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Report on Decarbonization Technologies

for the Spanish Ceramic Tile Manufacturers' Association (ASCER)

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Report on the state of the art of decarbonization technologies in the Spanish ceramic tile industry

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Purpose

The Spanish ceramic tile industry has made substantial efforts in recent decades to innovate through more efficient systems able to reduce CO_2 emissions. Since 1985, the industry has cut its CO_2 emissions by 52.5% mainly through the replacement of liquid fuels with natural gas, the introduction of technological changes like roller kilns, the incorporation of cogeneration systems in the process, and the implementation of energy efficiency measures.

The greenhouses gases in the atmosphere have risen to unprecedented levels, encouraging the promotion of international and European agreements and protocols of differing kinds to try and reduce greenhouse gas emissions.

At a European level, in 2016, the Paris Agreement was signed, establishing a timeline for partial emission reduction targets of 20% by 2020 and 40% by 2030, taking 1990 figures as a baseline.

Subsequently, in late 2019, the EU Green Deal was launched. This plan includes specific steps to combat climate change. It raises the 2030 emission reduction target from 40% to 50% and aims to transform Europe into the first continent to be climate neutral by 2050.

The Spanish ceramic tile industry, which has made significant efforts to reduce energy consumption and greenhouse gas emissions, is thus faced with an important challenge which needs to address rapidly in order to guarantee its long-term sustainability and competitiveness.

The aim of this report is to present an outline of current and future decarbonization technologies foreseen in the Spanish ceramic tile industry, including a comparative description of them and their technology readiness levels (TRL), in addition to a technical and economic analysis for 2025-2026, 2030 and 2050.

Characterization of the Spanish ceramic tile industry

This section focuses on characterizing the Spanish ceramic tile industry in order to give a general overview of consumption levels, emissions and other considerations to be taken into account in this study.

In 2019, the Spanish ceramic tile industry was made up of 137 companies, 120 of which were subject to the Emissions Trading System. It has an annual output of 510 million m^2 of tiles, with global CO_2 emissions of 2.9 million tonnes and free allowances of 2.5 million tonnes. The ceramic tile industry is concentrated in the area of Castellón, where 95% of Spain's tiles are produced.

14.1 TWh of natural gas and 1.4 TWh of electricity provide the necessary energy to fuel the Spanish ceramic tile industry's manufacturing process. Natural gas is consumed in the manufacturing process and in cogeneration units in a ratio of 62% and 38% respectively. The gas that is consumed in cogeneration is used for the simultaneous production of thermal energy (approx. 68%)–used in the spray-drying process to prepare the raw materials–and of electricity (32%), 22% of which is consumed in the tile production process (self-consumption). Of all the involved energy consumption, spray drying accounts for 36%, drying for 9%, and the product firing stage for the remaining 55%. A diagram of the requirements of the different stages is shown in Figure 1.

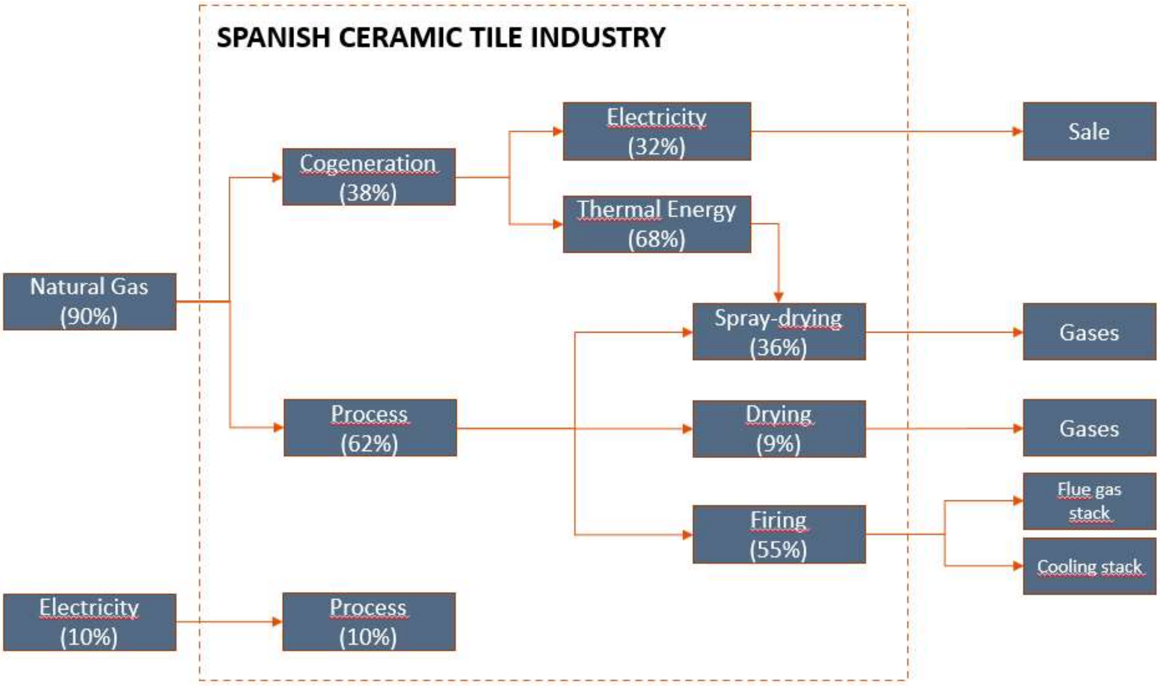


Figure 1: The distribution of energy consumption by the Spanish ceramic tile sector (in percentages)

During ceramic tile manufacturing, in addition to the CO_2 emitted from the combustion at different stages, the process itself also generates CO_2 through the breakdown of calcium carbonate. These last emissions account for 9% of the total. Figure 2 shows the percentages of CO_2 released during each stage of the process.

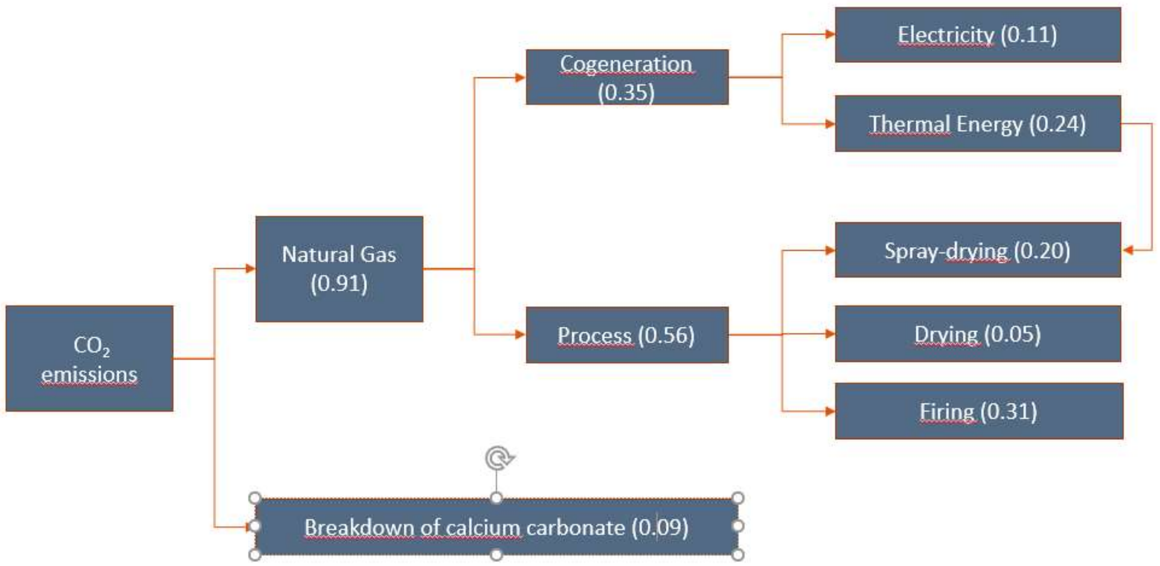


Figure 2: Distribution of CO_2 emissions by the Spanish ceramic tile sector (in percentages)

From an economic point of view, it is important to stress that, in 2019, the mean price of a tonne of CO_2 was €24.8, with a big rise being envisaged in coming years. In fact, in 2021, the price has already risen to €48 per tonne.

By way of a summary, the following table shows the most important factors that were considered in this study. The CO_2 prices were taken from a report that compiles the mean price of a tonne of CO2, estimated by several analysts.

Table 1: Forecast for the Spanish ceramic tile industry and factors considered in this study

	2019	2020	2021	2022	2023	2024	2025-2026	2026-2030	2050
Natural gas consumption (GWh)	14.1		14.1	14.1	14.1	14.1	14.1	14.1	
CO2 emissions (Mt)	2.9	2.7	2.9	2.9	2.9	2.9	2.9	2.9	
CO2 emission allowances (Mt)	2.5	2.3	1.9	1,9	1.9	1.9	1.9	1.6	from 1.6 to 0
Price of CO2 (euros/t)	24.8	24.8	42.4	47.4	50.6	56.4	58.40	86.35	67.20

Existing decarbonization technologies in the Spanish ceramic tile industry

Following an analysis of alternative decarbonization technologies, this section includes a description of the ones that might foreseeably be applicable to the ceramic tile industry, which are the subject of this study. These technologies include the use of biomethane and green hydrogen as fuel, the electrification of production processes, and carbon capture.

Biomethane

Biomethane is produced by upgrading biogas; a gas in turn obtained from the controlled biological breakdown of organic matter in an oxygen-free environment [1]. In Europe, biogas is mainly obtained from biomass from crops (energy crops, agricultural waste and sequential cropping), from animal manure, solid urban waste or sewage sludge, and from the controlled capture of biogas from landfill sites [2]. To obtain biomethane, the percentage of CH_4 (methane) in a biogas stream is increased from approximately 50 to over 90% by eliminating the CO_2 (carbon dioxide) and H_2S (hydrogen sulphide, which would corrode equipment) [3].

The resulting biomethane is considered to be a renewable natural gas and, unlike biogas, it can be used for the same purposes as natural gas from fossil fuels. In addition, biomethane also has a higher purity than the latter [4]. Table 2 shows a comparison of the compositions of natural gas, biogas, syngas and biomethane.

Given all the above, the replacement of natural gas with biomethane in the Spanish ceramic tile industrial processes is considered to be the simplest way of decarbonizing the industry, since it would not require adaptations to industrial ceramic tile-making processes or to the current transport and distribution network.

Table 2: Comparison of natural gas from fossil fuels, biogas, syngas and biomethane

Component	**Natural gas [5]**	**Biogas [6]**	**Syngas* [7]**	**Biomethane [8]**
	Composition (ranges in %)			
Methane	*87.0-98.0*	*50-75*	*10*	*>90*
Ethane	1.5-9.0	N.A.	N.A.	N.A.
Butane	0.1-1.5	N.A.	N.A.	N.A.
Pentane	<0.4	N.A.	N.A.	N.A.
N2	5.5	0-10	N.A.	N.A.
CO	0.05-1.0	25-50	17.5	N.A.
O2	<0.1	0-2	N.A.	N.A.
H2	N.A.	0-1	35.0	<5
H2S	N.A.	0-3	N.A.	N.A.
CO	N.A.	N.A.	34.5	<2

*N.B.: Synthesis gas (syngas), obtained through the gasification, at high temperatures, of forestry or agricultural biomass.

The most important difference is that biomethane is renewable. Because it is biogenic in origin, it has a neutral carbon footprint [9].

Green hydrogen

Green hydrogen is obtained through the electrolysis of water, using electricity generated by renewable energies. Hence, it is deemed to be an energy vector all set to play a key role in the decarbonization strategies of energy-intensive industries in order to comply with the EU's Energy Roadmap 2050 [10].

The characteristics of this fuel differ from those of natural gas [11, 12]:

- Its heat of combustion is lower than that of natural gas. As a result, a higher volume is needed to obtain the same amount of power.
- Its adiabatic flame temperature is about 170ºC higher than that of natural gas. Consequently, the generation of thermal NO_x is higher in the case of hydrogen combustion. It is also important to remember that current systems are designed for a temperature range obtained with natural gas, and this increase could have a negative effect on them.
- Hydrogen flames are not visible, unlike natural gas flames. This makes them hard to detect and so more precautions must be taken in safety systems.
- Hydrogen's reaction speed is faster than that of natural gas. Thus, the use of hydrogen is expected to entail a slight decrease in flame length.

The influence of these properties on the design of burners and on the quality of end products is still under research, as explained in the decarbonization guide for the Dutch ceramic industry, drawn up by the TNO. During a recent webinar [13], SACMI, a leading ceramic tile kiln manufacturer, announced that, at a laboratory level, it had developed burners able to burn up to 50% hydrogen by volume without any apparent effect on the quality of end products.

According to the National Renewable Energy Laboratory (NREL) [14], several studies have been conducted to determine what percentage of hydrogen can be used as a replacement in blends without any modifications to end users' production facilities. Although a case-by-case assessment must be made, 2 to 5 % blended hydrogen might be regarded as acceptable. SACMI is aiming at blends with a maximum of 10% hydrogen, where it would only be necessary to check the connections to ensure their gas tightness. For higher percentages, the burners would have to be changed.

Ceramic tile manufacturing kilns can have a useful life of over 40 years. Hence, the investment required for their adaptation to allow combustion with high concentrations of hydrogen could be a financial problem [15].

In order to incorporate the use of hydrogen, the required modifications would mainly revolve around the burners and the kilns' auxiliary systems, in addition to the dryers and spray dryers. It is important to take into account the higher volume of gases to be transferred and hydrogen's own diffusion capacity, which might affect the pipes, as well as possible emissions associated with a higher temperature flame.

To reduce the said temperature, diffusion burners [16] tend to be used, where the air-fuel mix occurs more slowly. Gas recirculation is currently also being proposed in order to reduce the temperature that is reached. This recirculation can be external or internal. Burner manufacturer E&M [11] is inclined to opt for the external recirculation of 15 to 20% of the total combustion gases. It also suggests working with natural gas/hydrogen blends of up to 15 to 20% hydrogen so as to ensure more stable combustion, lower NO_x emissions and better flame detection.

According to the roadmap presented by Cerame Unie, the European Ceramic Industry Association, in the long term, new ground-breaking technology is expected to be developed, together with improvements of existing ones. This will ensure major improvement in the development of kilns and in changes to raw materials so as to achieve more efficient combustion.

The electrification of processes

Fossil fuels prevail in the use of thermal energy in the Spanish ceramic tile industry. One of the technological options that is being considered for the industry’s decarbonization is the electrification of production processes.

The aim of this section of the report is to study the possibilities of electrifying the sector, since its current energy needs are known to be covered by 10% electricity and 90% thermal energy [19] from natural gas. Special emphasis will be placed on the stages in the production process that use the greatest amount of energy, such as spray drying (which consumes 36% of the thermal energy), drying (9%) and the firing process (55%). For this purpose, an analysis will be made of the possibility of replacing conventional kilns (powered by natural gas) with electric ones in order to achieve a big drop in emissions by the industry. Although electric kilns (with heating elements) are used for a limited number of firing processes in the ceramic sector, there is no experience of continuous electric kilns being used on a large scale in the ceramic tile industry [17]. Outlined below are the existing possibilities from a technological point of view, and the requirements and main barriers to the industry's electrification.

Spray-drying systems

"Wet-milling" is the most commonly used process in the preparation of ceramic tile bodies in Spain and Europe. This consists of milling the combined raw materials with water and spray drying the suspension to obtain solid spherical granules [18]. This stage in the production process calls for a high amount of energy, since the hot gases that are used to dry the suspension must have a temperature of close to 500ºC. The solid granules that are obtained from the wet-milling process have a big particle size and they are almost spherical. These properties lead to powders with a good flow. This is very important during the pressing stage, because with the right flow, it is easier to fill the moulds in the presses and to obtain tiles with a uniform thickness and apparent density [19].

