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Life cycle assessment of a new industrial process for sustainable construction materials

Adelfio Luca [a,*], Giallanza Antonio [b], La Scalia Giada [a], La Fata Concetta Manuela [a], Micale Rosa [b]

[a] Department of Engineering, University of Palermo, Viale delle Scienze, Bld 8, 90128 Palermo, Italy
[b] Department of Engineering, University of Messina, Contrada di Dio, 98166 Messina, Italy

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ABSTRACT

One of the key sectors for the green transition of European countries is construction, that is more and more asked to evolve towards innovative ecological binders and green cost-effective processes. The construction sector is highly energy intensive, and the cement production is one of the main sources of environmental pollution in the world. In this regard, GeoPolymers (GP) seem to be promising for a sustainable replacement of cementitious materials. Therefore, the Life Cycle Assessment (LCA) of the industrial production of different formulations of Geopolymer Concrete (GC) was performed in this study after scaling up the Life Cycle Inventory (LCI) from a laboratory scale to an industrial one. Based on LCA results, the Global Warming Potential (GWP) indicator demonstrated a lower greenhouse gas emission of the proposed GC production in respect to the CC manufacturing process, while no significant difference was observed in the GWP scores of the considered GC formulations when referring to the functional unit. Nevertheless, the usage of the innovative GC formulations, on an industrial scale, would avoid a significant reduction of sand and kaolin extracted, with a consequent decrease on the environmental impact. Finally, the economic assessment showed that the combined production of thermal and electrical energy by a cogeneration system could provide a significant cost reduction when the percentage of electricity fed into the public network is higher than 39%.

1. Introduction

Ongoing climate change and ecological degradation are challenging for the whole world. Accordingly, Europe adopted the New Green Deal as a strategy to become a competitive resource-efficient economy by reducing gas emissions and carbon footprint. This strategy includes circular economy programs oriented towards the Life Cycle Engineering (LCE) of products, thus saving natural resources and increasing industrial wastes reuse (Laurent et al., 2019). The construction industry is recognized as one of the least green sectors (Luangcharoenrat et al., 2019; Tafesse et al., 2022), and the need for a more sustainable use of natural resources has been also recognized at the EU level by the Raw Material Initiative (Policy and Strategy for Raw Materials Internal Market, 2020). Accordingly, the European Green Deal (2020) refers to construction as one of the key sectors for the green transition of European countries, meaningfully contributing to the carbon neutrality that must be achieved by 2050 (New Circular Economy Action Plan, 2020). Adopted in March 2020, the New Action Plan for the circular economy (2020) also highlights the importance of products LCE, aimed at reducing the consumption of raw materials and preventing wastes along the entire life cycle of products (Hauschild et al., 2017). So far, construction has been responsible of several adverse environmental effects, such as large consumption of energy, high use of non-renewable raw materials, greenhouse gas emissions, and dust pollution (Solís-Guzmán et al., 2013; Saeli et al., 2019a; Tomatis et al., 2020; Peng et al., 2021).

With this recognition, the production of alternative construction materials needs to be further investigated to mitigate the environmental impact of the construction sector (de Carvalho Araújo et al., 2019; Saeli et al., 2020b; Revuelta-Aramburu et al., 2020). Previous studies on

Abbreviations: BFA, Biomass fly ash; CalS, Calcareous sludge; CC, Conventional concrete; CHP, Cogeneration system; ELCD, European reference Life Cycle Database; GP, Geopolymer; GC, Geopolymer concrete; GWP, Global warming potential; LCA, Life cycle assessment; LCI, Life cycle inventory; MK, Metakaolin; NPV, Net present value; TCI, Total capital investment; TOC, Total operating cost.

* Corresponding author.
E-mail addresses: luca.adelfio@unipa.it (A. Luca), antonio.giallanza@unime.it (G. Antonio), giada.lascalia@unipa.it (L. Scalia Giada), concettamanuela.lafata@unipa.it (L. Fata Concetta Manuela), rosa.micale@unime.it (M. Rosa).

