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# Life cycle assessment of implementation of an innovative solar thermal technology in Italian ceramic industry

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ABSTRACT

In recent years, the depletion of fossil fuel reserves, coupled with the European Union targets to increase the integration of renewable energy into the energy mix has prompted both industries and the scientific community to shift their focus towards alternative systems driven by sustainable energy sources. The imperative for renewable energies arises from the necessity to decrease dependency on fossil fuels, particularly to mitigate carbon dioxide emissions. The existing literature extensively documents how integrating renewable energy into industrial processes can help reduce environmental impact. The novelty of this study lies in the life cycle assessment (LCA) of ceramic sanitaryware production in Italy, specifically evaluating the use of thermal energy from a solar thermal system in the drying and firing processes, thereby reducing fossil fuel consumption. To this end, an LCA was conducted to assess the environmental impacts of replacing natural gas in the drying process with thermal energy from the SunDial solar thermal technology. The LCA methodology was applied to quantify the energy and environmental burdens of the system throughout its entire life cycle, including manufacturing, operation, and end-of-life stages. The functional unit is 1000 kg of sanitaryware production. Data was collected from the Ecoinvent database, and the assessment was performed using SimaPro software. The results indicate a 4 % reduction in global warming potential (GWP) due to the implementation of SunDial, which covers 20 % of the process's energy demand. On a national scale, considering the entire Italian sanitaryware production, this translates into a savings of 180 tons of $CO_2$ emissions.

## 1. Introduction

The depletion of fossil fuel reserves, coupled with the European Union's 2030 targets to increase the integration of renewable energy into the energy mix production, and the 2030 Agenda for Sustainable Development, has prompted both industries and the scientific community to shift their focus towards alternative systems driven by sustainable energy sources. The imperative for renewable energy sources arises from the necessity to decrease dependency on fossil fuels, not only to address the depletion of reserves but also to mitigate their environmental impact, particularly in terms of carbon dioxide emissions.

The demand for sustainable energy solutions in industrial processes has led to increased attention toward solar thermal technologies. Among these, the ASTEP (Application of Solar Thermal Energy to Processes) project represents a significant innovation, designed to deliver thermal energy up to 400 °C for industrial applications across both high- and low-latitude regions. The ASTEP system comprises three key subsystems: the SunDial solar collector [1], an advanced rotary Fresnel system capable of dual-axis solar tracking; a Thermal Energy Storage (TES) unit utilizing phase change materials (PCM) for efficient energy management; and a Control System designed to ensure operational precision. These features enable the ASTEP system to address the limitations of conventional Fresnel systems, which struggle to provide high-temperature heat in high-latitude regions.

The system has been implemented in two case studies: a dairy factory in Greece and a steel tube manufacturing facility in Romania. The economic and environmental assessments reveal significant energy cost savings and reductions in carbon emissions, demonstrating the potential of ASTEP to enhance industrial sustainability while providing long-term financial benefits. This paper builds on the findings of prior research, such as the study by Gobio-Thomas et al. [2], which analyzed the life cycle costs, levelized cost of energy (LCOE), and benefit-cost ratio (BCR) of ASTEP, highlighting its viability as a renewable energy solution for industrial applications.

The life cycle assessment (LCA) is often the methodology chosen to perform the evaluation of the environmental impact of industrial processes, services, products and buildings such as Nessi et al. that used the LCA methodology to evaluate the energetic and environmental

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performance of public network water and of refillable bottled water as an alternative to one-way bottled water [3], or Papong et al. that evaluate the environmental performance associated with PLA bottles produced from cassava in Thailand in comparison with traditional PET bottles [4]. Also, Bianco et al. [5] compared bottled water and a drinking water dispenser made of pine wood using this methodology. The LCA is often used to evaluate the carbon footprint of the systems, for instance Cascini et al. [6] proposed a Carbon Footprint Assessment to evaluate the environmental impact associated with the life cycle of two commercial refrigeration systems with walk-in cold rooms, and Maalouf et al. [7] that presented a comprehensive model designed to evaluate the carbon footprint of integrated solid waste management systems. LCA is also used to evaluate the environmental performance of new systems such as Roumpedakis et al. [8] that made an investigation on a solar cooling and heating system. Falegari et al. [9] utilized the integration of Building Information Modeling (BIM) and Life Cycle Analysis to assess the impact of climatic factors and certain passive design strategies on a building's life cycle, examining their influence on its overall energy performance.