Only a few companies in the industry use the "dry-milling" process to prepare the solids, or else a kneading process, to obtain a mass that can be shaped, ready for extrusion.

During the preparation of the raw materials, a high amount of electricity is consumed in the milling and extrusion stages, in addition to the electricity used to drive pumps, electric motors etc. When wet-milling is used, high amounts of thermal energy are also used to spray dry the clay suspension.

The Instituto de Tecnología Cerámica (Institute for Ceramic Tile Technology) led one of the latest studies based on the technical viability of an alternative way of obtaining the necessary granules by dry-milling and granulating the raw materials [18]. This process substantially reduces the energy costs and environmental impact in comparison with "wet-milling". The following conclusions were reached:

- The granulates in industrial tests performed adequately during the pressing, drying, glazing and firing processes. No breaks or manufacturing defects were observed.
- The water absorption and density values of fired industrial tiles are conditioned by the apparent density of the tiles when they are pressed. The amount of shrinkage during the firing of red and white-body tiles is similar to that of tiles made with spray-dried powder. In the case of red-body stoneware, the shrinkage values are lower.
- The industrial tiles made with the above granulates have better dimensional characteristics (calibre, rectangularity and flatness) than ones made with spray-dried powders. This is due to the higher apparent density of dry-milled materials and to the fact that the shrinkage-temperature slope does not rise for any of the granulates.

From the quantification of the water and energy consumption and CO_2 emissions associated with the dry-milling and granulation stages in relation to current wet-milling and spray-drying processes, it can be established that the dry-milling process:

- consumes 80% less water.
- consumes 80% less thermal energy, but between 12 to 18% more electricity, which represents a 65% total reduction in energy consumption.
- releases 80% fewer CO_2 emissions.

On the other hand, there were some constraints to its application:

- Although the tiles with the new granulates (dry-milling) are less porous, they have larger pores because the granules have not become fully deformed.
- The presence of large pores on tiles made with dry-milled granulates means that the mechanical resistance values of green and fired products are slightly lower than tiles made with spray-dried powders (wet-milling), despite the lower density of the latter. This is because cracks can spread more easily through the pores of tiles made with dry-milled granulates.

  To boost the mechanical resistance of green and fired tiles, the milling, granulation and pressing variables were modified. The best results were achieved–or ones comparable to those obtained with wet-milling processes (the most widely used industrial process today)–when the moisture level was increased during the pressing of the dry-milled granulates.

Consequently, from the above referenced report, some difficulties can be seen in the replacement of wet-milling technology and subsequent spray drying with dry-milling methods. Dry-milling is a technology that has not been developed at an industrial level, and adjustments and specific analyses of the manufacturing parameters are needed to achieve similar results in terms of quality.

Drying systems

In general, drying in the ceramic tile industry is achieved through forced hot air convection. This air is heated using natural gas burners. The thermal heat-transfer process is as follows: hot air (approx. 200ºC) in contact with the ceramic tiles transmits heat by convection to the latter. This heat is then transmitted by conduction to the inside of the materials or tiles (after pressing, there tends to be a moisture content of 5 to 7% and after drying it should be close to 0.5%) in a process that can last from 25 minutes to one hour, depending on the type of drying. The aim is to ensure a uniformly distributed temperature inside the tiles so that they dry properly.

To analyse the electrification of this part of the process, two types of technologies were studied: electric kilns (with heat elements) and microwave ovens (MW), both powered with electricity but with certain technical differences. Outlined below are some characteristics of each one of the processes:

- Drying in electric kilns: With this type of system, the heat is mainly transferred by radiation from the heat elements and it tends to involve high electricity consumption.
- Drying in microwave ovens: In microwave ovens, energy is transmitted by electromagnetic waves. When they hit a material containing water, the microwaves make the molecules rub together, transforming electromagnetic energy into thermal energy (with an increase in temperature). This type of heating process has some advantages over the conventional system.

The conventional drying system used by the ceramic tile sector has several limitations which electrified drying can help to overcome. These constraints include:

- The drying time, since this must be done slowly (with times of up to an hour).
- The presence of thermal gradients. For instance, if the tiles heat up too fast, this can cause stress or breaks due to the thermal gradients.

If electric kilns (with heat elements) are used for drying, the process is not very different from conventional drying in terms of the last two characteristics and it has the disadvantage of high electricity consumption.

However, if microwave technology is used for drying, the electromagnetic waves act on the materials, heating them rapidly to a temperature just above the air temperature inside the dryer (heating the whole tile internally instead of heating it from the outside to the inner core, as with conventional gas-fired dryers or ones with electric heating elements). This means that the moisture moves from the inside of the solid to the surface. Once it reaches the surfaces, it evaporates in conventional style.

Consequently, if microwave technology is used in ceramic tile sector drying processes, it increases the speed at which the tiles dry and it reduces the possibility of defects during this stage of the process. Furthermore, 36% less energy is needed to dry tiles with microwave technology in comparison with conventional hot gases [20].

Figure 3 shows a microwave drying system for ceramic products. Although it is already being used for some applications, it does not yet have the TRL to be implemented in the ceramic tile industry.

Figure 3 Microwave drying system for ceramic tiles [21]

Lastly, another analysed option is the use of hybrid systems. This consists of combining conventional drying systems based on hot gases with microwave technology to achieve a swifter, more effective process with less energy consumption, although it is not totally emission free. This hybrid system is still in an early stage of development [22].

Firing systems

As might be expected, the firing stage is the most important manufacturing phase. It is also the stage requiring the greatest amount of thermal energy; over 50% (see Figure 4). This is due to the high temperatures that the kilns reach and the firing time inside them. The firing cycle's duration depends on the size of the ceramic tiles, the kiln's load etc., but generally it lasts between 40 and 70 minutes. The maximum firing temperature (between 1100 and 1200ºC) also depends on these factors.

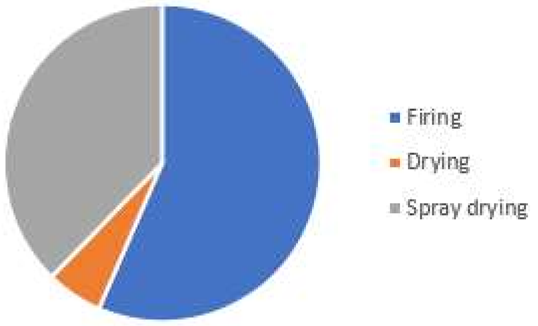


Figure 4 Distribution of thermal energy consumption during the tile manufacturing process [23]

Given all the above, it is important to note the difficulties involved in replacing natural-gas-fired kilns with electrified ones, whether they are heated with heating elements or by microwave technology. For instance, if they were replaced with kilns with electric heating elements, a high amount of energy would be required, and this would have to come from renewable sources. A large-scale continuous roller-type electric kiln able to provide efficient, cost-effective electrical heat would be very different from the current gas-fired kilns, and substantial efforts to develop them in collaboration with manufacturers would be needed to be able to produce the whole current range of products and to guarantee the necessary quality standards.

The main difficulties in estimating this kind of electric kiln's consumption during the firing stage include:

- There is no experience of large-scale continuous electric kilns in the ceramic tile industry [17].
- Most electric kilns used in the ceramic tile industry are batch or chamber-type kilns, not continuous ones like those currently used for ceramic tile manufacturing. This is a challenge since the required type of electric kiln would have to be completely redesigned in order to replace the current gas-fired ones.
- Given the characteristics of continuous kilns, in the case of electrically powered ones, careful analyses of heat losses must be made in order to reduce their electricity consumption.
- To guarantee the same production capacity as a current natural-gas-fired kiln, this kind of electric kiln would have to be very high powered. This would have a direct impact on the cost of the equipment (CAPEX) and on the running costs (OPEX).

Figure 5 Electric batch kiln for ceramics (Blaauw)

As explained in the section on the drying process, the other option is to use microwave technology. The advantage is the lower energy consumption compared with kilns with electric heating elements. In this case, however, they must heat the ceramic tiles as opposed to just evaporating moisture (as with the drying process), and not all ceramic materials react in the same way when they are heated with microwave technology [24]. Consequently, in some cases, they must be heated to high temperatures first (500ºC) so that a microwave can then be used when they have reached this temperature. This means that microwave technology must be combined with another heating system, such as kilns with electric heating elements. Another constraint to the application of microwave technology is the high temperature that needs to be reached during firing (1100 and 1200º C).

However, some ceramic materials (not ceramic tiles) can currently be fired with microwave technology, using small-scale intermittent kilns. This technique has mainly been applied to advanced ceramics [25, 26, 27]. Given all the above reasons, microwave kilns have been discarded as a feasible firing technology. Instead, electric kilns with heating elements are proposed as a replacement for today's gas-fired kilns, providing that the necessary developments are made to achieve the level of technification required by the ceramic tile industry.

Carbon capture

Carbon capture, use and storage (CCUS) technologies seek to avoid emissions of large amounts of CO_2 into the atmosphere. A carbon capture technology system can be defined as the whole process that is required to produce the same product as with current systems, but generating a concentrated stream of CO_2 capable of been compressed, transported and used or stored geologically on a permanent basis. [25]

Capture All CCUS technologies feature a gas-separation stage and, depending on where this stage occurs, CCUS can be classified as:

- Post-combustion CCUS technologies, where the gas-separation stage is carried out at the end of the process, and the concentration of CO_2 at the entry of the separation stage ranges from 3 to 14%. [26]
- Pre-combustion CCUS technologies, where the gas-separation stage is carried out at the beginning of the process after a gasification phase, and the concentration of CO_2 at the entry of the separation stage ranges from 15 to 60% by volume (dry basis). [27]
- Oxy-fuel technologies, where combustion takes place with an oxidizer containing a high percentage of oxygen in order to obtain an output stream with a high concentration of CO_2 ranging from 80% to 98% by volume (dry base). [28]

The gas-separation stage can be performed using differing methods, such as absorption, adsorption, use of membranes or cryogenic distillation, among others. The choice depends on the type of CCUS technology that is used. In some cases, the above methods can be used in more than one of the three CCUS technologies, i.e. membranes and absorption can be used with post and pre-combustion.

In the ceramic tile industry, the energy that is needed for the spray drying, drying and firing processes is obtained from the combustion of natural gas. Hence, a post-combustion technology is the most suitable carbon capture system so as not to have to alter a manufacturing process for which specific conditions are needed, because:

- Oxy-fuel processes would require newly designed equipment, with big changes to the temperatures that are needed to obtain products of the required quality standards. Special equipment for the sector would need to be re-engineered and validated.
- Pre-combustion would first require partial oxidation of the natural gas, separating the CO_2 and using the resulting hydrogen as fuel. This line would be equivalent to a hydrogen one, with the inclusion of a prior CO_2 separation stage at a high cost, and it would not avoid CO_2 emissions from the breakdown of carbonates.

One benefit of using post-combustion technology is that not only the CO_2 originating from the combustion of natural gas can be captured, but also from the breakdown of materials during the firing process.

As Table 3 shows, the ceramic tile industry releases gas streams with a low concentration of CO_2 (between 1 and 4% by volume) due to the excess air used in the process. This range does not fit in with the ideal range for post-combustion technologies (3%-14%), which are more efficient with higher concentrations of CO_2 in the stream to be captured. Carbon capture from concentrations of 3 to 5% is possible, but at a very high cost. Most of the systems at a commercial level or in the prototype stage work with concentrations of over 5 to 10 %.

Table 3: Characterization of streams in the Spanish tile sector [29]

Section / Parameters	Spray drying	Drying	Firing (flue gas stack)
Flow rate ($Nm^3/h)_{wet}$	15000-125000	2000-7000	5000-15000
T(°C)	90-115	50-150	150-300
P (bar)	Atmospheric	Atmospheric	Atmospheric
H_20 (m^3 water/m^3 total)	0.15-0.25	0.04-0.11	0.05-0.10
CO_2 (% by volume)	1-4	1-3	1-4
O_2 (% by volume)	16-25	16-20	15-18

Consequently, due to the low concentrations of CO_2 in output streams, the necessary conditions are not met for post-combustion technologies to be introduced to the ceramic tile industry.

In the case of streams with a concentration of over 3%–and bearing in mind that the ceramic tile sector's emission streams are at atmospheric pressure–, the most relevant technologies would be:

ABSORPTION

Separation is carried out by putting the gas into contact with a liquid (the absorbent). Once the absorbent has captured the CO_2, the stream is taken to a second stage, where changing conditions leads to the release of the CO_2. The regenerated absorbent without CO_2 is sent back to the first stage again, and the CO_2 is released with a high concentration. Absorption can be:

- Chemically achieved, with a chemical reaction between the CO_2 and the absorbent. This is the most technologically mature process. Regeneration is achieved by using a boiler to raise the temperature, with this consumption playing a determining role in appraisals of the technology's costs. The most commonly used absorbents are amines, with a technological readiness level (TRL) of 9 [3]. The amines are used in an aqueous solution and different types of amines can be combined in the same solution. The most common is ethanolamine (MEA), in a 30% (w/w) aqueous MEA solution. This operation is performed at more or less atmospheric pressure and, generally speaking, the temperatures are within a range of 40 to 60º C and 100 to 140º C in the absorption and regeneration stages respectively [31]. The main disadvantages are the breakdown of the amines, with their subsequent loss of effectiveness, the equipment's corrosion and impacts on the environment and on people's health.
- Through physics, with no chemical reaction between the absorbent and the CO_2. Higher pressures tend to be used in comparison with chemical absorption, with a drop in pressure for the regeneration process. The physical absorbents are known as Selexol and Rectisol.

At partial low pressures, chemical absorption is needed to capture the CO_2. High energy consumption is then needed to separate it at the regeneration stage. On the other hand, at high pressures, physical absorption is recommended. The capacity to absorb CO_2 will depend on the chosen absorbent, and the absorbent's flow will condition the amount to be captured. In turn, this determines the scale of the equipment and the energy needed for regeneration. The absorbent must also be as stable as possible to prevent it from breaking down.

The regeneration stage accounts for most of the energy consumption associated with the process, with typical values in the range of 2 to 4 GJ per tonne of CO_2 [32]. In the case of amine-based systems, this energy is thermal in the form of steam and electricity. The energy consumption for the carbon capture process would represent a 16% increase in the ceramic tile sector's energy needs (2,500 GWh).

At the same time, in amine-based post-combustion systems, it is very important to achieve gas desulfurization levels of 10 ppmv of SO_2 so as to prevent the amines from breaking down [33]. This means that, on certain occasions, the gases must first be filtered, increasing the cost of the technology's introduction.

One example of this technology's application can be found in a decarbonization study for the Dutch ceramic industry [34], which takes a natural gas plant as a reference with 5% CO_2 emissions, using amines for carbon capture.

ADSORPTION

Separation is achieved by putting the gas into contact with a solid (the adsorbent) to which it sticks. During the first stage, the CO_2 is taken up by the adsorbent and, once it is saturated, regeneration is carried out through cyclical changes. There are two types of adsorption:

- Chemical adsorption, in which a covalent bond occurs between the CO_2 and the adsorbent.
- Physical adsorption or physisorption in which the CO_2 is attracted to the adsorbent through van de Waals force.

Adsorbents can be classified into the following groups: zeolites, MOF (metal organic frameworks, a class of crystalline materials made up of metal ions or metal clusters bound by organic ligands [35]), carbonaceous materials, functional adsorbents or combinations of them.

The advantages of this technology are that it can be used in different pressure and temperature-related conditions, and it has a low environmental and corrosive impact. The drawbacks are the lack of real data to guarantee an optimum design and the need for certain components, like water, to first be removed through a drying stage.