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innovative construction materials have already demonstrated the environmental performance advantages of Geopolymer Concrete (GC) over Conventional Concrete (CC) when used as alternative cementitious materials (Nguyen et al., 2018; Saeli et al. 2019b, Saeli et al. 2020a). GCs are inorganic binders consisting of a solid alumina-silicate reactive source, often Metakaolin (MK), which interacts with a solution to make a stable gel (Davidovits, 1979). Therefore, the present study investigated a new GC obtained by the reuse of the Biomass Fly Ash (BFA) produced by a Portuguese paper-pulp industry and used to partially replace MK. Based on the production process data available on a lab scale, the energy consumption due to the innovative GC production process was calculated to predict its environmental performance on an industrial scale. Nowadays, emerging production processes are more and more carried out on a lab scale in a first instance, aiming to acquire useful information to verify and optimize their industrial sustainability by a preliminary Life Cycle Assessment (LCA) analysis (Shibasaki et al., 2007). Actually, LCA addresses to the assessment of the potential environmental impact of an industrial process, aiming to make proper decisions to improve its sustainability (ISO 14040, 2006). Despite traditional LCA deals with well-defined and mature manufacturing processes, recent developments of LCA focus on new processes which are not yet industrially optimized in terms of energy consumption, environmental impact, and costs (Piccinno et al., 2016). Obviously, the lab scale of a process is significantly smaller than the industrial one, and this diversity results in large differences in processes efficiencies and operating conditions (Caduff et al., 2011). Nevertheless, data obtained on a lab scale may be used to perform preliminary LCA studies to validate early industrial design optimization based on environmental sustainability (Cucurachi et al., 2018). LCA may be implemented in different industrial sectors to assess the environmental footprint of production systems, such as agricultural (Mostashari-Rad et al., 2020) or biodiesel productions (Nabavi-Pelesaraei et al., 2022a). Moreover, different literature contributions use the LCA approach to predict the environmental impact of different waste management scenarios, in order to optimize systems efficiency and to minimize the most impacting factors (Nabavi-Pelesaraei et al., 2017; Nabavi-Pelesaraei et al., 2022b). With relation to the construction industry, other studies have already performed LCA to quantify the environmental burden of different building material formulations (Zang et Wang, 2017; Garcia-Ceballos et al., 2018; La Scalia et al., 2021b). Therefore, the best GC formulations proposed by Saeli et al. (2020a) on a lab scale were considered in the present study, and preliminary LCA of their industrial production was then performed based on La Scalia et al. (2021a), scaling up the Life Cycle Inventory (LCI) from lab to industrial scales. Afterwards, the GC environmental performance was compared with the one of the CC using the Global Warming Potential (GWP) indicator. Three different scenarios for the GC industrial production were considered in terms of energy supply. Finally, a preliminary economic analysis was carried out for every scenario based on the related investment and operation costs.

2. Materials and methods

Using LCA, the present study aimed to evaluate the environmental impact of the industrial production of GC described in La Scalia et al. (2021a). LCA was performed in accordance with the ISO guidelines 14040/14044 (ISO 14040, 2006), and the Simapro software (https://simapro.com/) was used to carry out the analysis. LCI was based on a referenced laboratory production system, and the industrial scale up data were provided in previous studies (Saeli et al, 2020a; La Scalia et al.,2021a). LCI data were obtained by literature contributions, Ecoinvent database (https://ecoinvent.org/the-ecoinvent-database/) and European reference Life Cycle Database (ELCD) (https://lca.jrc.ec.europa.eu). The adopted life cycle impact assessment method was based on GWP, which allowed to compare the climate effect of different emissions based on the kg CO_2 eq.

2.1. Goal and scope

The environmental burden of GC production system was analysed by its comparison with the one of CC. The chosen functional unit referred to the production of 1 m^3 of concrete addressed to the construction sector. As shown in Fig. 1, system boundaries included raw materials extraction or production, transport, and manufacturing processes. Since the analysed production system comprises the reuse of wastes deriving from another industrial sector, the "cut-off system model" was used as multi-functional processes approach, which considers the waste or recyclable materials cut off from the primary production system and free from environmental burdens. As concerns the logistic issues due to the waste involved in the present study, the GC production plant was assumed to be located at the waste production site.