In the ceramic industry, the majority of LCA studies have been focused on ceramic tiles, with only a few studies based on the ceramic sanitaryware. Pini et al. [10], Almeida et al. [11], Muthukannan et al. [12] and Vieira et al. [13] used LCA methodology to evaluate the environmental impacts and energy consumption of the production of ceramic tiles. The authors found that the manufacturing process of ceramic tiles produced the greatest environmental impact, with the firing step identified as one of the main areas with the highest environmental load, contributing significantly to global warming potential due to the use of natural gas. Viera et al. [13] reported that natural gas consumption during the burning stage of ceramic materials in the manufacturing process, contributed significantly to ozone layer depletion, abiotic depletion and global warming. Lo Giudice et al. [14] used LCA methodology to identify environmental impact hotspots in the Sicilian traditional ceramic sector. The results showed that electricity consumption used for heat treatment in the manufacturing of the ceramics produced the highest environmental impact in the categories of Global Warming, Respiratory Inorganics and Non-Renewable Energy. Sappa et al. [15] used LCA to evaluate the environmental impacts and energy consumption of producing ceramic tiles using municipal solid waste incineration bottom ashes (MSWBA) mixed together with traditional feldspathic sands and clays. The results showed large environmental and energy benefits when the bottom ash was reused in the manufacturing of the ceramic tiles instead of disposal in landfill as hazardous waste which causes significant environmental impact. Saavedra and Osma [16] used LCA methodology to evaluate the impact of various nanoparticles on energy and material consumption in the ceramic tile industry. The results showed that addition of magnetite nanoparticles at 1 % to the clay used in the production of ceramic tiles, significantly reduced environmental impact by up to 20 % in GWP and up to 19 % less impact in non-carcinogenic toxicity and terrestrial ecotoxicity.

LCA methodology has also been used to assess the environmental impact of the manufacturing industry when thermal efficiency optimization is applied to their processes. Jianwei [17] investigated the optimization scheme of green manufacturing process by integrating thermal efficiency optimization with LCA techniques. The author used LCA for the environmental impact assessment of the manufacturing process before and after the thermal efficiency optimization is carried out to quantify the effect of the optimization measures. The LCA results showed that energy consumption and greenhouse gas emissions in manufacturing processes were reduced through the use of thermal efficiency optimization.

The ceramics industry is energy intensive resulting in significant environmental impact. Therefore, there is increased focus on the decarbonization of the ceramics industry to meet the EU's 2030 and 2050 climate change targets for industries. Furszyfer Del Rio et al. [18] investigated the decarbonization of the ceramics industry and found that in the EU, the manufacturing of ceramics emits around 19 Mt $CO_2$, while bricks manufacturing is responsible for 2.7 % of carbon emissions annually. Furthermore, in Asia alone, it is estimated that the brick sector consumes more than 110 million tonnes of coal per year. Moreover, one of the main obstacles in decarbonizing the ceramics industry is the lack of knowledge from local manufacturers to implement low-carbon processes. In the perspective of small manufacturers, another barrier is the lack of willingness to adopt more efficient technologies due to lack of incentives and regulations to stimulate upgrading assets with long-lives.

Wang et al. [19] conducted an evaluation and comparison of the environmental impacts of ceramic tiles manufactured in China using both traditional and cleaner production technologies, employing a life cycle assessment approach from a "cradle to gate" perspective. The findings indicated that energy consumption and emissions from fuel combustion were the primary contributors to the environmental impact associated with tile production. The drying and firing steps accounted for 54.67 % of the total energy consumption. Türkmen et al. [20] evaluated four different scenarios to improve the sustainability of ceramic tile production in Turkey. The results showed that the scenario combining furnace heat recovery, energy-efficient combustion, and reduced tile thickness is the most eco-friendly option among the four scenarios analyzed. Implementing this scenario achieves a 21.0 % reduction in global warming potential (GWP). Yuan et al. [21] focused on the ceramic tiles manufactured using industrial waste fly ash. They conducted a comparative LCA across scenarios by varying the fly ash additions from 0 % to 30 %, examining six environmental impact categories, including climate change and fossil depletion. Notably, the 30 % addition scenario, achieved the most substantial benefits, reducing climate change impacts by 8 %.

Concerning the sanitary ware manufacturing, Lv et al. [22], based on the data acquired from a leading factory in China, evaluated the material and energy flows, and the environmental impacts and economic cost of the production of the sanitary. They concluded that firing and drying consumed the highest amount of coke oven gas, while casting and body preparation were electricity-intensive, and casting was also the largest consumer of water. Moreover, firing, drying and raw material extraction were the processes with the greatest environmental impacts.

Silvestri et al. [23] made an analysis of a sanitaryware industry in Italy. They performed the analysis using a cradle-to-gate approach that considered the product life cycle from resource extraction to the factory gate. The considered factory implemented a mature, green-based manufacturing and it represented a reference point for estimating how the environmental impact can be reduced through energy saving technologies and water recycling. These technologies were compared to conventional ones and a potential improvement, based on a cogeneration system implemented into the plant, was used to assess whether the economic improvement resulted in reduced environmental impact. Results showed that the economic benefit due to the implementation of cogeneration produced a slight increase in its environmental impact.