Regeneration is carried out through a change in temperature or pressure, the creation of a vacuum, using steam, or through a combination of them. The required energy consumption during the regeneration stage is normally higher than the amine-based stage, with consumption of 4.5 to 9 GJ per tonne of CO_2 [32]. For adsorption systems, electrical energy and/or thermal energy in the form of steam is used. In this case, the regeneration process would involve an increase in the sector's energy needs of between 23% and 46% (3,600-7,200 GWh).

Processes based on the use of pressure tend not to be easily applicable to the ceramic tile industry, because the streams to be separated are very big, the pressure is initially atmospheric, and the gases contain additional elements, compounds and impurities that might damage the adsorbent. The best option is the temperature-based one (TSA). The current technology has a TRL of 6 to 7 [32] [30]. Grande y Asociados conducted a theoretical assessment of a gas adsorption process at a natural gas power generation plant with output gases featuring a 3.5% concentration of CO_2 by volume. In terms of energy requirements, results of 2 GJ per tonne of captured CO_2 were obtained [36].

This case study has also given rise to new designs in adsorption processes which are still in the development stage, and there are some interesting CO_2 recovery projects from streams with a low concentration of CO_2, such as those being run by Innosepra [37].

DIRECT AIR CAPTURE

Apart from post-combustion technologies, another alternative to CCUS technologies in streams with a low concentration of CO_2 is direct air capture (DAC), based on the use of chemical absorbents through cyclical carbonation processes [38]. There is a reference to the use of this technology, without detailing its specific application to the tile sector due to the high dilution of CO_2 in output streams [39]. The technology currently has a TRL of 7 [32] and very high investment and running costs, and so further technological headway is required. It currently works with CO_2 concentrations of around 400 ppmv (a concentration of 0.04% by volume), and technology must be developed to withstand concentrations typical of the tile sector (a 1% concentration of CO_2 is equivalent to 10,000 ppmv).

Transport

Captured CO_2 can be transported by means like lorries, ships or pipelines. The specific means of transport will depend on technical and financial factors. One important factor is the composition of the transported CO_2, with the avoidance of impurities–insofar as this is possible– that might damage the pipes or tanks in which it is carried. When ships or lorries are used, the optimal physical conditions are pressures of between 7 and 9 bars and temperatures close to -50º C. If pipelines are used, pressures of over 74 bars and temperatures of between 20 and 30º C should be ensured [40]. Compression, normally to 100 bars, accounts for 20% of the regeneration cost [32]. In some countries, the use of existing petrochemical pipelines to carry CO_2 are now being considered. This would substantially reduce the price.

Storage

To store the CO_2, a suitable site must be found which meets the right physical and geological conditions. Normally these sites are deep saline aquifers, oil and gas reservoirs, or deep carbon layers. Storage sites are usually classified into two main groups: onshore and offshore. Storage of CO_2 in geological formations is achieved through compression and injection, using wells prepared for this purpose. Spain has some peculiarities due to the shortage of domestic crude oil and natural gas. This not only implies the virtual non-existence of reserves, but also far less data relating to the subsoil from geological surveys by oil companies. As a result, not only does Spain have limited storage capacity, but it also fails to hold precise data on saline aquifers [41].

Uses Given the chemical characteristics of CO_2, it can be used in different industrial processes on both a small and a large scale. There is currently substantial interest in the development of applications for chemical conversion processes that use CO_2 as a base element and also applications for the production of fuel, algae cultures and algal biomass production.

The current main drawback is certain industries' lack of awareness of the potential of all this, in addition to the necessary investment to incorporate it into one of the production processes.

It is worth highlighting the fact that only part of the CO_2 from CCUS technologies can be used for industrial applications, since the amount of CO_2 emissions and the amount that can therefore be captured is much higher than the amount required by industry. The world demand for CO_2 for industrial use is expected to reach around 0.5 billion tonnes by 2030 [42]. This represents just 2.5% of the CO_2 emissions generated by the sector internationally in 2019 [43]. It is impossible to find an industrial use for all the CO_2 captured with CCUS technologies. Even so, the industrial sector has begun to work on different initiatives aimed at boosting the use of CO_2 as a raw material, many of which still need to reach a higher level of technological readiness.

One possibility along these lines which fits in with the use of more economical sustainable materials is mineralization or recarbonation, where the captured CO_2 is made to react with alkaline earth metal oxides (like CaO) to produce carbonates (e.g., calcium carbonate, used in the tile sector). These oxides can come from industrial sectors where they are not taken advantage of, such as the steel, paper, mineral or cement sectors [44]. In this way, not only would CCUS technologies be more financially advantageous, but the industrial sector in question would also move toward a circular economy. At a European level, in order to take advantage of synergies in industrial centres or regions, projects on the subject are being developed aimed at seeking industrial symbioses [45].

Legislation Specific Spanish legislation: Act 40/2010 of December 30th on the geological storage of carbon dioxide. This transposes Directive 2009/31/EC. As can be inferred from its title, this act focuses on regulating geological storage on the understanding that carbon transport and capture are regulated by existing legislation.

CCUS technologies have not yet been regulated in depth at a Spanish or an international level. There are differences in the frameworks established by different countries and even concerning the different steps involved in the chain: capture, transport and storage.

As for carbon capture, although the necessary administrative formalities for installations of this kind will depend on the corresponding industrial activity, with compliance with the pertinent legislation (e.g., the issue of an Environmental Impact Statement and an Integrated Environmental Authorization), there are certain gaps in matters relating to production by carbon capture plants (the purity of the CO_2 and the emission thresholds of captured CO_2 streams).

As for transport, this is the less specifically regulated stage of the three. In most cases, it is not even specifically regulated but, instead, it is based on legislation governing the transportation of hazardous liquids or oil and gas pipelines.

Lastly, the storage stage is possibly the one with the most legislation at present or the most fully developed legislation, with the regulation of aspects like the difference between injection and storage or between operators and owners.

More detailed legislation must be developed to be able to manage the three stages in the chain, with cooperation among all the involved stakeholders.

One way of minimizing the costs of the whole chain is to create industrial hubs or regions with a shared interest in using CCUS technologies for decarbonization purposes, with shared CO_2 transport networks and end uses. At a European level, some projects have currently been developed in northern Europe where CO_2 is stored in empty offshore fields. Again, a shared commitment by all the interested parties is needed, since not only are technical aspects concerned, but ones relating to borders, management and legislation.

Technical and economic viability of possible decarbonization technologies for the Spanish ceramic tile industry

In this section, an analysis is made of the technical and economic viability of implementing the different technologies under consideration in this study in order to meet the Spanish ceramic tile industry's decarbonization objectives. For this purpose, the Spanish ceramic tile industry's current emissions and consumption data have been taken into account, together with the state of the said technologies and their future evolution in 2025-2026, 2030 and 2050 timeframes.

For each of the technologies, an outline is given of the methodology, the variables to be considered, and the results of the technical and economic viability analysis.

Biomethane

Biomethane is currently at a TRL that allows for its commercialization [46]. By analysing biomethane production in Europe, its maturity can be demonstrated. Although biomethane production differs from one member state to another, this is a currently available technology.

However, the biomethane industry today cannot meet the Spanish ceramic tile industry's demand for natural gas. Although in 2020, the UNE 0062:2020 Specification on Renewable Gas Guarantees of Origin was published, in Spain, the Biomethane Guarantee of Origin Management System has not yet been regulated because this regulation is still in the development phase [47].

Irrespective of the relevance of biomethane and its TRL, this renewable gas cannot currently be implemented due to the lack of a regulatory framework and its low availability. This is demonstrated by the 2020 Prior Public Consultation on the Biogas Roadmap by the Spanish Ministry for Environmental Transition and Demographic Affairs [48]. Biomethane's availability is another constraint in its introduction as a replacement for natural gas. The available forecasts for forthcoming decades show that biomethane could come to cover 30% of the natural gas demand by 2040 (Figure 7). At present, biomethane prices cannot compete with natural gas ones, as a later analysis in this report will show.

Current biomethane production in Europe and Spain

This quantification takes into account the biomethane currently available in Spain and its distribution via current natural gas pipelines. According to the European Biogas Association, the biomethane market grew by 16% in 2019. In the said year, there were 725 biomethane plants in operation in Europe, with a total output of 26 TWh (2.43 bcm - billions of cubic metres) [49].

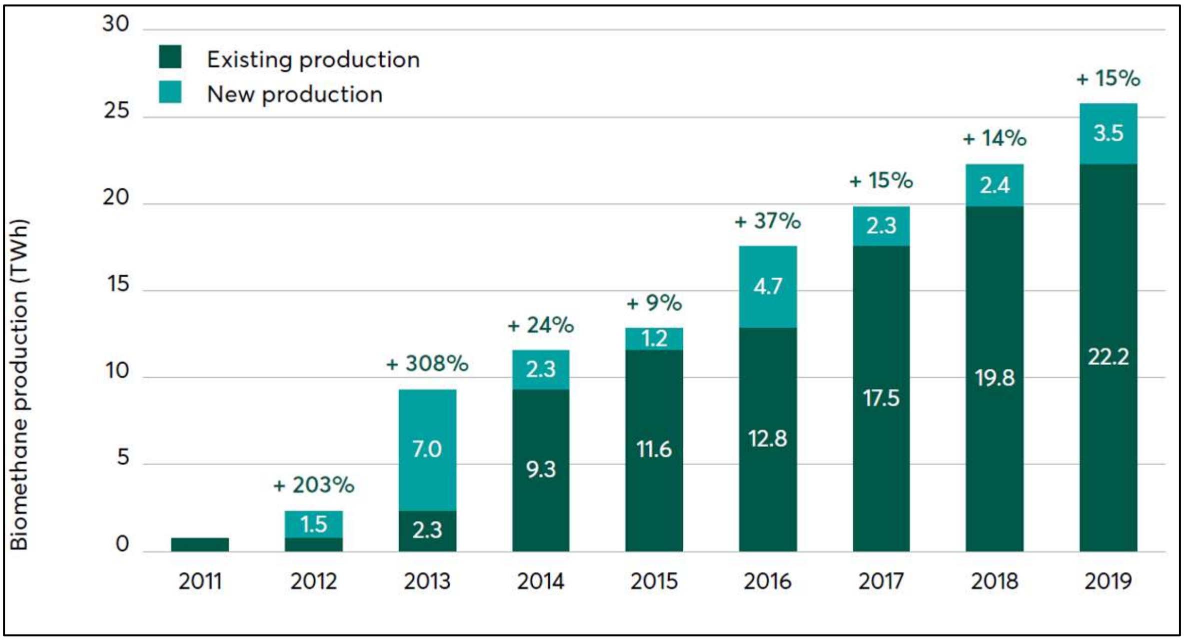


Figure 6: Current biomethane production in Europe. Source: 2020 Statistical Report by the European Biogas Association [43]

Biomethane production in Spain differs significantly from the panorama in Europe. Although in 2019, Spain had about 210 biogas plants, there were only two biomethane plants in operation that injected biomethane into the natural gas grid. One of them has produced biomethane since 2009 from management of the organic fraction of Madrid's solid waste, while the other obtains it from the anaerobic digestion of sewage sludge. Spain currently produces 97 GWh of biomethane according to the 2020 Statistical Report by the European Biogas Association [49]. This is a much lower amount than the natural gas used by the Spanish ceramic tile industry during the same period (~14 TWh GWh) (Table 1).

Forecasted biomethane production in Europe by 2030-2050

This quantification takes into account the fact that the availability of biomethane in Spain depends on the European natural gas network. This would guarantee the use of a renewable natural gas (biomethane) by the Spanish ceramic tile industry. Figure 7 shows the forecasts for biomethane production and natural gas consumption for the different periods taken into consideration in this report. The figures for biomethane production are taken from the 2020 Statistical Report by the European Biogas Association [49].

Biomethane production is compared with natural gas consumption during the same period, using data from the "The Sustainable Credentials of Gas" report [50]. This report presents four possible scenarios in natural gas consumption in Europe. The existence of these different scenarios in forthcoming decades is due to the fact that the consumption of natural gas will largely depend on its gradual replacement with other energy sources like the ones analysed in this report: biomethane, hydrogen and electrification.

The data for the natural gas consumption forecasts shown in Figure 7 was taken for a scenario in which there are supposedly sufficient reserves of this gas to maintain similar consumption levels to previous decades.

The main message that can be inferred from Figure 7 is that biomethane production forecasts for the four considered periods are lower than the envisaged demand for natural gas. In 2020, biomethane only managed to cover 3.7% of natural gas consumption in Europe. For the other periods under consideration, the expected percentage of biomethane production is still lower than the demand for natural gas. From the consulted sources, by 2040 biomethane production is expected to cover over 30% of the demand for natural gas.

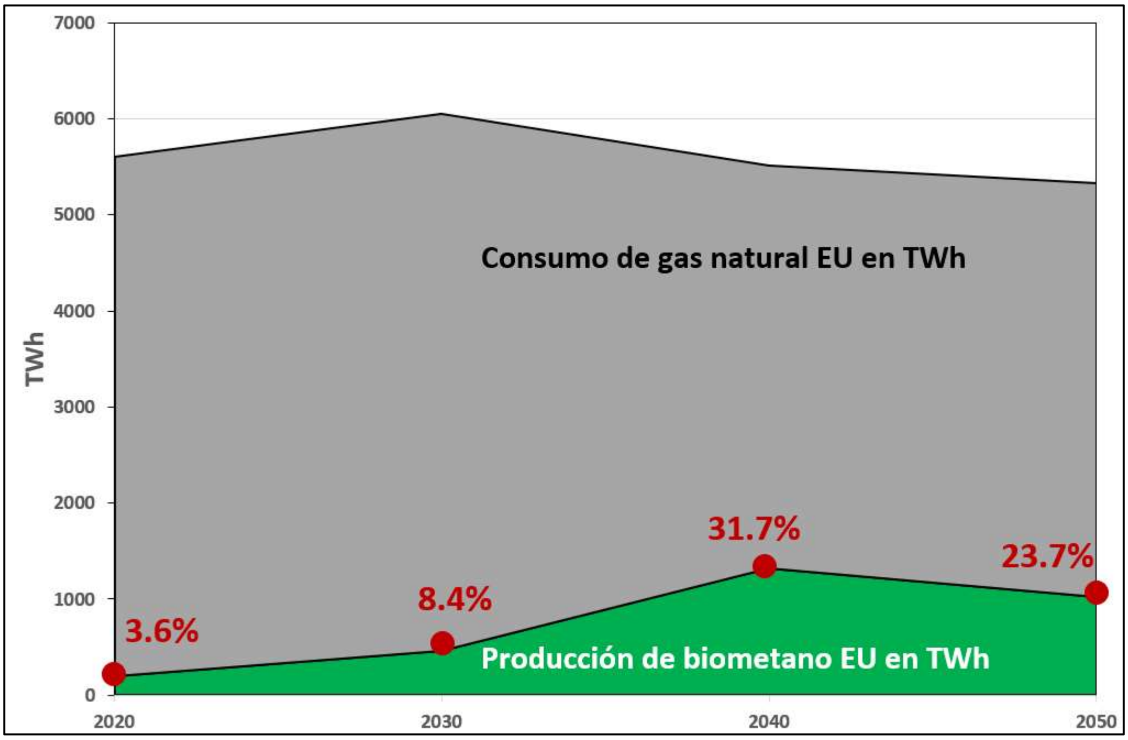


Figure 7: Forecasted natural gas consumption and biomethane production in Europe. Source of data for natural gas: [50]. Source of data for biomethane: 2020 Statistical Report by the European Biogas Association [49] (in TWh, left axis Y). The red circles compare biomethane production with natural gas consumption (right axis Y)

Figure 8 was drawn up using the Spanish ceramic tile industry's forecasted natural gas consumption by 2030, the forecasted costs of CO_2 emission allowances and the estimated forecasted natural gas and biomethane costs. This figure compares the costs of natural gas consumption and CO_2 emission allowances with the costs of replacing them with biomethane. As mentioned earlier, biomethane has a neutral carbon footprint. As a result, the costs of biomethane do not include costs associated with CO_2 emission allowances.