2.2. Geopolymer concrete mix design

The environmental impact of three different GC formulations was investigated. Differing in the percentage of the reused waste derived from the paper-pulp industry, the main constituents of the three GC formulations are shown in Table 1.

2.3. Life Cycle inventory (LCI)

LCI was based on the industrial scale-up, where every laboratory process was analysed to select the best technological solution for mass production. In this regard, some changes in respect to the laboratory-scale processes were necessary, owing to the different production volume and the higher production capacity required. To consider all factors that may influence LCI, the inventory analysis was based on the study proposed by Piccinno et al. (2016). In particular, Authors provided a framework to scale up production processes for LCA studies when only laboratory data are available.

For every process and raw material, the following sections summarize the LCI scale up procedure.

2.3.1. Production system and raw materials

The production chain of GC is presented in this section, and all raw materials are listed with the aim to provide a structured path for the LCI procedure. Fig. 2 shows the flow chart of the production system, where materials and processes are represented by rectangular boxes, with or without rounded edges respectively. In addition, continuous lines refer to the manufacturing flow of reference materials, while dot lines indicate the new flows due to the production of aggregates using wastes.

Processes involved in the GC production system can be classified in two categories. The first one includes processes that need heat (i.e., calcination and drying), while the second one refers to mixing, grinding and filtering processes where mechanical energy is necessary.

As regards the description of raw materials, only the main useful characteristics for LCA purposes are listed below (Table 2). For more details (e.g., mechanical properties and chemical composition), readers may refer to La Scalia et al. (2021a). Table 2 also shows the LCI reference for the extraction or production of the raw materials involved in the production system.

As aforementioned in Section 1, the GC production system is hypothesized to be located in Portugal alike the considered paper mill that produces the reused waste. The expected production capacity of the plant is based on the annual waste production rate of the Kraft process carried out by the paper mill. The amount of wastes produced per year are shown in Table 3.

The hypothesis of processing the overall quantity of wastes in two shifts of 8 h for 220 days per year was considered. As a result, the production capacity of the proposed manufacturing system is about 177,778 tons per year, with a daily production rate of about 808 tons. Table 4 summarizes the amount of raw materials needed by the different formulations of GC.