In another work Silvestri et al. [24] evaluated the implementation of reusing olive mill wastewater in a ceramic industry and considered the possibility of reusing it in the brick-making process, instead of fresh water. The authors found that this had economic and environmental implications, both for the brick and the olive oil production industry. To produce bricks, lower consumption of energy and water would be the environmental advantages, while the economic advantages derives from a cheaper production process. Furthermore, the reuse of the olive mill wastewater reduces the environmental impact associated with disposal of wastewater.

Monteiro et al. [25] proposed a methodological approach to assess the environmental and economic life-cycle performance of alternative improvement scenarios for a ceramic sanitaryware manufacturing plant.

Desole et al. [26] have recently presented an LCA investigation on ceramic sanitaryware focusing on the production process and analyzing three different scenarios. Their results show the considerable environmental impact of the production processes in terms of energy consumption and materials.

Due to the increasing interest in reducing the environmental impacts of manufacturing plants using solar thermal power plants, Gobio-Thomas et al. [27] conducted a systematic review on this topic. The authors found that solar thermal plants produce significantly less GHG emissions than fossil-fuelled power plants. Natural gas used as auxiliary fuel increases the GHG emissions of the solar thermal plants. The authors explained that a better alternative is the replacement of natural gas with renewable energy sources such as biofuels that have less environmental impact. Moreover, using different environmental software tools and life cycle impact assessment (LCIA) methods resulted in conflicting LCA results. Therefore, standardization is required in the environmental assessment software tools and LCIA methods to prevent discrepancies in the LCA results.

Based on the literature review and the authors' knowledge, very few studies evaluate the environmental impacts of the drying and firing processes in the ceramic industry using alternative renewable energy technologies. Some authors, such as Lv et al. [22] and Silvestri et al. [23], have suggested that the drying and firing processes have the greatest environmental impact in the ceramic industry. However, alternative renewable energy sources for these processes have not been thoroughly investigated. The objective of this study is to demonstrate that the use of solar collectors, such as the SunDial [1], which is part of the ASTEP system, can help reduce the environmental impact of industrial processes that currently rely on fossil fuels. Therefore, the novelty of this study is is the life cycle assessment of ceramics sanitaryware production in Italy, when thermal energy from a solar thermal system to applied to its drying and firing processes, reducing the use of fossil fuels.

## 2. Materials and methods

The Life Cycle Assessment (LCA) process consists of four steps: goal and scope definition, inventory analysis, impact assessment, and results interpretation, as described by the ISO 14040 framework [28] and ISO 14044-guidelines and requirements [29].

### 2.1. Goal, scope definition and system boundaries

The initial step in an LCA involves defining the scope, goal, system boundaries, and functional unit. Establishing the goal and scope for products or services is a preliminary and essential phase of the LCA. The goal of this paper is to make a comparison and assess the environmental impacts between a conventional sanitaryware production and one where during firing and drying processes the use of a solar thermal plant is implemented. Therefore, two cases are studied: in the first case, that is named *Reference case*, a conventional sanitaryware production line is considered using an approach from cradle to gate following the work of Silvestri et al. [23] that is used to validate the results. For the second case, that is named *Case study*, the same approach of the *Reference case* is used, but in it the implementation of a solar thermal plant, that satisfies the 20 % of energy demand during the drying and the firing processes substituting the natural gas consumption, is considered. The life cycle stages and boundaries covered the raw material storage, transport, and production processes of the sanitaryware as reported in Fig. 1 and Tables 1 and 2. The raw materials extraction and the sanitaryware transportation after their production are not considered in this paper. The functional unit is 1000 kg of product.

### 2.2. Inventory analysis

The second step in the Life Cycle Inventory (LCI) involves data collection and calculation procedures that quantify the input and output flows of a product system. This evaluation is performed using the SimaPro 9.5 software, utilizing the Ecoinvent database version 3.9 from which are taken the data of the processes in Table 1 and 2.

Data are collected and processes that define the product system, are established using the Ecoinvent database. In both considered cases the Italian electricity grid and natural gas grid are considered during this analysis. For the *Reference case*, the analysis began with the extraction of

**Table 1**
Processes for Reference study [23]

| Processes | Value |
|---|---|
| Clay; Kaolin; Quartz; Feldspar; Calcium Carbonate; Water; Materials for glaze and their transportation | 1742.62 kg |
| Electricity medium voltage in Italy for preparation process | $1.26*10^3$ MJ |
| Electricity medium voltage in Italy for shaping | 9.364 MJ |
| Gas Natural for drying | 21.57 $m^3$ |
| Heat from natural gas for drying | 850 MJ |
| Electricity medium voltage in Italy for glazing | 124.848 MJ |
| Gas Natural for firing | 122.2 $m^3$ |
| Heat from natural gas for firing | 4814.8 MJ |
| Electricity medium voltage in Italy for polishing and packaging | 777 MJ |