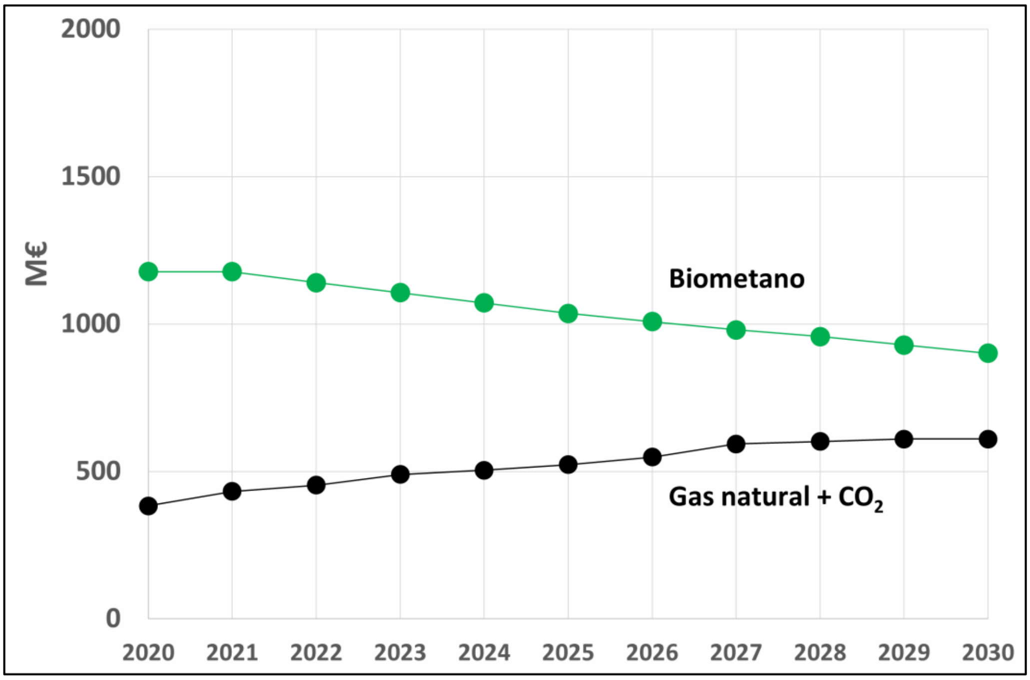


Figure 8: A yearly comparison of the costs of natural gas consumption and CO_2 emission allowances and the costs of their replacement with biomethane. Figure with data taken from the following sources: [51], [52]. The biomethane costs only include the feedstock and technology costs. Hence, they exclude the estimated commercialization and transmission costs.

The natural gas and biomethane costs were obtained from the sources shown in the following figure:

Figure 9: Original sources from which the data for the natural gas costs (A) and biomethane costs (B) were drawn [51], [52]. The biomethane costs only include the feedstock and technology costs, as shown in the original figure. Hence, they exclude the estimated commercialization and transmission costs.

Current viability

Neither the availability of biomethane nor its costs would allow the Spanish tile sector to decarbonize its production process or maintain its current production levels. As mentioned previously, due to the purity of biomethane, it could replace natural gas without the industry having to modify its processes.

Natural gas from fossil fuels meets about 90% of the ceramic industry's energy needs; that is, ~14.1 TWh (Table 1). In 2020, biomethane production at a European level was reported to account for about 193 TWh (18 bcm) (Figure 7). In the same year, Spain's reported biomethane production was no more than 0.1 TWh. When natural gas consumption in Europe is analysed, it can be seen to have a much higher demand than the amount of biomethane that is produced. This shows that, when the same period is analysed, biomethane production would only be able to cover 3.7% of European natural gas consumption. In the case of Spain, the demand for natural gas in 2020 was 360 TWh [53].

Thus, biomethane production at a European level could have covered 53.6% of Spain's reported natural gas demand.

It is important to add that the use of biomethane is also strongly conditioned by its price in comparison with that of natural gas. It is hard for biomethane producers to reach an agreement on a shared price, since biomethane production is largely dependent on the cost of feedstock and its harvesting, pre-treatment and transmission, among other factors, like the biogas purification process used to obtain biomethane and the associated technology. At present, biomethane (83.5 €/MWh) is triple the price of natural gas (26.5 €/MWh). This is proportionally reflected by biomethane costs in relation to the costs of natural gas + CO2 allowances shown in Figure 8.

With this information, it is possible to conclude that, at present, although, from a technical point of view~~,~~ biomethane is the best alternative for replacing natural gas in the ceramic tile industry, its availability (much lower than the demand by the sector) and its cost make it economically unfeasible.

Viability by 2030

The availability of biomethane in Europe by 2030 is expected to be over 400 TWh (>40 bcm). In the case of Spain, the information for 2030 is not known. Without a Biomethane Roadmap, it is impossible to determine the availability in Spain by this date. At a European level, the availability of this renewable gas has been estimated. The international price of biomethane (64 €/KWh) is still expected to be above the estimated price of natural gas (35.3 €/KWh). Furthermore, the cost of CO_2 emission allowances will rise in coming decades. Between 2020 and 2030, it will rise from 24.8 to 86.4 €/tonnes of emitted CO_2 (Table 1), with direct repercussions on the Spanish tile sector's output.

If Figure 8 is analysed, where a comparison is given of biomethane costs in relation to the costs of natural gas + CO_2 emissions from 2020 to 2030, it can be seen that the trend in both lines is for them to cross at a point after 2030. However, by 2030, the use of biomethane in the Spanish tile sector is still up to 32.5% more costly than the current alternative, taking into account the cost of natural gas plus the assigned CO_2 emission allowances.

In accordance with the analysis for 2030, based on data from the consulted sources on the availability and costs of biomethane in relation to the costs of natural gas, it will still be unviable from an economic perspective for the Spanish tile sector to replace natural gas with biomethane in its processes.

Viability by 2040

To offer an exhaustive analysis, Figure 10 extends the comparison of biomethane costs in relation to the costs of natural gas plus CO_2 emission allowances for 2040 and 2050.

From 2030, there is no available information for natural gas consumption by the Spanish tile sector. Nonetheless, to conduct an economic analysis for the 2040 and 2050 periods, similar consumption for up to 2030 of 14 TWh might be assumed.

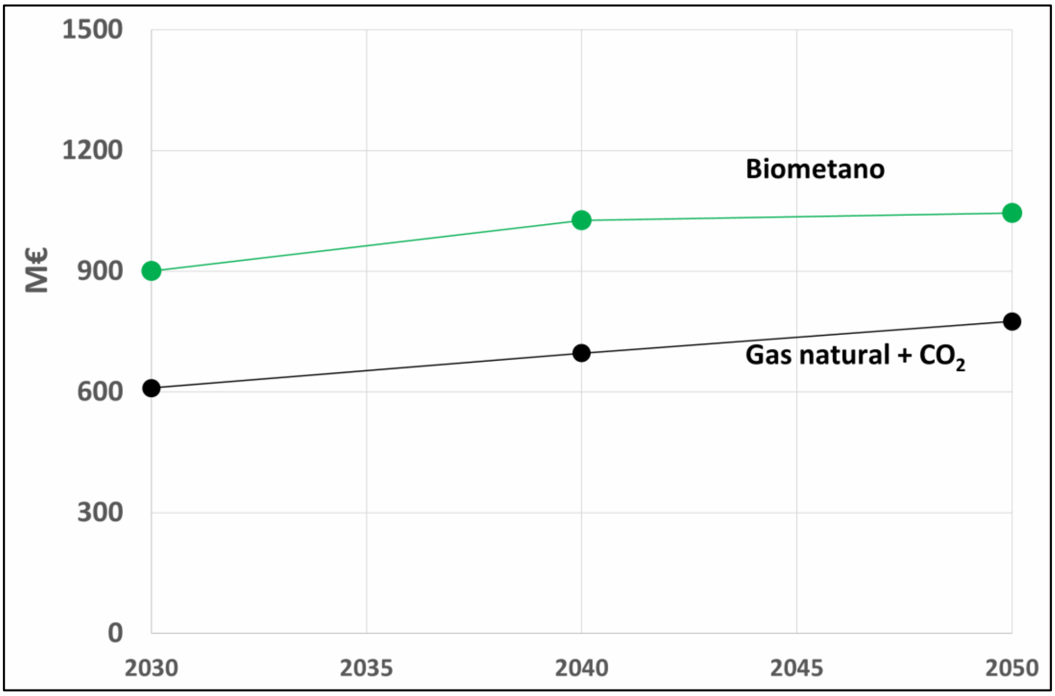


Figure 10: Comparison for 2030, 2040 and 2050 of the costs of natural gas consumption and CO_2 emission allowances in relation to the cost of replacing them with biomethane. Data taken from the following sources: [51], [52]. The biomethane costs only include the feedstock and technology costs. Hence, they exclude the estimated commercialization and transmission costs.

According to the Statistical Report by the European Biogas Association, by 2040, the availability of biomethane in Europe is estimated to reach over 1000 TWh. In principle, the amount of available biomethane in Europe by this date might have important implications for energy-intensive industries like those of the Spanish tile sector. However, Figure 7 shows that the amount of biomethane will only account for 31.7% of the total expected European demand for natural gas.

Irrespective of where it is produced, biomethane is expected to be distributed through the European natural gas grid. Renewable gas guarantees of origin could boost the use of biomethane by the Spanish ceramic tile industry.

According to the consulted sources, the price of biomethane (72.8 €/MWh) will still be higher than that of natural gas (39.4 €/MWh) in 2040. The comparison in Figure 10 indicates that the costs of biomethane will still be 67.7% higher than those of natural gas plus CO_2 emission allowances.

According to the consulted sources and the conducted analysis, by 2040, it will still not be financially viable for the Spanish tile sector to introduce biomethane in its processes.

Viability 2050

As with 2040, by 2050, the availability of biomethane in Europe is estimated to stand at over 1,000 TWh. According to the consulted sources, it is not clear whether biomethane production will go up in relation to the previous decade. Its production will largely depend on the availability of feedstock for biogas. In comparison with the demand for natural gas shown in Figure 7, biomethane production will account for around 23.7% of the total.

By 2050, the cost of biomethane will still be 74.2% higher than the costs of natural gas and the assigned CO_2 emission allowances.

For this period of the analysis, biomethane continues to be unviable from an economic point of view.

Green hydrogen

Green hydrogen looks to become one of the key energy vectors for the decarbonization of industry. The development of green hydrogen is not only important in helping to achieve emission reduction targets, but also in maintaining and boosting the European Union's economic and industrial capacity to compete. At present, the hydrogen market is very limited [54], but 2020 was a key year in the development of a hydrogen strategy, both at a European level with the approval of the European Hydrogen Strategy 55] and at a national level by different countries, including Spain, which has launched a Hydrogen Roadmap [56].

In this context, the technical and economic viability of replacing natural gas with green hydrogen as fuel in the Spanish ceramic tile industry for the 2025-26, 2030 and 2050 timeframes will largely depend on factors relating to the hydrogen market, in terms of both the availability of hydrogen and its price, which is expected to follow a downward trend in forthcoming years. As for its viability from a purely economic perspective, the comparative trend in the price of natural gas plus CO_2 emission allowance costs in relation to the price of hydrogen will also play a key role, since forecasts point to a progressive increase in the costs associated with natural gas [54] [51]. Consequently, in the long term, green hydrogen might foreseeably cost less. At the same time, the technological deployment of new or adapted burners and equipment (e.g. kilns) to work with hydrogen will also play a key role in the technical feasibility of hydrogen as an energy vector for the Spanish tile sector.

The current situation of the green hydrogen market

At present, hydrogen consumption in Spain stands at around 500,000 Tm/year (in energy terms, some 20 TWh/year), with grey hydrogen mainly being used as a raw material by refineries and the manufacturers of chemical products [56]. In most cases, hydrogen is directly produced in the plant where it is used through natural gas steam reforming [56]. As for green hydrogen, the first green hydrogen plant in Spain is not expected to enter into operation until late 2022, with a target output of 1,500 Tm/year (some 59 GWh) from 100% renewable sources [57].

With regard to the natural gas grid, according to a study by operators of the gas grid in France, current natural gas pipelines could carry a maximum of 6% hydrogen (by volume), mixed with methane [54].

As a result, green hydrogen is currently seen as a technology pending development, since its production has not taken off at a commercial level and the natural gas grid is currently very limited when it comes to carrying hydrogen to different consumption points.

A vision of the green hydrogen market by 2025-2026, 2030 and 2050

The European Green Hydrogen Strategy [55] establishes three key timeframes for the progressive deployment of green hydrogen at a European level:

- First phase (2020-2024), focused on decarbonizing current hydrogen production through the installation of at least 6 GW of electrolysers and the production of up to 1,000 kTm/year of green hydrogen (some 39,400 GWh/year in energy).
- Second phase (2025-26), the point when green hydrogen begins to play a role in the equilibrium and flexibilization of the electricity network, with the installation of at least 40 GW of electrolysers and the production of up to 10,000 kTM/year of green hydrogen (some 394,000 GWh per year).
- Third phase (2030-2050), when green hydrogen technologies are expected to reach maturity and to be deployed on a large scale.

In keeping with European targets, in the Green Hydrogen Roadmap [56], specific landmarks are established at a Spanish level, in particular:

- The installation of at least 4 GW of electrolysers by 2030 and a partial objective of between 300 and 600 MW by 2024.
- By 2040, green hydrogen will account for at least 25% of all hydrogen consumption by all consumer industries.

As for its distribution, the current natural gas grid can be used to transport hydrogen, and so the transformation of the gas grid will play a key role in the changeover to a hydrogen economy. Until 2035, hydrogen can be deployed by transporting a blend of hydrogen and natural gas, without the need for a specific transmission network. However, between 2035 and 2050, the large-scale conversion of the gas network to carry hydrogen is envisaged [54].

In line with a study conducted by natural gas distributers in France [54], who have better knowledge and practical experience and who have also made adaptations to the distribution network, the percentage of hydrogen that can be mixed with natural gas could reach a figure of 10% during the period from 2021 to 2035, finally rising to an upper limit of 20% by volume during the initial phases of the hydrogen deployment strategy.

Lastly, as mentioned previously, the price factor plays a determining role in the potential implementation of green hydrogen as an energy vector in industry. As it takes off on a large scale, a downward price trend is expected, accompanied by an increase in the price of natural gas and CO_2 emission allowance costs. According to the latest report for the sector by BloombergNEF [58], the costs of green hydrogen will drop by 85% in relation to their current ones, and it will be cheaper than natural gas in most markets by 2050.

Viability by 2025-2026

Although there is no specific target for the reduction of greenhouse gas emissions by 2025-26, the different agreements and roadmaps establish a series of partial targets for their progressive reduction. In particular, at a European level, to comply with the Paris Agreement, the European Commission has set a target of a 20% reduction by 2020 and a 40% one by 2030 (in relation to 1990). Subsequently, more ambitious targets were set in the EU Green Deal, with reductions of 55% by 2030 and neutrality by 2050. In our feasibility analysis for the 2025-26 timeframe, in order to meet the set targets, an average reduction of around 35% in emissions must be achieved by then.

Under this premise, in order to achieve this target in the Spanish ceramic tile industry, 21% of the energy from natural gas would have to be replaced with hydrogen. This would mean using a blend (by volume) of 68% H_2 to 32% natural gas, hence requiring a yearly amount of 2,950 GWh (75 kTM H2) of hydrogen to cover the industry's needs.

