification of thermal processes (NG50/NG0) nor the preparation of raw materials following the dry route (DRY) seemed to be interesting measures when an overall life cycle approach was used, unless the electric generation was dramatically decarbonized using renewable sources of energy, since the environmental burdens would shift to other categories and processes.

In the evaluation of the different technological scenarios, the objectives for 2020 were found to be almost fulfilled thanks to the technological advances already being implemented in the European sector of ceramic tile manufacturing. However, the objectives for 2050 are far from being met, and the implementation of endogenous widespread technology will not be enough. Therefore, a combination of endogenous and exogeneous breakthrough technologies must be applied. These breakthrough technologies mainly lie on a decrease in the dependence on non-renewable fuels, the implementation of highly efficient energy measures and the application of product eco-design innovations.

Consequently, to support the ceramic tile industry in this context, it is necessary to find realistic solutions without jeopardizing its survival in a low-carbon economy. In this regard, further research is needed to evaluate technical and economic feasibility of the studied scenarios. In addition, other technical alternatives could be studied, such as using new glaze compositions or evaluating measures to promote the transition of the ceramic tile sector to a circular economy, among others.

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The authors are responsible for the choice and presentation of information contained in this paper as well as for the opinions expressed therein, which are not necessarily those of UNESCO and do not commit this Organization.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.07.176.

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Appendix A. Supplementary data

Supplementary material associated with this article can be found in the online version:

- Sensitivity analysis
- List of abbreviations

The following are the supplementary data related to this article:

Multimedia Component 1

Multimedia component 1

alt-text: Multimedia component 1

Multimedia Component 2

Multimedia component 2

alt-text: Multimedia component 2

Highlights

- EU 2020 CO_2 reduction target for the ceramic tile industry can be met through current technologies.
- The ceramic tile industry will not meet EU CO_2 reduction target for 2050 unless they combine several measures along the life cycle.

- Twenty-five technological scenarios have been found and assessed.
- Endogenous and exogenous breakthrough techniques are required to attain the 2050 EU low-carbon targets.

Queries and Answers

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