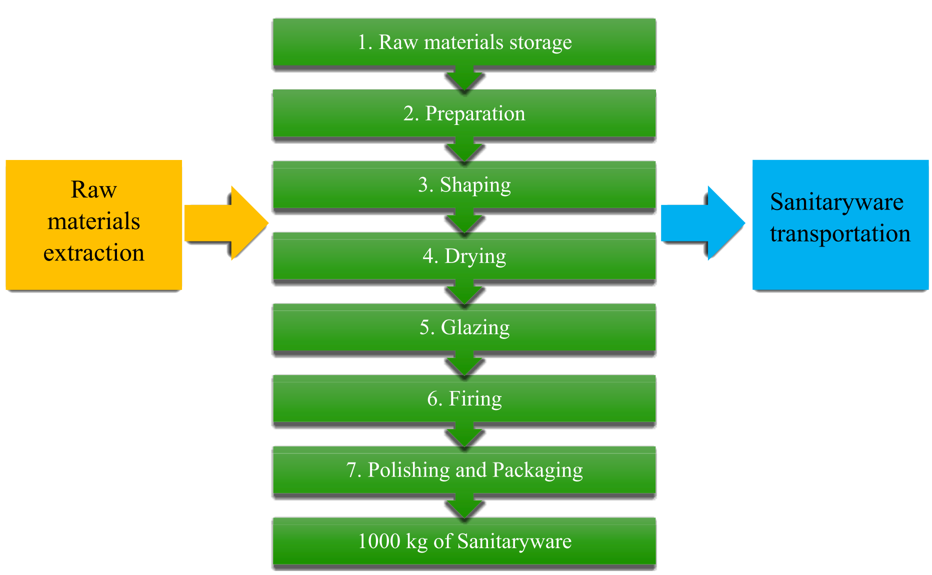


**Fig. 1.** System boundaries for sanitaryware production.

**Table 2**
Processes for Case study with 20% of natural gas saving

| Processes | Value |
|---|---|
| Clay; Kaolin; Quartz; Feldspar; Calcium Carbonate; Water; Materials for glaze and their transportation | 1742.62 kg |
| Electricity medium voltage in Italy for preparation process | $1.26*10^3$ MJ |
| Electricity medium voltage in Italy for shaping | 9.364 MJ |
| Gas Natural for drying | 17.256 $m^3$ |
| Heat from natural gas for drying | 680 MJ |
| Heat from solar collector for drying | 170 MJ |
| Electricity medium voltage in Italy for glazing | 124.848 MJ |
| Gas Natural for firing | 97.76 $m^3$ |
| Heat from natural gas for firing | 3851.84 MJ |
| Heat from solar collector for firing | 962.96 MJ |
| Electricity medium voltage in Italy for polishing and packaging | 777 MJ |

raw materials such as clay, kaolin, quartz, feldspar, and calcium carbonate, and the transportation of these materials was also considered. The various production processes were then considered, as shown in Fig. 1 and Table 1. Since the analysis aims to focus only on energy aspects, the various processes were characterized solely by these. After the extraction of raw materials and their transportation to the factory that are given by Table 1 of the Silvestri et al. paper [23], the preparation phase occurs, where the electrical consumption is $1.26*10^3$ MJ. The shaping phase is characterized by an electrical consumption of 9.364 MJ, while in the drying phase, 21.57 $m^3$ of natural gas are used, which is combusted. The combustion produces 850 MJ of energy from natural gas. In the glazing phase, 124 MJ of electrical energy are consumed, while in the firing phase, 122.2 $m^3$ of natural gas are used per 1000 kg of product, with a heat production of 4814.8 MJ. In the final phase, 777 MJ of electrical energy provided by the Italian grid are consumed.

The second case (Table 2), also known as the *Case study*, is a variation of the reference case where a solar thermal system is used to reduce the use of natural gas. The underlying assumption is to use a solar thermal system to obtain 20 % of the energy required in the drying and firing processes, thereby reducing natural gas combustion. This assumption was made basing it on the ASTEP project aims. A sketch of the proposed Case study is shown in Fig. 2. In the drying process, the volume of natural gas is reduced to 17.256 $m^3$, and consequently, the heat produced by its combustion (680 MJ) is also reduced. Instead, the remaining part of the necessary heat, 170 MJ, is from a solar thermal system reproduced by a process present in Ecoinvent that accounts for heat production due to solar collectors. The same approach is applied in the firing process, where natural gas consumption decreases from 122.2 $m^3$ to 97.76 $m^3$, and the produced heat drops from 4814.8 MJ to 3851.84 MJ. The heat produced in this phase by the solar thermal system must therefore be equal to 962.96 MJ.