The above data contrasts, nonetheless, with forecasts from different sources on the availability of green hydrogen at this time point, showing that it is not feasible for these percentages of hydrogen to be reached in the Spanish tile sector by 2025-26. On the one hand, the Spanish Ministry for Ecological Transition [56] envisages the existence of electrolysers with an installed capacity of some 300 to 600 MW by 2025-2026, which would mean that Spain's production capacity would still be very low–between 75 and 150 kTm/year of hydrogen (in energy, some 2,950-5,900 GWh/year)–, and it would not cover the overall potential demand for hydrogen by the country's different industrial and transport sectors. On the other, in distribution terms, until 2035, no in-depth adaptations to the natural gas grid are envisaged to transport blends with a high percentage of hydrogen (or pure hydrogen). Consequently, during the period from 2025 to 2026, it would not be viable to distribute blends with a percentage of hydrogen of over 20% [54].

In addition to the aforementioned constraints in the production capacity and availability of hydrogen for distribution, according to the forecasted price trends, by 2025 to 2026, hydrogen will still not be able to compete with natural gas. Forecasts by the Spanish Ministry for Ecological Transition (Figure 9) and several analysts (Table 1) point to an increase in the price of natural gas and in CO_2 emission allowances from the current 26.5 €/MWh and 24 €/Tm of CO_2 to 32.2 €/MWh and 58 €/Tm of CO_2 respectively. However, the envisaged drop in the price of green hydrogen will still be a limited one, and so although there would be no constraint in terms of its availability, its use would still not be cost effective. To meet the target of a 35% drop in emissions by partially replacing natural gas with hydrogen, the price of hydrogen in the tile sector would have to stand at around 48 €/MWh, as opposed to ~37 €/MWh if natural gas continues to be used. The following figure shows what the global fuel costs would be for the Spanish ceramic tile industry. These costs were estimated by calculating the hydrogen that would be needed to bring down CO_2 emissions in line with the established targets.

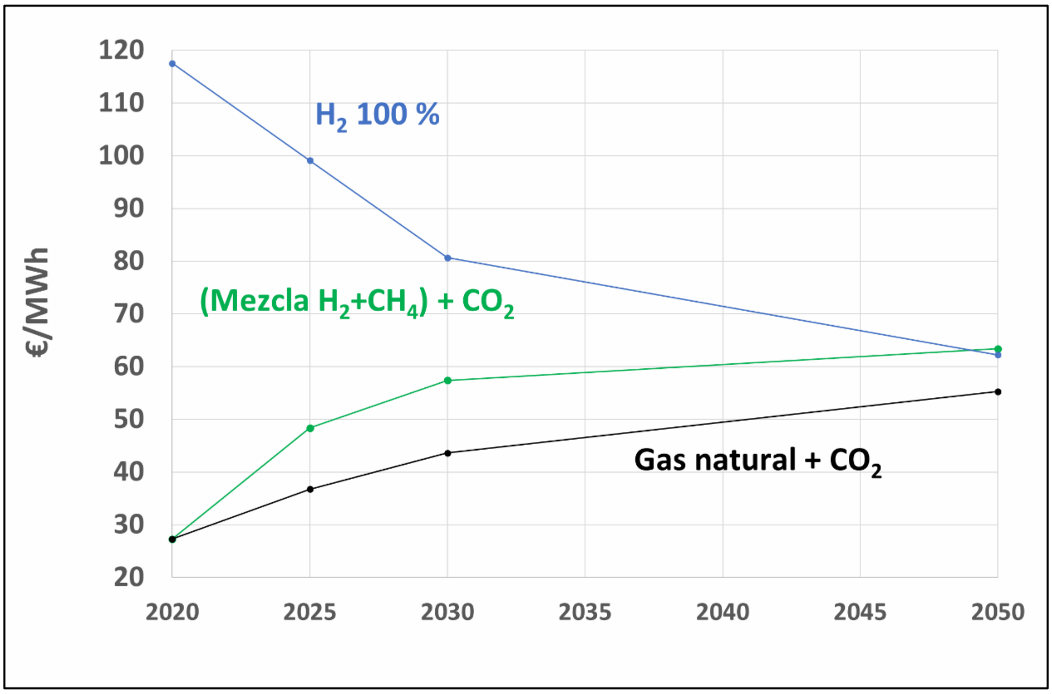


Figure 11: A comparison for 2025, 2030 and 2050 of the costs of natural gas consumption and CO_2 emission allowances in relation to the costs of partially replacing natural gas with green hydrogen in order to meet the emission reduction targets set for the different timeframes (35% for 2025-2026, 55% for 2030, and 100% for 2050).

Viability by 2030

According to the EU Green Deal, the 2030 greenhouse gas emission target is to cut emissions by 55% in relation to the baseline figure for 1990. Bearing in mind the sector's current energy consumption and emissions, this means that it would be necessary to replace 48% of the energy from natural gas with hydrogen. This is the equivalent of a fuel with 88% hydrogen by volume and it would imply a yearly hydrogen demand by the Spanish tile sector of about 6,760 GWh (172 kTm).

As with the viability analysis for 2025, once again these estimations of the necessary hydrogen demand to meet the Spanish tile sector's partial decarbonization target for 2030 contrast with the forecasted availability of green hydrogen for the above timeframe.

Although according to the Green Hydrogen Roadmap [56], there will be an installed electroyser capacity of 4 GW in Spain by 2030, the yearly production capacity of green hydrogen will stand at around 1,000 kTm (some 39 TWh/year), and so coverage of the potential demand by the whole of the transport and industry sectors will still be very limited. In addition, as mentioned earlier, it is not until 2035 to 2050 that the deployment of a fully prepared hydrogen grid is expected to occur, and so it will not be feasible to have supplies with a blend of 88% hydrogen.

In conclusion, for the 2030 scenario, it will not be possible to achieve a 55% drop in emissions by the Spanish tile sector by introducing green hydrogen as a fuel. This is basically due to the fact that, from the forecasts for that point in time, green hydrogen will still not be produced on a large scale and neither will the grid be fully adapted to carry supplies to the consumption points. Furthermore, according to the forecasted prices, like the 2025 to 2035 timeframe, although an increase in the costs of natural gas and emission allowances of up to ~35.3 €/MWh and ~86 €/Tm CO_2 is envisaged, if a linear drop in the forecasted price of green hydrogen per KPMG [59] is taken into consideration from 2020 to 2050, hydrogen will still not be competitive for the sector from an economic point of view [11].

Viability by 2050

It is during the period from 2035 to 2050 that green hydrogen is expected to be deployed on a large scale, with the in-depth conversion of natural gas infrastructure and adaptations by end users to modify or replace their equipment and processes to operate with hydrogen. The forecasts for hydrogen's contribution to the final energy demand at a European level stand at around 13% to 24% [54].

Although there is no specific forecast for the expected production capacity for 2035 to 2050, everything seems to indicate that the availability of hydrogen will not be a constraint for its introduction by the Spanish ceramic tile industry.

Within this time period, however, the trend in green hydrogen prices in relation to the costs of natural gas and CO_2 emission allowances will be a key factor in determining whether green hydrogen is the right instrument to achieve the Spanish tile sector's decarbonization targets while also guaranteeing its capacity to compete.

Although envisaged green hydrogen prices differ depending on the consulted source, according to a recent article [59], they could drop from 70-120 €/MWh in 2018 to 27-970 €/MWh by 2050.

For its part, natural gas could reach a price of 42 €/MWh in around 2050 [51], with higher and higher CO_2 emission allowance costs due to the increasingly lower envisaged allowances given to the industry and their growing prices, which might rise to 67.20 €/Tm CO_2 by 2050, according to the figures estimated by several analysts (see Table 1). In this respect, everything seems to indicate that, in the long term, green hydrogen will be more cost-effective than natural gas in terms of the fuel's associated costs. If a mean price of around 62 €/MWh is taken for 2050, the associated costs of using green hydrogen in the sector will still be higher than those of continuing to use natural gas (Figure 11), and so at an economic level, the trend in the price of green hydrogen will definitely be a key factor in whether it is a viable option.

From the perspective of the emission reduction targets set in the EU Green Deal, where a scenario of neutrality is posed for 2050, green hydrogen is regarded to be a possible means of decarbonization, although it would require the implementation of additional measures to mitigate emissions not from fuel; that is, emissions associated with the process, which are inevitable and account for approximately 9% of the total emissions.

In conclusion, for the 2050 scenario, the forecasts seem to show that there will be the necessary infrastructure and hydrogen market for its implementation as an energy vector in the decarbonization of the Spanish tile sector, although full decarbonization will not be possible unless it is accompanied by other measures to offset the emissions derived from the process and to make its use economically viable.

The electrification of processes

The electrification of the processes that consume the most thermal energy and therefore release the highest emissions, like spray drying, drying and firing, will boost the electricity demand (12-18% for spray drying, 954% for drying and 4,927% for firing), as can be seen from the identification of the existing technologies for decarbonizing these processes. The characteristics of the electricity demand are shown below from the perspective of their technical and economic viability, taking into account a yearly production of 9.7 million tonnes of ceramic tiles in 2020 (data taken from the ceramic tile industry):

Table 4. Electricity demand

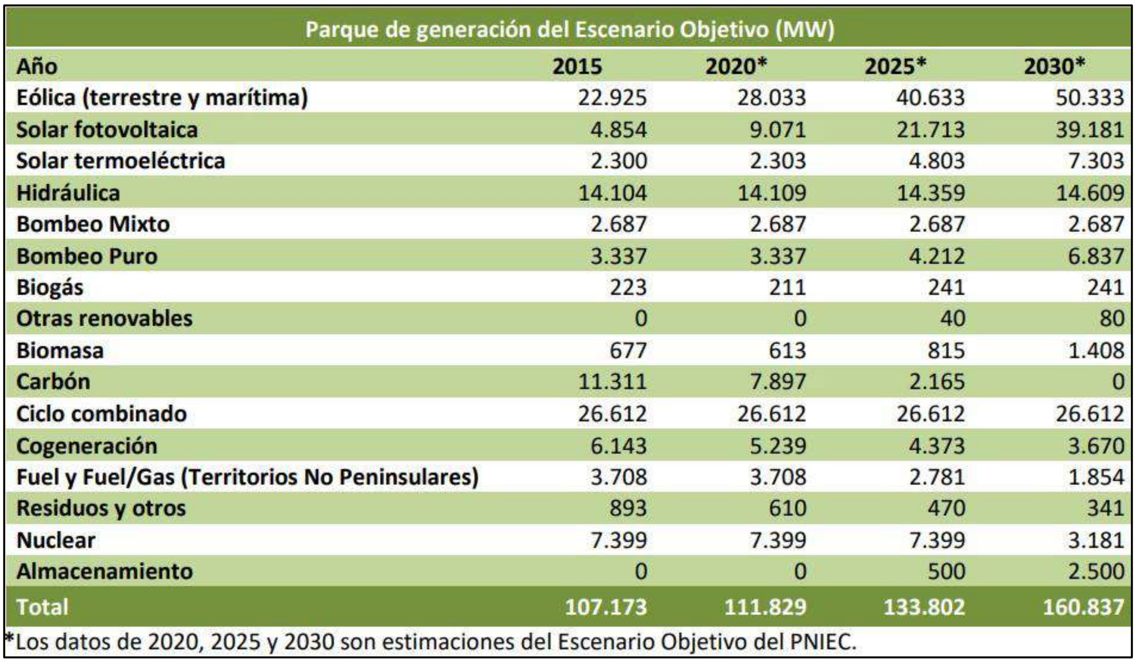
Stages	Current electricity consumption (2020)	Electricity consumption after full electrification	Increase in electricity consumption
Spray drying	**71 GWh**	**81 GWh**	**12-18%**
Drying	**109 GWh**	**1,036 GWh**	**954**
Firing	**201 GWh**	**9,893 GWh**	**4,92**
Total	**380 GWh**	**11,011 GWh**	**2,895%**

In this study, the characterization of the Spanish electricity market is analysed from two perspectives for the years 2025 and 2030 from data provided in the Spanish Integrated National Energy and Climate Plan (PNIEC), drawn up by the Spanish Ministry for Ecological Transition & Demographic Affairs. Following the said years, there are no estimations or forecasts by the given bodies. Outlined below are:

- the energy mix in order to assess the origin of the generated electricity and
- the envisaged amount of generated electricity and the capacity of the electricity grid to meet the increased demand by the Spanish ceramic tile industry.

Electricity generation

The target scenario proposed in the PNIEC involves a considerable increase in the capacity for renewable energy generation in comparison with the current situation. [60]



Parque de generación del Escenario Objetivo (MW)

Año	2015	2020*	2025*	2030*
Eólica (terrestre y marítima)	22.925	28.033	40.633	50.333
Solar fotovoltaica	4.854	9.071	21.713	39.181
Solar termoeléctrica	2.300	2.303	4.803	7.303
Hidráulica	14.104	14.109	14.359	14.609
Bombeo Mixto	2.687	2.687	2.687	2.687
Bombeo Puro	3.337	3.337	4.212	6.837
Biogás	223	211	241	241
Otras renovables	0	0	40	80
Biomasa	677	613	815	1.408
Carbón	11.311	7.897	2.165	0
Ciclo combinado	26.612	26.612	26.612	26.612
Cogeneración	6.143	5.239	4.373	3.670
Fuel y Fuel/Gas (Territorios No Peninsulares)	3.708	3.708	2.781	1.854
Residuos y otros	893	610	470	341
Nuclear	7.399	7.399	7.399	3.181
Almacenamiento	0	0	500	2.500
Total	**107.173**	**111.829**	**133.802**	**160.837**

*Los datos de 2020, 2025 y 2030 son estimaciones del Escenario Objetivo del PNIEC.

Figure 12. Trend in the installed electricity capacity (MW) according to the target scenario [61]

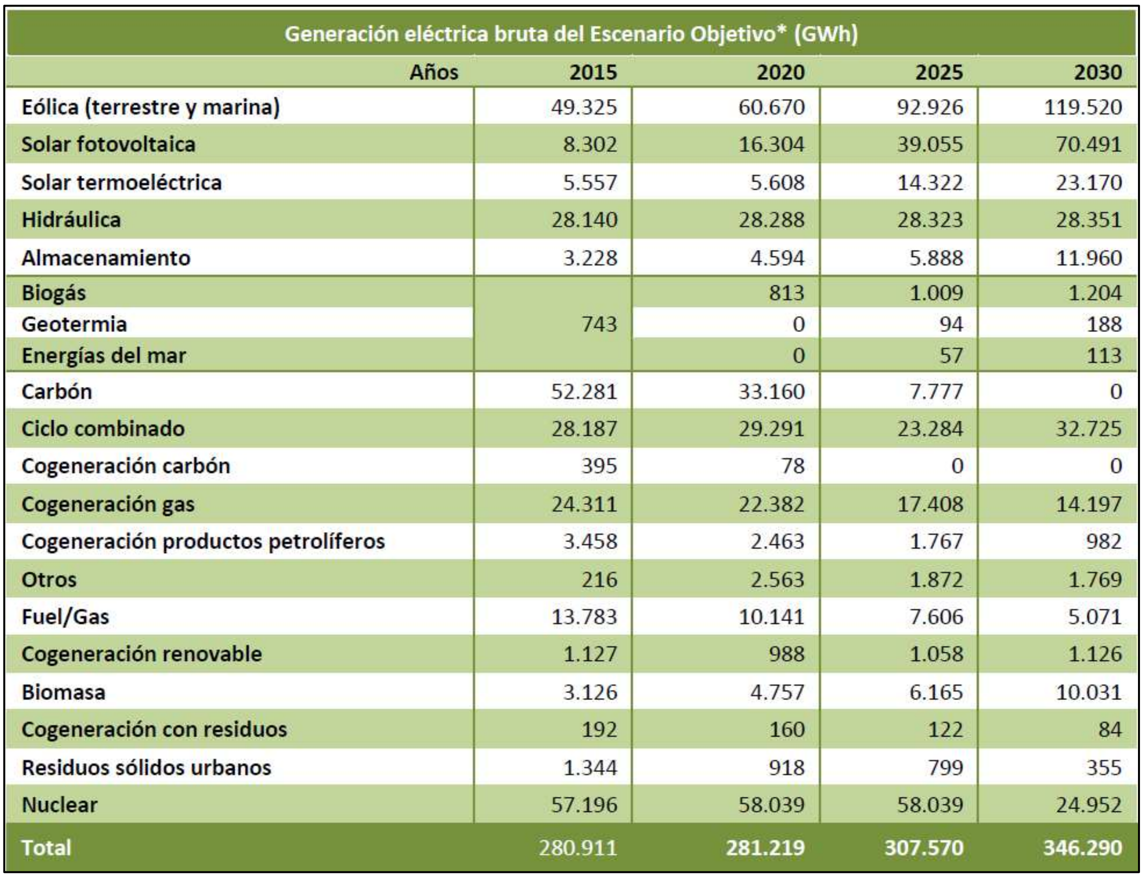
In the target scenario, the total installed power capacity is raised to 161 GW by 2030. This represents a 44% increase (49 GW) in relation to the figure of 112 GW in 2020 and 134 GW in 2025. The main increases come from offshore and onshore wind power and photovoltaic solar energy, each accounting for 22 GW and 30 GW respectively. In 2020, Spain only had about 9 GW of photovoltaic energy, and the aim is to boost this to 40 GW by 2030. This represents an average of 3.1 new GW per year. By 2030, Spain would no longer have to count on coal or on half its existing nuclear power stations.