All the data are secondary data from Ecoinvent database, scientific literature, and reports. Due to this reason, an uncertainty analysis is not

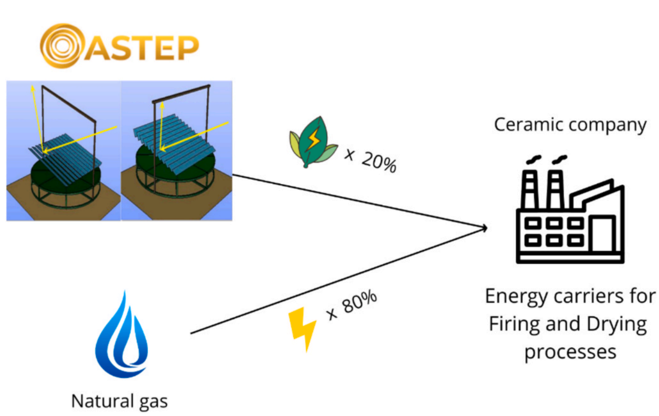


**Fig. 2.** Case study model.

performed. The chosen functional unit is 1000 kg.

### 2.3. Life cycle impact assessment

The third step is the Life Cycle Impact Assessment (LCIA). The aim of this phase is to identify and quantify the most relevant environmental issues and to convert every input from the LCI table into a contribution to these environmental issues.

In this work two different characterization methods are chosen to evaluate the results. A first comparison was made using the CML 2001 baseline method [30,31]. The CML (Center of Environmental Science of Leiden University) guide categorizes impact assessment categories into three groups: obligatory impact categories (indicators commonly used in most LCAs), additional impact categories (indicators are available but not frequently included in LCA studies), and other impact categories (no operational indicators are available, making it impossible to include them quantitatively in LCA).

When multiple methods are available for obligatory impact categories, a baseline indicator is chosen based on the principle of best available practice. These baseline indicators are category indicators at the "mid-point level" (problem-oriented approach). Baseline indicators are recommended for simplified studies.

The most important categories of the CML 2001 method are: abiotic depletion elements (AD), abiotic depletion fossil fuels (ADf)), acidification (A), eutrophication (E), global warming (GW), human toxicity (HT), ozone-layer depletion (OD) and photochemical ozone creation (POC), fresh water aquatic ecotoxicity (FWAE), marine aquatic ecotoxicity (MAE) and terrestrial ecotoxicity (TE).

A second characterization method is chosen to perform the comparison between the *Reference* and the *Study cases*. This method is the ReCiPe 2016 [32]. It includes both midpoint (problem oriented) and endpoint (damage oriented) impact categories, available for three different perspectives (individualist (I), hierarchist (H), and egalitarian (E)). At the midpoint level, 18 impact categories are addressed. It is evident that environmental mechanisms and damage models introduce uncertainty: the modeled relationships are based on current scientific understanding, which involves a degree of incompleteness and uncertainty. Three perspectives can be identified for the ReCiPe: individualist (I), hierarchist (H), and egalitarian (E). These perspectives are not intended to represent archetypes of human behavior, but rather to categorize similar assumptions and choices. For example: the Individualist perspective (I) focuses on short-term interests, emphasizes widely accepted impact types, and is optimistic about technological solutions for human adaptation. The Hierarchist perspective (H) is grounded in commonly accepted policy principles, including typical timeframes and other relevant issues. The Egalitarian perspective (E) is the most precautionary, considering the longest timeframes and including impact types that are not yet fully established but for which some preliminary evidence exists. For this study the ReCiPe midpoint method is chosen with Hierarchist perspective. This section does not include equations because the methods mentioned already cover the impact categories through complex models, which are explained in their references.

## 3. Results and Discussion

As described above, the aim of this LCA is to make a comparison between a conventional sanitaryware production and one where the use of a solar thermal plant is implemented during firing and drying processes. The functional unit considered is 1000 kg. First, a validation between the reference case and the literature given by the work of Silvestri et al. [23] is made using the CML 2001 characterization method, considering midpoint impact categories. The results of this comparison are shown in Table 3 and Fig. 3. In Fig. 3, the green color indicates a decrease and the red colour indicates an increase of the considered category in the *Case study* in respect to the *Reference case*.

The R*eference case* can be effectively validated through the literature

**Table 3**
CML 2001 results and validation.

| Impact category | Unit | *Reference case* | *Case study* | Percentage difference | Literature case [23] |
|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | $1.74*10^{-3}$ | $2.75*10^{-3}$ | +58.05 % | $1.65*10^{-2}$ |
| Abiotic depletion (fossil fuels) | MJ | $1.57*10^{4}$ | $1.40*10^{4}$ | −10.83 % | $3.49*10^{4}$ |
| Global warming (GWP100a) | kg $CO_2$ eq | $1.15*10^{3}$ | $1.10*10^{3}$ | −4.35 % | $1.81*10^{3}$ |
| Ozone layer depletion (ODP) | kg CFC-11 eq | $2.51*10^{-5}$ | $2.31*10^{-5}$ | −7.97 % | $3.31*10^{-4}$ |
| Human toxicity | kg 1,4-DB eq | $4.87*10^{3}$ | $4.98*10^{3}$ | +2.26 % | $3.84*10^{2}$ |
| Fresh water aquatic ecotox. | kg 1,4-DB eq | $2.95*10^{4}$ | $2.95*10^{4}$ | 0.00 % | $2.28*10^{2}$ |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | $1.69*10^{8}$ | $1.69*10^{8}$ | 0.00 % | $7.60*10^{5}$ |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 2.72 | 3.56 | +30.88 % | 1.62 |
| Photochemical oxidation | kg C2H4 eq | $1.38*10^{-1}$ | $1.38*10^{-1}$ | 0.00 % | $2.64*10^{-1}$ |
| Acidification | kg $SO_2$ eq | 2.65 | 2.73 | +3.02 % | 5.46 |
| Eutrophication | kg PO4— eq | $8.45*10^{-1}$ | $8.80*10^{-1}$ | +4.14 % | 1.43 |

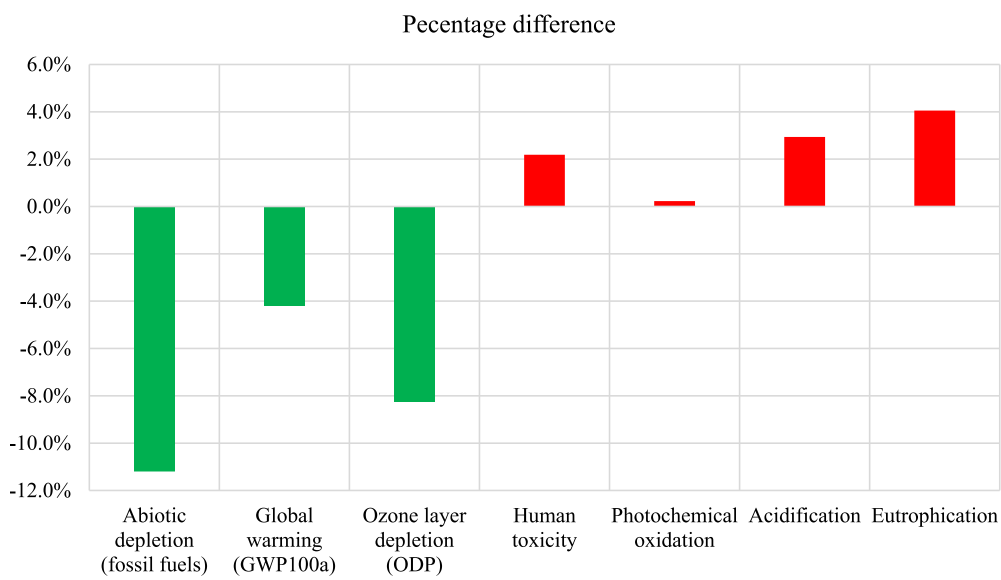


**Fig. 3.** CML percentage difference between Reference case and Case study.

because it focuses solely on energy consumption aspects, which are directly comparable to the literature case. By isolating the energy consumption impacts, such as abiotic depletion of fossil fuels and global warming potential, the reference case aligns well with the data and methodologies found in existing studies. This targeted approach ensures that the comparison is both relevant and accurate, as it assesses the same key environmental indicators without the influence of other variables that might complicate the analysis. Consequently, the validation remains robust and reliable, given that both the reference case and the literature case are assessed under similar conditions regarding energy use. For global warming potential (GWP100a), the reference case shows 1150 kg $CO_2$ equivalent, which is also lower than the 1810 kg $CO_2$ equivalent reported in the literature. These differences validate the reference case findings, as both cases are focusing on energy consumption. The lower values in the reference case indicate that the energy-related environmental impacts are comparatively lower, supporting the validity of the data when considering only energy consumption aspects.

The authors agree with the reviewers that including more comparisons from the literature would be beneficial. However, conducting an LCA comparison between different studies or systems is challenging due to variations in methodologies and functional units, as highlighted by Ardente et al. [33], who discussed the criteria for selecting a functional unit. For this reason, no additional comparisons have been included, and the authors believe that the validation already performed is sufficient to achieve the paper's objectives.

The comparison between the *Reference case* and the *Case study* reveals varying environmental impacts across different categories. For abiotic depletion (kg Sb eq), the case study has a 58 % higher impact than the reference case. In terms of abiotic depletion (fossil fuels) (MJ), the *Case study* shows a 11 % lower impact than the *Reference case*, indicating slightly more efficient fossil fuel use. The global warming potential (GWP100a) (kg $CO_2$ eq) of the *Case study* is 4 % lower than the *Reference case*, suggesting a minor reduction in carbon dioxide emissions. Ozone layer depletion (ODP) (kg CFC-11 eq) is also slightly lower in the case study by 8 %, reflecting reduced impacts on the ozone layer.

For human toxicity (kg 1,4-DB eq), the *Case study* shows a 2 % higher impact than the *Reference case*, indicating a slight increase in potential harm to human health. Freshwater aquatic ecotoxicity and marine aquatic ecotoxicity (both in kg 1,4-DB eq) remain unchanged between the *Reference case* and the *Case study*, showing no difference in impact. Terrestrial ecotoxicity (kg 1,4-DB eq) in the *Case study* is 31 % higher than in the *Reference case*, indicating a greater impact on terrestrial ecosystems.