Compared to the country's current capacity, it is this 49 GW increase (44%) in the generation of electricity in Spain that must be the basis of the decarbonization of all Spanish industry and the provision of electricity supply required for the electric vehicles. It is important to specify that there are no forecasts by the Spanish public authorities for after 2030.

According to the PNIEC, the integration of renewable sources into the electricity generation system will be accompanied by the following initiatives:

- The promotion of the necessary infrastructure networks.
- Maximized use of the available capacity through efficient power allocation processes.
- Simplified administrative and environmental procedures for processing licences for installations so that these formalities do not hinder the construction of power generation facilities and the necessary infrastructure to put them into operation, particularly in the case of increases in power capacity.
- A review of the functioning of the electricity market, if necessary, in order to make optimum use of the country's potential for generating renewable energies.

Following this outline of the electricity generation system, shown below are the resulting electricity generation figures:



Generación eléctrica bruta del Escenario Objetivo* (GWh)

Años	2015	2020	2025	2030
Eólica (terrestre y marina)	49.325	60.670	92.926	119.520
Solar fotovoltaica	8.302	16.304	39.055	70.491
Solar termoeléctrica	5.557	5.608	14.322	23.170
Hidráulica	28.140	28.288	28.323	28.351
Almacenamiento	3.228	4.594	5.888	11.960
Biogás	743	813	1.009	1.204
Geotermia		0	94	188
Energías del mar		0	57	113
Carbón	52.281	33.160	7.777	0
Ciclo combinado	28.187	29.291	23.284	32.725
Cogeneración carbón	395	78	0	0
Cogeneración gas	24.311	22.382	17.408	14.197
Cogeneración productos petrolíferos	3.458	2.463	1.767	982
Otros	216	2.563	1.872	1.769
Fuel/Gas	13.783	10.141	7.606	5.071
Cogeneración renovable	1.127	988	1.058	1.126
Biomasa	3.126	4.757	6.165	10.031
Cogeneración con residuos	192	160	122	84
Residuos sólidos urbanos	1.344	918	799	355
Nuclear	57.196	58.039	58.039	24.952
Total	280.911	**281.219**	**307.570**	**346.290**

Figure 13. Gross electricity production for target scenario (PNIEC) (Source: Spanish Ministry for Ecological Transition and Demographic Affairs, 2019)

Balance eléctrico del Escenario Objetivo (GWh)				
Años	**2015**	**2020**	**2025**	**2030**
Generación eléctrica bruta	281.021	281.219	307.570	346.290
Consumos en generación	-11.270	-10.528	-10.172	-10.233
Generación eléctrica neta	269.751	270.690	297.398	336.056
Consumos en bombeo y baterías	-4.520	-6.381	-7.993	-15.262
Exportación	-15.089	-9.251	-26.620	-48.325
Importación	14.956	18.111	12.638	8.225
Demanda en barras de central	265.098	273.170	275.424	280.694
Consumos en sector transformación de la energía	-6.501	-7.552	-6.725	-6.604
Pérdidas en transporte y distribución	-26.509	-25.161	-25.022	-24.868
Demanda eléctrica final de sectores no energéticos	232.088	**240.457**	**243.677**	**249.222**

Figure 14. Electrical energy balance for the target scenario, PNIEC (Source: Ministry for Ecological Transition and Demographic Affairs, 2019).

The main conclusions for the target scenario are:

- The final electricity demand will rise from 240.5 TWh in 2020 to 249.2 TWh by 2030, an increase of 4%.
- The net import/export balance is clearly export-orientated by 2030, with a figure of 40 TWh, thanks to the high penetration of renewable energies in the grid supply system.
- The percentage of renewable energy in the electricity sector will go up by 32% over this period, rising from 42% in 2020 to a share of 74% by 2030.

According to data on the development of electrified technologies alternative to current thermal ones, the full electrification of the ceramic tile industry would involve an increase of at least 814% in the sector's current electricity consumption, rising from a yearly consumption of 1,489 GWh in 2020 to 12,119 GWh by a horizon of full decarbonization.

That is, for the proposed electrification process, 10,630 GWh would have to be destined to the ceramic tile industry alone. When this is compared with the increase in the electricity generated by the Spanish grid supply system, which would rise by 8,800 GWh between 2020 and 2030, this implies allocating 121% of this whole increase to the ceramic tile industry alone. Hence, there is a shortfall in the generation of electricity when the forecasts are taken into account.

As for the electricity costs, according to simulations by REE (Red Eléctrica Española), the change in the electricity mix contemplated in the PNIEC for the period from 2021 to 2030 will lead to a 31% drop in the mean marginal generating cost by 2030 in relation to the baseline scenario. Hence, no increased cost in relation to now is envisaged, since the goal is to replace energy from fossil fuels with renewable sources, whose cost is lower.

However, when the historical data is taken into account, the mean price of electricity in 2019 was 47.71 €/MWh, 16.8% less than 2018, 20.2% higher than 2016, and similar to the mean price of the seven previous years from 2012 to 2018.

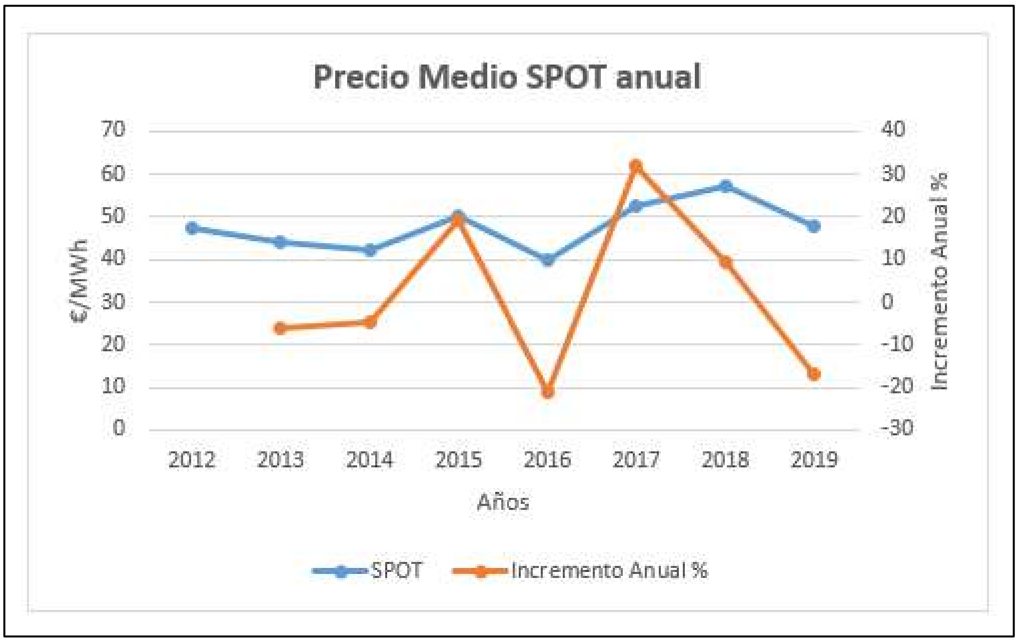


Figure 15. Annual average SPOT price [62]

Throughout 2019, the price of electricity dropped substantially in relation to 2018, although it did not reach 2016 prices. The demand for energy without CO_2 emissions fell in relation to 2018, thanks to climate conditions and high use of hydraulic energy, wind power and gas in the last quarter of 2019, with this being one of the factors that influenced the drop in price. Meanwhile, the percentage of renewable energies used throughout 2019 was similar to 2018. Even so, coal production dropped considerably, and the price of a Brent barrel remained stable throughout the year, with yearly figures below those of 2018.

The forecasts for coming years are more promising, since prices will remain low, perhaps rising or falling but not much.

Under the PNIEC, 70% of all generated electricity must come from renewable sources by 2030. This kind of energy is attracting growing interest. According to data by REE (Red Eléctrica de España), over 100 GW of all newly installed renewable energy sources already have permission to connect to the grid. This is almost as much as the current total installed capacity covered by all the renewable technologies. Of the aforesaid figure, 76.7 GW correspond to photovoltaic solar energy panels and the remaining 25.3 GW to wind power. If this amount of renewable energy joins the market because these technologies have a variable cost close to zero, they will drastically reduce the price of electricity.

However, if we take the worst-case scenario from forecasts and trends, average prices over the next few years might be estimated as being somewhere within the 40 to 50 €/MWh bracket, bearing in mind the fact that an increase in cost is not envisaged in the forecasts.

If a trend is therefore taken with a final electricity cost of between 50 to 60 €/MWh (cost of energy plus network access rates) and the estimated 10,630 GWh increase in electricity consumption is factored in, full decarbonization would lead to an increase in the sector's electricity bill of between €532 M and €638 M.

The development of the electricity grid

From an analysis of the "Proposal for the development of the electricity grid for the period 2021-2016", without the development of the mainland electricity grid, energy policy objectives would not be achieved. If this could not be counted on, the likelihood of achieving the energy policy objectives established in the PNIEC would be much lower. Despite the possibility of connecting to the grid, not all the potential generated renewable energy could be integrated due to grid limitations and a large amount would be dumped. Instead of this, a high amount of thermal energy would need to be provided through technical constraints, with the resulting increase in associated emissions and variable costs.

In short, if only the 2020 grid were available, by 2026, not all the potential renewable energy could be integrated, and some 23,400 GWh/year of producible renewable energy would be wasted.

On the other hand, with a grid with no limitations, the energy policy objectives could be achieved, although its development would have a high social and environmental impact and the investment costs would exceed the set limits. Whatever the case, it is not possible to avoid renewable energy dumping just through the grid's internal development. Complementary mechanisms would be needed, in particular managed storage aimed at maximizing the advantage that is taken of renewable sources as a whole.

For the development of the electricity grid ready for 2026, from an analysis of the limitations and flows that can be observed in the baseline scenario (the 2020 network), an assessment has been made of possible alternative action in order to overcome the said constraints so that, in the end, the only alternatives that are incorporated are ones that offer a balance between the energy objectives to be achieved and safe supplies, environmental sustainability and economic efficiency.

Figure 16. The electricity grid's reinforcement needs

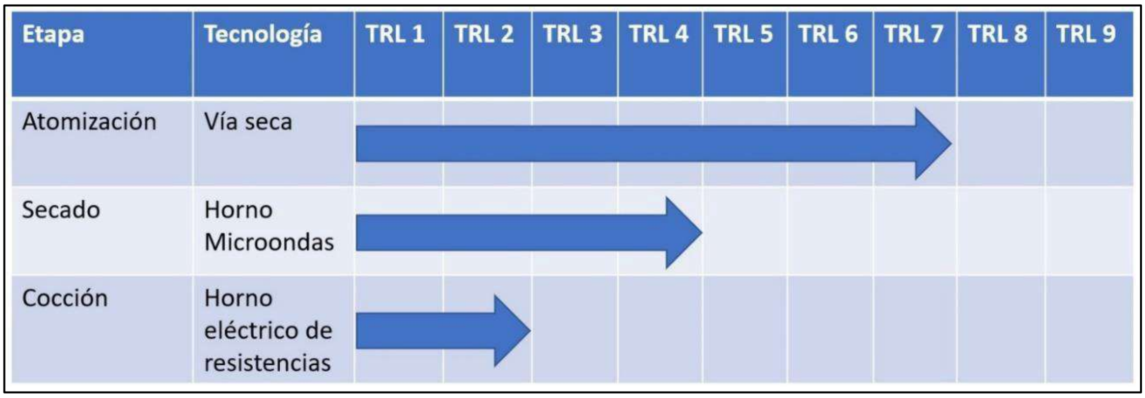
The province of Castellón's electricity grid can be seen to be in need of reinforcement. This calls for the guaranteed deployment of new electricity lines.

Technical viability of the three stages

The analysis of the technical viability of the different technologies commented on above for the electrification of the sector focuses on the three main stages that consume the most thermal energy, which thus need electrifying. Outlined below are the characteristics of each one from a technical point of view:

- Spray drying: The technology with the greatest current potential for replacing wet milling and subsequent spray drying is the dry milling system. However, although this technology does exist, and studies and demo projects have been run with good results in terms of its functioning and reduction in pollutant emissions, full verification is still needed of the quality of the end products and to check whether the obtained granulation is similar to the current process under any scenario. For this reason, it has been assigned a TRL of 7. This TRL means that the basic technological components are integrated and tested out with real elements for analysis in a real environment, but without yet achieving a representative scale.
- Drying: In the case of this stage in the manufacturing process, microwave technology seems to be the technology that unites all the necessary conditions to replace the current drying system due to the temperature levels (approx. 200º C) and drying capacity of microwaves. With this technology, although several research projects are currently exploring its application to ceramic materials, there are still difficulties to be overcome, such as how to heat the tiles uniformly and the scale of the ovens for this sector. Given all the above, this technology has a TRL of 4. That means that studies have been made at a laboratory level to validate this technology's use in the ceramic tile industry. Good results were achieved, but it must be studied in greater detail in the ceramic tile industry and its use must be developed on a large scale.
- Firing: In the case of firing, the only technology that could replace gas kilns are electric kilns. Electric kilns have been tested out in the ceramic sector with good results, but for other common ceramic materials, not ceramic tiles, using batch kilns. Consequently, in this case, it has a TRL of 2, meaning that applied research has been conducted but limited to certain types of materials and applications. A lot of work has yet to be done in order to demonstrate its use on a reasonable scale for the continuous kiln sector.

The above analysis is summarized in Figure 17, where the types of technology and current TRL are shown. It must be remembered that for these technologies to be sufficiently mature for their introduction in industry, they must reach a TRL of 9, which means that the product, process or service can be commercially launched and that it is accepted by a group of clients (including the authorities).



Etapa	Tecnología	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Atomización	Vía seca	→	→	→	→	→	→	→		
Secado	Horno Microondas	→	→	→	→					
Cocción	Horno eléctrico de resistencias	→	→							

Figure 17 TRL level of the different stages

N.B.: TRL (technology readiness level) is a measure of the maturity of a technology.