Photochemical oxidation (kg C2H4 eq) shows no difference between the two cases, remaining the same. Acidification (kg $SO_2$ eq) in the *Case study* is 3 % higher than in the *Reference case*, suggesting a slightly greater potential for acid rain formation. Finally, eutrophication (kg $PO_4$— eq) is 4 % higher in the *Case study* compared to the *Reference case*, indicating a modest increase in nutrient enrichment impacts. Overall, the *Case study* generally exhibits slightly higher impacts in most categories compared to the R*eference case*, except for abiotic depletion (fossil fuels) and global warming potential, where it shows a slight reduction, and several categories where impacts are unchanged.

Secondly, another comparison between the *Reference* and *Case study* was made using ReCiPe 2016 midpoint method. The results of this analysis are reported in Table 4 and Fig. 4. The description of Fig. 4 is the same as the Fig. 3, in this case the Recipe method is shown.

The comparison between the R*eference case* and the *Case study* shows some notable differences across several environmental impact categories. For global warming (kg $CO_2$ eq), the *Case study* has a 4.2 % lower impact than the *Reference case*, indicating slightly reduced carbon emissions. In stratospheric ozone depletion (kg CFC11 eq), the *Case study* shows a marginally lower impact by 0.5 %. Ionizing radiation (kBq Co-60 eq) is 1.7 % higher in the case study, suggesting a slight increase in radiation impact. The ozone formation for human health (kg NOx eq) and terrestrial ecosystems (kg NOx eq) categories show minimal differences, with the *Case study* being 0.9 % and 0.8 % lower, respectively.

Fine particulate matter formation (kg PM2.5 eq) is 4 % higher in the case study, indicating increased impacts on air quality. Terrestrial acidification (kg $SO_2$ eq) and freshwater eutrophication (kg P eq) are higher in the case study by 2.8 % and 7.1 %, respectively. Marine eutrophication (kg N eq) is 2.5 % higher in the case study, reflecting increased nutrient runoff into marine environments. Notably, terrestrial ecotoxicity (kg 1,4-DCB) in the case study is 32.4 % higher, indicating a significantly greater impact on land ecosystems, while freshwater ecotoxicity and marine ecotoxicity are 2.4 % and 2.2 % higher, respectively.

For human carcinogenic toxicity and non-carcinogenic toxicity (kg 1,4-DCB), the *Case study* shows 6.4 % and 1.9 % higher impacts, respectively. Land use (m2a crop eq) in the C*ase study* is 3.5 % higher, suggesting increased land occupation. Mineral resource scarcity (kg Cu eq) is 4.4 % higher in the *Case study*, while fossil resource scarcity (kg oil eq) is 11.3 % lower, indicating better fossil resource efficiency. Finally, water consumption ($m^3$) is slightly higher by 0.8 % in the case study. Overall, the *Case study* generally shows slight increases in several impact categories compared to the *Reference case*, with some notable exceptions in fossil resource scarcity and global warming potential.

**Table 4**
Recipe 2016.

| Impact category | Unit | *Reference case* | *Case study* | Percentage difference |
|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | $1.18*10^3$ | $1.13*10^3$ | 4.24 % |
| Stratospheric ozone depletion | kg CFC11 eq | $6.25*10^{-4}$ | $6.22*10^{-4}$ | 0.48 % |
| Ionizing radiation | kBq Co-60 eq | $5.80*10^1$ | $5.90*10^1$ | −1.72 % |
| Ozone formation, Human health | kg NOx eq | 2.24 | 2.22 | 0.89 % |
| Fine particulate matter formation | kg PM2.5 eq | $8.01*10^{-1}$ | $8.33*10^{-1}$ | −4.00 % |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 2.34 | 2.32 | 0.85 % |
| Terrestrial acidification | kg $SO_2$ eq | 2.11 | 2.17 | −2.84 % |
| Freshwater eutrophication | kg P eq | $1.82*10^{-1}$ | $1.95*10^{-1}$ | −7.14 % |
| Marine eutrophication | kg N eq | $1.98*10^{-2}$ | $2.03*10^{-2}$ | −2.53 % |
| Terrestrial ecotoxicity | kg 1,4-DCB | $1.36*10^3$ | $1.80*10^3$ | −32.35 % |
| Freshwater ecotoxicity | kg 1,4-DCB | $2.06*10^2$ | $2.11*10^2$ | −2.43 % |
| Marine ecotoxicity | kg 1,4-DCB | $2.68*10^2$ | $2.74*10^2$ | −2.24 % |
| Human carcinogenic toxicity | kg 1,4-DCB | $5.64*10^1$ | $6.00*10^1$ | −6.38 % |
| Human non-carcinogenic toxicity | kg 1,4-DCB | $3.66*10^3$ | $3.73*10^3$ | −1.91 % |
| Land use | m2a crop eq | $1.41*10^1$ | $1.46*10^1$ | −3.55 % |
| Mineral resource scarcity | kg Cu eq | 7.57 | 7.90 | −4.36 % |
| Fossil resource scarcity | kg oil eq | $3.79*10^2$ | $3.36*10^2$ | 11.35 % |
| Water consumption | $m^3$ | 7.73 | 7.79 | −0.78 % |

The amount of GWP reduction due to use of the solar thermal system increases when we consider not only 1000 kg of product, but the entire product volume of the ceramic in Italy that is equal to 3.6 million of units. If, as considered in this study, the solar thermal system supplies only 20 % of energy during the drying and firing process, it is possible to save 180 ton of $CO_2$ emissions considering the overall Italian sanitaryware production.

## 4. Conclusion

This study evaluated the environmental impact of implementing an innovative solar thermal technology, specifically the SunDial system, in the Italian ceramic industry through a Life Cycle Assessment (LCA). The primary goal was to compare the environmental effects of a conventional sanitaryware production process using natural gas with a more sustainable approach that integrates solar thermal energy for the drying and firing stages. The principal assumption that was made is to consider only the energy aspects of the sanitaryware production processes. The findings of this study demonstrate a reduction in global warming potential and fossil resource scarcity when the solar thermal system is employed, achieving an approximate 4 % reduction in $CO_2$ emissions considering a functional unit equal to 1000 kg. This aligns with the European Union's targets for renewable energy integration and highlights the potential benefits of solar thermal technology in reducing the carbon footprint of industrial processes. However, the study also identified slight increases in other environmental impact categories, such as terrestrial ecotoxicity, acidification, and particulate matter formation, when using the solar collector system. These increases are likely due to the indirect environmental burdens associated with the manufacturing, installation, and maintenance of the solar thermal system.

Overall, while the introduction of solar thermal technology in the ceramic industry can contribute to significant reductions in greenhouse gas emissions and fossil fuel use, it is essential to consider a balanced view of its environmental impacts. Further research is recommended to optimize the use of solar thermal technology, investigate alternative energy mixes, and explore additional sustainable practices to fully leverage the environmental benefits of renewable energy in industrial applications. By doing so, the ceramic industry can move closer to achieving both economic and environmental sustainability, aligning with broader global efforts to reduce carbon footprints and promote cleaner energy solutions.

Based on the data presented, it is possible to save 180 tons of $CO_2$ emissions across the entire Italian sanitaryware production sector. By simultaneously enhancing the thermal efficiency of the process and increasing the use of renewable energy sources, it will be possible to meet the European Union's decarbonization targets for industries.

## CRediT authorship contribution statement

**Bernardo Buonomo:** Supervision, Conceptualization. **Oronzio Manca:** Supervision, Conceptualization. **Sergio Nardini:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Renato Elpidio Plomitallo:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lisa Gobio-Thomas:** Writing – review & editing, Supervision, Conceptualization. **Valentina Stojceska:** Writing – review & editing, Supervision, Methodology, Conceptualization.

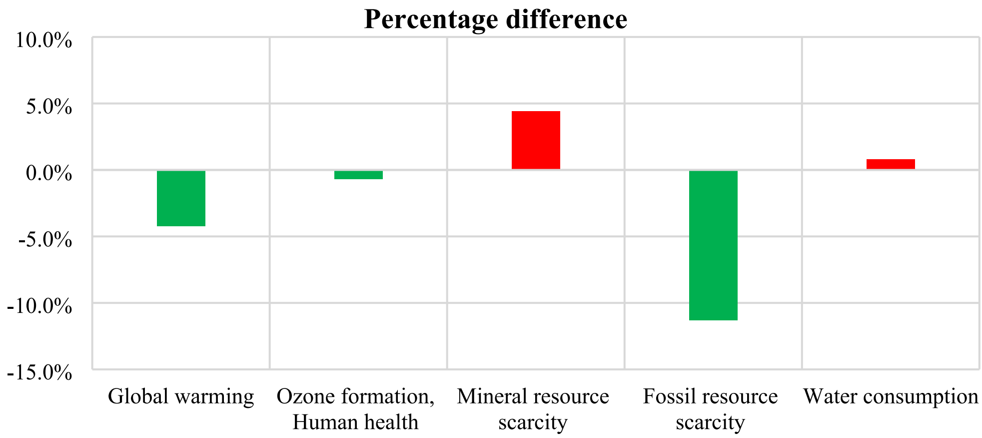


**Fig. 4.** Recipe 2016 percentage difference between Reference case and Case study.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sergio Nardini reports financial support was provided by European Union's Horizon 2020 Research and Innovative Programme. Renato Elpidio Plomitallo reports a relationship with University of Campania Luigi Vanvitelli that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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