Carbon capture

Costs of capture, transport and storage

When the associated costs of introducing a CCUS technology are considered, the costs of the whole chain must be taken into account: carbon capture, transport and use/storage. There are two fundamental criteria for determining the associated costs of a certain technology: the investment costs (equipment) and the running costs (the required energy to run the process, mainly for the regeneration stage). Both costs are reflected in a parameter that serves as a benchmark for comparisons. This parameter is the cost per tonne of captured CO2, which relates the investment and running costs to the amount of captured carbon [27].

For each of the technologies under consideration:

- A wide variety of theoretical and experimental data on post-combustion capture systems can be found, and the cost of the technologies varies depending on additional factors. The capture cost is around 80 euros per tonne of captured CO_2 [63], based on an input stream with a typical concentration for natural gas combustion plants (a CO_2 concentration of between 5 and 10%) and an industrial scale. Furthermore, when a comparison is made of the required energy consumption for the regeneration stage, amine-based absorption is currently more economical than adsorption technology.

- In the case of direct air capture, the estimated costs are between 94 and 232 euros per tonne of captured CO_2 [38], a very high envisaged amount for such a low concentration of CO_2.

Taking into account a scale economy once again, the lower the transport capacity, the much higher the transport cost, as shown in Figure 18. The Spanish tile industry has a maximum capacity of 3 million tonnes, which would imply a cost of between 4 and 16 euros per tonne of CO_2.

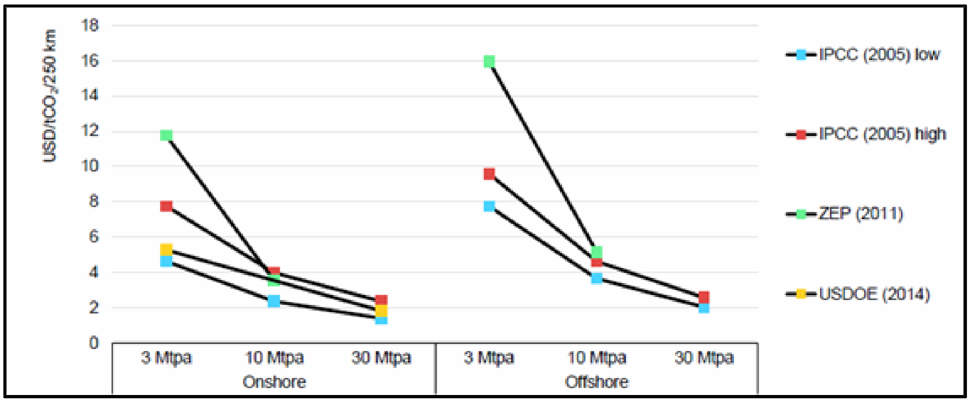


Figure 18. Carbon transport costs. IPCC=Intergovernmental Panel on Climate Change, USDOE=US Department of Energy, ZEP=Zero Emissions Platform [64]

In general, the capture costs represent somewhere between 70 to 80% of the total capture, transport and storage costs [65]. As a result, the global capture, transport, and storage costs can be estimated:

- as being around 100 to 114 euros per tonne using post-combustion capture systems.
- as being around 118 to 330 euros per tonne using direct air capture systems.

One approximate way of assessing the viability of a certain technology is to compare the CO_2 emission price with the price per tonne of captured CO_2 using the said technology. This technology can be considered to be economically viable when the corresponding price per tonne of captured CO_2 is below the emission price.

The Spanish ceramic tile industry

Bearing in mind the fact that the capture and transport costs are almost 100 euros per tonne of captured CO_2 for post-combustion technologies (based on the combustion of natural gas and in CO_2 concentrations of between 5 and 10%), in the case of the Spanish tile sector, an additional increase in cost should be taken into account for the following reasons:

- The need to install additional equipment to adapt to the gases used by the tile sector:
    - In order to try and increase the low concentrations of CO_2 in the sector to boost the efficiency of the carbon capture process, changes in the process or additional equipment would be needed. This would have to be validated on an industrial scale through changes in processes, which might jeopardize the quality of products.
    - Given the presence of certain substances, like SO_2, which would deteriorate the absorbents, or the need for a previous drying stage in adsorption, prior processing equipment would be needed.
    - Given the presence of certain high-temperature streams, some changes would be needed since both post-combustion and direct air capture technologies require lower input temperatures.
- The need for the technology to have a higher TRL. The estimated costs are based on theoretical studies, similar gas streams (not from the same sector, but based on the same

fuel) and they have not been validated on a commercial scale. Furthermore, increased costs due to modifications to the existing equipment must be taken into account. To incorporate the new capture units, as with all extensions to plants, factors must be taken into account like the availability of space or the plant's age.

- The scale of the installations. The scale is directly correlated with the amount of gases to be treated. The bigger the scale, the lower the investment and running costs. The costs of these installations are based on the cost-capacity factor shown below:

$$\text{Cost A} = \text{Cost B} * (\text{Capacity A}/\text{Capacity B})^{0.6}$$

For CCUS technologies, the cost will drop as the scale of the installations goes up. It has been observed that for installations with capacities of over 0.5 to 0.6 million tonnes of CO_2 per year, the cost stabilizes, and so when future plants are designed, capacities of over 0.4 million tonnes of CO_2 are recommended [66]. The Spanish ceramic tile industry stands out for its geographical distribution and for the size of the companies that comprise it. Hence, initially, carbon capture should be considered for the companies that generate the most CO_2 emissions. There are seven companies in the sector with emissions of between 0.1 and 0.13 million tonnes of CO_2 per year [67] and they account for 35% of the sector's emissions. Because the installations would have a yearly capacity of less than 0.4 million tonnes, the cost for each of them would rise considerably.

Viability by 2030-2050

The purpose of developing post-combustion technologies is to reduce energy consumption during the regeneration stage (OPEX) and so this is where the development of new components (absorption) and materials (adsorption) would be targeted. The following graph shows the slope of the reduction in energy consumption through to 2050.

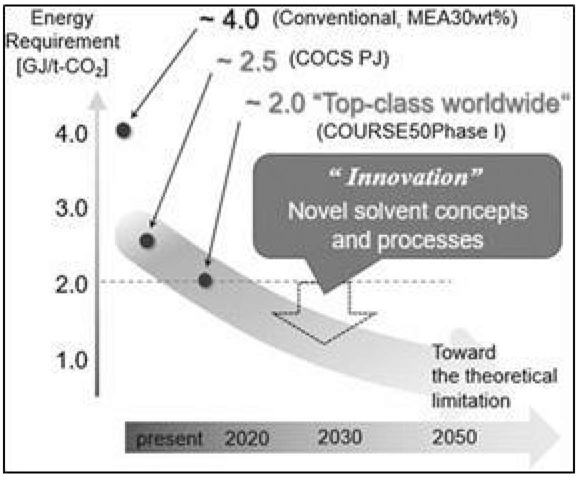


Figure 19: Trend in the costs of the required energy consumption for post-combustion technologies [68]

In addition to the need to reduce energy costs, there are proposals at a European level aimed at reducing investment costs (CAPEX). The following objectives have been defined for CCUS technologies [69]:

- To reduce investment costs by 20% by 2030 and 30% by 2050.
- To reduce the required energy consumption for carbon capture by 15% by 2030 and 25% by 2050.
- To use more sustainable, more economical materials.
- To make more flexible (the capacity to treat different types of streams) and modular the plants.

  There are already some initiatives aimed at standardizing and modularizing the technology, and it is hoped that, in the future, the costs associated with this will drop. One example is "JustCatch^{TM}" technology developed by Aker Carbon Capture [70].

Among the post-combustion technologies under consideration, amine-based processes, with a TRL of 9, are all set to reduce the aforementioned costs in coming decades and to be validated on an industrial scale in various scenarios.

As for adsorption, which currently has a TRL of 6 to 7 with promising results in terms of the required energy consumption for regeneration, it is expected to reach a commercial development stage during this current decade.

These mid and long-term CO_2 cost objectives (2030) are focused on achieving costs of less than 40 euros per tonne of captured CO_2 [32]. When this price is compared with the expected prices of emission allowances, this technology will become economically viable by 2030.

Conclusions

Outlined below are the conclusions that have been reached during the course of this study from currently available information and forecasts published in different sources. The envisaged technical and economic readiness level that the different technologies might reach is uncertain, since in some cases the emergence of ground-breaking technologies is expected that might alter the future outlook as we see it today. For this reason, a short-term review of the state of the technologies is considered to be useful in achieving a more accurate forecast for the 2015 horizon.

Biomethane

In this report, an assessment was made of biomethane as a replacement for the natural gas used by the Spanish tile sector. At present, natural gas from fossil fuels accounts for 90% of all the sector's energy consumption. This is equivalent to 14 TWh.

- Due to its physical and chemical properties, biomethane–which is produced by upgrading renewable biogas with a high methane content (CH_4>96%)–could replace natural gas.
- From a technical point of view, due to biomethane's high purity and its potential distribution through the current natural gas grid, it could be directly used in processes by the Spanish ceramic tile industry.
- Spain's current biomethane production of just 0.1 TWh is not sufficient to meet the demand by the sector.
- The consulted sources envisage a rise in biomethane production in Europe, with figures of over 1,000 TWh by 2040 and 2050. However, the amount of biomethane that is produced during these periods will only amount to about 30% of the demand for natural gas. This points to a limited availability.
- Although Europe ranks first in the world in the creation of biomethane plants, renewable gas guarantees of origin are still being developed at a Spanish and a European level.
- From the economic study summarized in the following graphs, it can be concluded that, for the periods under analysis, biomethane's use in Spanish ceramic tile processes is not a viable option, because it would always be more costly (up to 74.2% more in 2050).

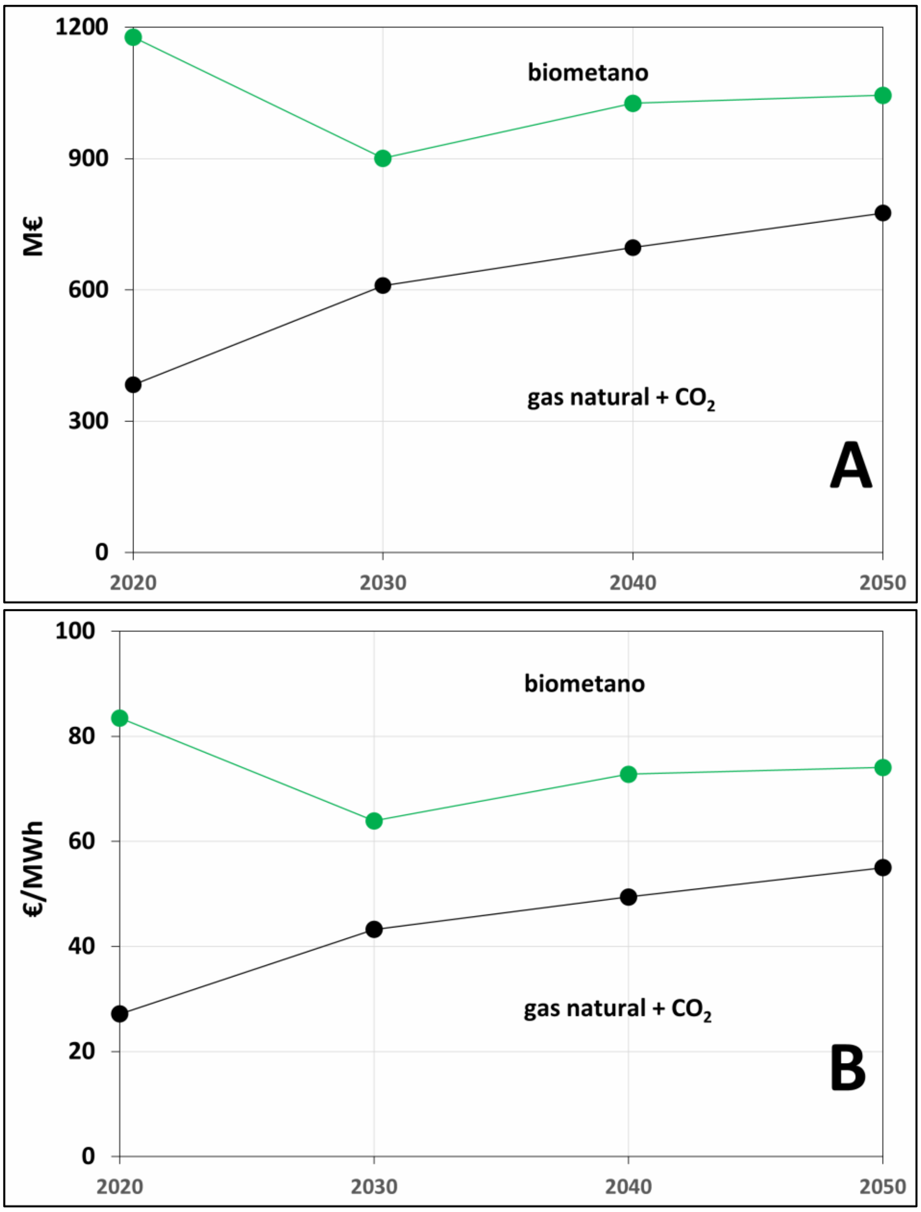


Figure 20: A yearly comparison of the costs of natural gas consumption and CO_2 emission allowances in relation to the costs of replacing them with biomethane. A comparison of the costs of biomethane or natural gas consumption in A) millions of euros and B) millions of euros per MWh.

Green hydrogen

A review has been made of the technological potential and the technical and economic viability of using green H2 in the ceramic tile industry.

- In technological terms, efforts mainly focus on the modifications that must be made to burners to replace 5 to 20% of the natural gas with hydrogen. It is also important to bear in mind that more NO_x is generated due to the increase in the adiabatic flame temperature, which points to the need for diffusion burners or gas recirculation to dilute combustion. The influence of the integration of this new energy vector on the quality of products is still under investigation, although at a laboratory level, tests have been made by a manufacturer, replacing up to 50% of the natural gas with hydrogen, and the results indicate that it does not affect the quality of the tiles.

- In terms of its technical and economic viability, green hydrogen is currently still pending development, given that its production has not been deployed at a commercial level and the natural gas grid still in a limited condition to carry it to different consumption points.
    - Through to 2030, the installation of approximately 4 GW of electrolysers has been envisaged in Spain for the production of some 1,000 kTm/year (39 TWh) to supply the industrial and transport sectors, in addition to the adaptation of the natural gas grid to carry a blend of hydrogen and natural gas in mixes of up to a maximum of 20% of H_2 by volume. However, to meet the target of a 55% reduction in emissions established in the EU Green Deal by partially replacing natural gas with green hydrogen in the Spanish ceramic tile industry, some 6,760 GWh (170 kTm) of H_2 a year would be required, supplied in the form of a blend of at least 68% H_2. This indicates that by 2030, the availability of hydrogen would still be very limited as a decarbonization technology for the sector. Furthermore, according to the consulted forecasts, during this timeframe, the price of green hydrogen would still be more expensive than natural gas. Its economic viability will also depend on the CO_2 emission cost that might be reached.
    - It is during the 2030 to 2050 period that the large-scale deployment of green hydrogen is envisaged through the in-depth conversion of natural gas infrastructure. Hence, *a priori,* everything seems to point to the fact that by 2050 the availability of hydrogen will not be a constraint in its introduction to the ceramic tile industry. During this period, the trend in hydrogen prices in relation to the costs of natural gas and CO_2 emission allowances will be a key factor. According to forecasts, everything seems to indicate that, in the long term, the use of green hydrogen could become more cost-effective than natural gas, although it will depend on the specific trend in hydrogen prices. As a result, at an economic level, foreseeably, support and funding mechanisms will be needed to make its use viable in industry. The following figures show a comparison of the fuel-associated costs if natural gas continues to be used or if it is partly replaced with green hydrogen in order to gradually comply with emission reduction targets.

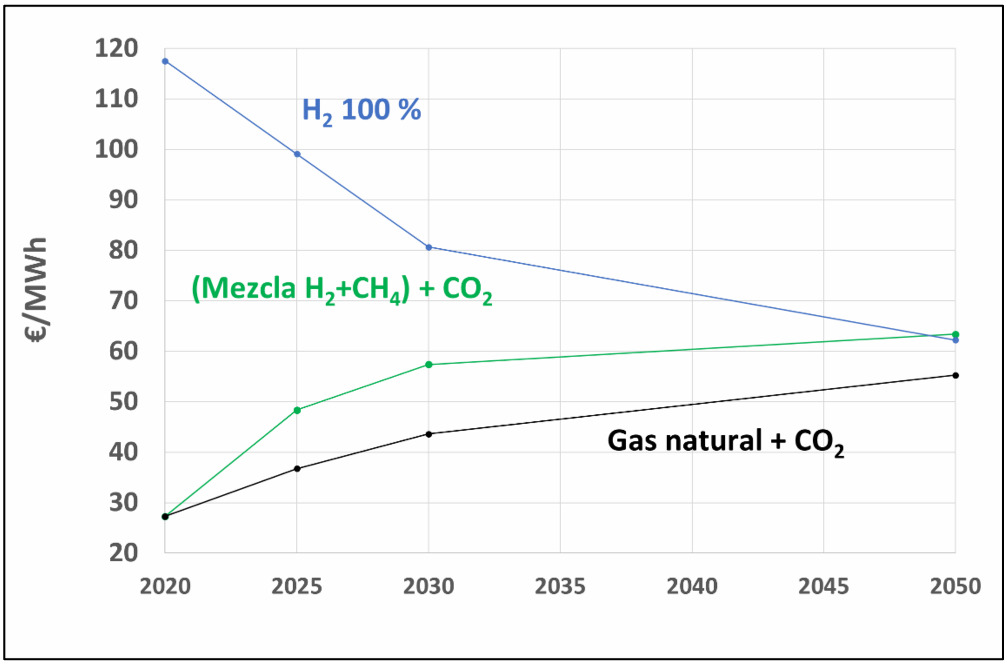


Figure 21: Yearly comparison of the costs of natural gas consumption and CO2 emission allowances compared to the cost of the gradual replacement of natural gas with hydrogen in order to comply with the partial emission reduction objectives for the different time horizons. Comparison of the costs in millions of euros (top figure) and millions of euros per MWh of consumed fuel (bottom figure).

- In the following graph, a comparison is made of the percentage of hydrogen required by the Spanish tile sector to meet the decarbonization objectives set for the 2025 to 2026, 2030 and 2050 timeframes and the percentage of hydrogen that the distribution network can supply.

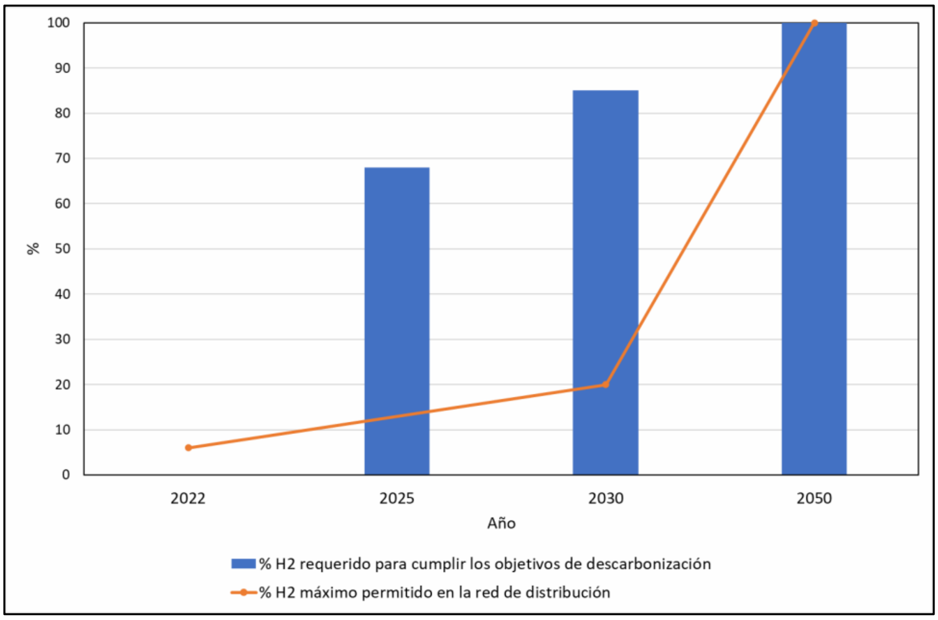


Figure 22: Comparison of the required % of H_2 to meet decarbonization objectives and the maximum permitted by the distribution network.

From Figure 20, it can be assumed that until 2050, the availability of renewable hydrogen for the Spanish ceramic tile industry will not be sufficient to allow its decarbonization.

Electrification

To draw conclusions on the potential for electrifying the Spanish ceramic tile industry, the stages in the production process with the highest energy consumption were analysed: spray drying, drying and firing. This is because these are the processes that consume the most thermal energy and so they generate the most emissions:

- The first point to highlight is the reduction in CO_2 emissions that the sector's electrification would represent. Because about 90% of the energy is thermal and thus pollutant, decarbonizing the sector could lead to savings of some 2.6 million tonnes of CO_2 per year [23], bearing in mind just the reduction due to the replacement of natural gas in the process (for the production of heat) but not the generation of CO_2 from the process itself. Figure 23 shows the proportion of emissions generated in each stage of the production process, with the following distribution: spray drying 36%, drying 9%, and firing 55%. From all the above, it can be concluded that the most important part to be decarbonized is the firing process, followed by the spray-drying and drying processes in that order.

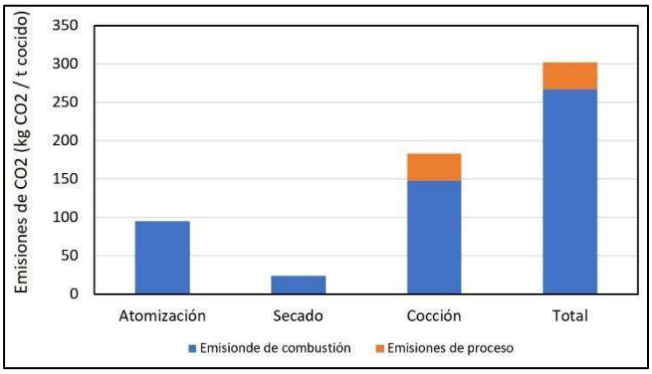


Figure 23. Specific carbon dioxide emissions by stage [71]

- The alternative to the wet granulation and spray-drying process is an electrified dry process. This demonstrates that, despite the technical feasibility, further development work and specific case studies are needed to achieve outcomes of similar quality levels. That is, it is not a question of the technology's direct replacement, but of modifications to the production processes.
- Drying is the process where the greatest potential can be seen for replacing conventional roller dryers with electric systems. However, the option that offers the greatest benefits, due to its TRL and costs, is microwave technology. Even though this part of the process is electrified, the reduction in emissions would not be as big as the reduction that could be achieved in the firing or spray-drying stages.
- It is in the firing process where the greatest barriers have been identified in the introduction of alternatives like electric kilns with heating elements or microwave ones. For conversion to electric heating systems, a very different kind of kiln would have to be designed and the hybrid kiln technology (with electric heating elements and microwaves) mentioned earlier is still in the development stage.
- Another important factor to take into account in the electrification of the three main stages of the process is the electricity that would be needed. Taking a scenario in which technologies like dry granulation, microwave drying ovens, and electric kilns could be developed, the energy demand would rise considerably from the present figure of 1,489 GWh/year to over 12,000 GWh/year. This can be seen in Figure 24, which shows the sector's electricity demand with current technology and the demand if the thermal part were electrified, in addition, obviously, to the current part powered by electricity. Hence, four scenarios can be envisaged: one where spray drying is electrified, leading to a very low rise in electricity consumption; another where the drying process is electrified with microwave technology, reducing the need for energy by 36%; a scenario in which firing is electrified with electric kilns, maintaining the same level of energy consumption (there are no references for large-scale electric kilns); and, finally, a scenario in which all the technologies are applied for the decarbonization of the three stages. It is also important to mention the fact that electric kilns might foreseeably consume more energy to reach the levels of current systems. Nonetheless, because systems of this type do not currently exist, it is hard to give an estimate.

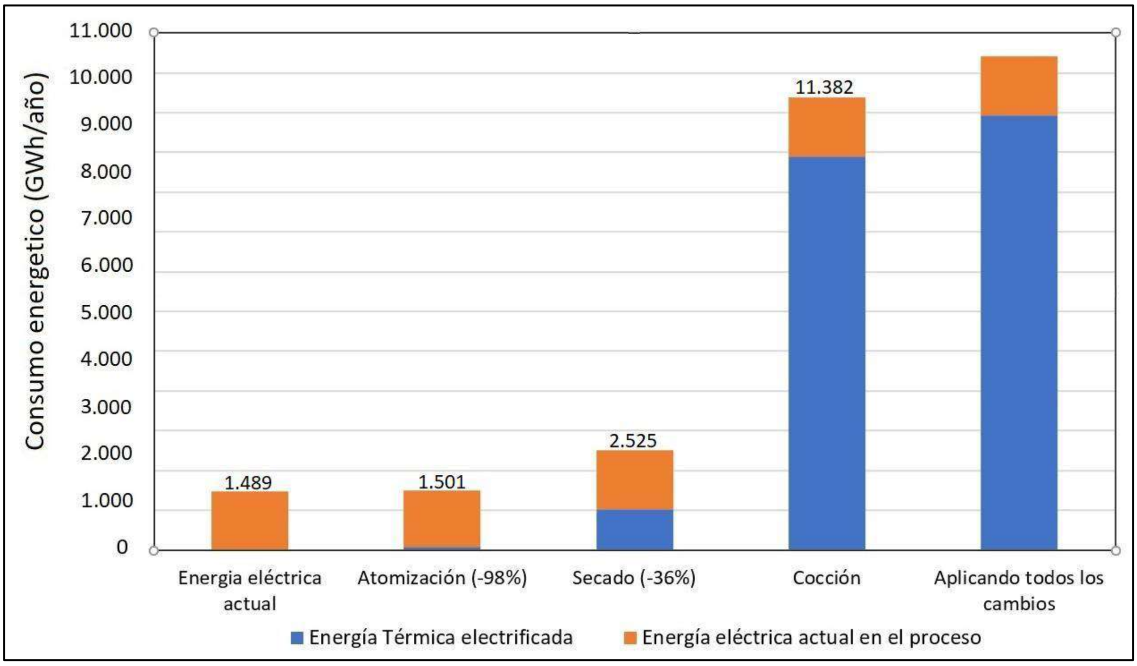
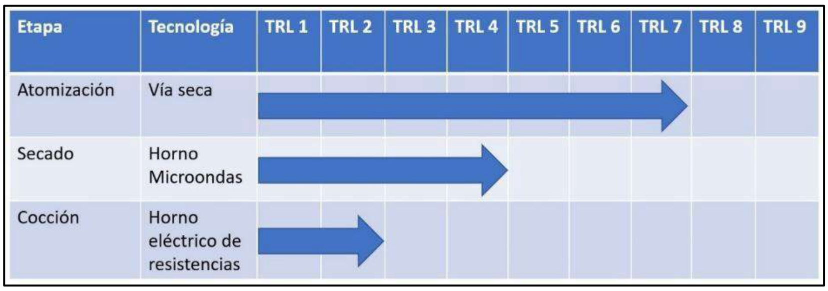


Figure 24. A comparison of the sector's electricity demand using current technology and the demand if the thermal part were electrified.

- A 49GW (44%) increase in Spain's electricity production capacity has been forecast in comparison with now. This is to be generated and distributed through the Spanish electricity grid to support decarbonization processes in the whole of Spanish industry and to provide electric vehicles with the required supplies.
- According to the PNIEC, the total envisaged electricity demand in Spain will rise from 240.5 TWh in 2020 to 249.2 TWh by 2030 (814%), an increase of 4% (8,800 GWh). For the proposed electrification process, an extra 10,630 GWh would have to be destined for the ceramic tile industry alone, accounting for 121% of the total increase for just this one sector. Hence, when the estimations are taken, there would be a shortfall in the generation of electricity. In such a scenario, this would lead to the instability of the electricity supply system.
- The trend in electricity prices must also be taken into account. These prices are currently much higher than natural gas prices [23]. According to the PNIEC, there will probably be a drop in electricity generation costs of around 31% by 2030. However, if we consider the historical data, the mean price of electricity in 2019 was 47.71 €/MWh, 16.8% less than 2018, 20.2% higher than 2016 and similar to the mean price of the seven previous years between 2012 and 2018. If a trend in the final cost of electricity of between 50 to 60 €/MWh (cost of energy + network access rates) is taken, bearing in mind the estimated increase in energy consumption of 10,630 GWh in the event of full decarbonization, this would lead to a rise in the sector's electricity bill of between €532 M and €638 M.
- There are no electricity generation forecasts by the public authorities beyond 2030.
- There is an observed need for the reinforcement of the province of Castellón's electricity network, according to the "Proposal for the development of the electricity grid 2021-2016", calling for the deployment of new power lines.

- Lastly, as mentioned in the section on the potential technical viability, these technologies have not yet been sufficiently developed to be applied to the Spanish tile sector. Some technologies are in a more advanced state of development according to their current TRL, such as spray drying with dry milling (see Figure 23), but others, like electric kilns, still require substantial development to become a viable option.



Etapa	Tecnología	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Atomización	Vía seca									
Secado	Horno Microondas									
Cocción	Horno eléctrico de resistencias									

Figure 23: Current TRL of electrification technologies.

Carbon capture

The introduction of carbon capture technology to the Spanish tile sector is currently not viable for the following reasons:

- The sector releases gas streams with a concentration of CO_2 of between 1 and 4%, and there is currently no commercially developed technology for such a range.
- The price per tonne of captured CO_2 is a benchmark parameter for the cost of carbon capture technologies.
- The application of post-combustion technologies to the tile sector would lead to a considerable increase in costs in relation to the reference cost of the said technologies. This is due to the following reasons:

  - The need to increase the concentration of CO_2 in gas streams to the right levels for the technologies. It is important to confirm whether this is possible in the ceramic tile industry without the quality of the end products being affected.
  - The need to eliminate certain components from gas streams that are not compatible with the technologies.
  - The need to introduce technologies on a smaller scale than the recommended one, due to the size of the companies in the Spanish tile sector.

- The reference cost of post-combustion technologies is currently about 80 euros per tonne of captured CO_2, and it is expected to fall below 40 euros by 2030, the point when the technology will be economically viable.
- The cost of the whole chain must be considered: capture, transport and storage. The transport cost would represent an addition 4 to 16 euros per tonne of captured CO_2.

- At a domestic level, one limitation in the implementation of carbon capture technologies is the availability of solutions for the captured CO_2's use or storage:
    - One way of lowering the cost of carbon capture technology is to use the captured CO_2 as a raw material in industry. The current demand for CO_2 in industry is just a small fraction of the CO_2 that can be captured and, although new initiatives are being developed, there are currently no industrial applications able to take advantage of all the CO_2 that can be captured.
    - As for storage, due to the shortage of Spanish natural gas and crude oil reserves, there is just a limited storage capacity and more in-depth information is needed on potential storage sites [41].

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