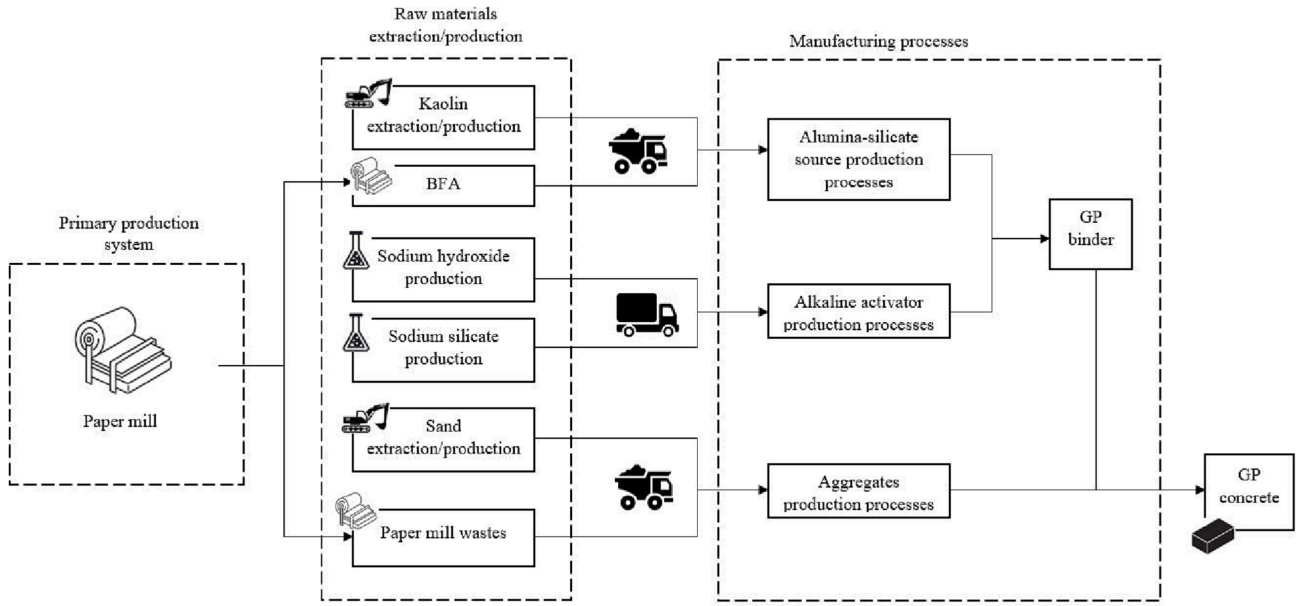

Fig. 1. System boundaries of GC production.

Table 1
Analysed GC formulations (La Scalia et al., 2021a).

Formulation n.	Alumino-silicate source	Activating solution	Binder/ aggregate ratio	Wastes used as filler typology	wt%
REF − 1	70% wt. BFA + 30% wt. MK	25% wt. Na hydroxide + 75% wt. Na silicate	1:3	–	0.0%
2				Cals + Drigs + Grets	5%
3				Cals + Drigs + Grets + BFA	7.5%

2.3.2. Metakaolin production

Metakaolin is obtained from the calcination process of kaolin as previously reported in Fig. 2. It consists of a heat treatment that typically takes place between 600 °C and 800 °C, during which the kaolin loses about 14% of its mass due to the hydroxylation process (Rashad, 2013). LCI of the kaolin extraction was based on ELCD database. The calcination process was modelled according to the heat transfer theory, that provides the equation (1) for the process heat (Q_p) computation.

$$Q_p = Q_{heat} + Q_{keep\ temp} \tag{1}$$

In (1), Q_{heat} and $Q_{keep\ temp}$ are the required heat to bring the kaolin to the process temperature and the needed heat to keep the same process temperature over the calcination time respectively. Q_{heat} and $Q_{keep\ temp}$ are calculated by the equations (2), (3).

$$Q_{heat} = c_p M_c (T_p - T_o) \tag{2}$$

$$Q_{keeptemp} = \frac{Ak(T_p - T_o)}{s} t_p \tag{3}$$

Based on the literature in the field (Rashad, 2013; Michot et al., 2008), a process temperature T_p equal to 750 °C and a process time t_p equal to 15 h were chosen in the present analysis. The room temperature (T_o) was set to 20 °C. The kaolin specific heat ($c_p =$ 1.134 kJ/(kg·°C)) was obtained by Michot et al. (2008), who performed experimental tests to investigate the specific heat trend of kaolin as a temperature function. The parameters k and s are the thermal conductivity of the insulation material and the insulation thickness respectively. According to Piccinno et al. (2016), the calcination process was assumed to be carried out in an industrial oven of stainless steel (with negligible thermal resistance), and with a layer of glass fiber (k = 0.042 W/(m·K)) whose thickness s was equal to 0.075 m. Assuming an oven volume equal to 11 m^3, the parameter A (27.381 m^2) is the surface area of the oven. M_c (9.9 tons) is the kaolin mass, considering an apparent density equal to 1.1 tons/m^3, as reported by kaolin producers. In fact, the metakaolin production capacity needed is about 1.7 tons per hour, assuming that the expected production rate of the BFA is around 3.98 tons per hour (see Section 2.3.1). To achieve these production targets, three industrial ovens are required.

After obtaining the calcined metakaolin, the grinding energy ($E_{grinding}$) needed to reduce the mineral granulometry can be calculated by the equation (4), provided by Bond (1951).

$$E_{grinding} = 10 \cdot w_i \cdot \left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}} \right) \tag{4}$$

In (4), D and d are the initial and final mean diameters of metakaolin particles respectively. w_i is the so called "work index" of the material i, determined by grinding laboratory tests depending on the given material. The quartz work index (12.77 kWh/tc[1]) (Bond, 1951) was used because it is the main mineral component of metakaolin. D is set to 8.70 µm, that is the most common average diameter of metakaolin particles calcined at 750 °C (Duxson, 2006), while d is set to 3 µm, according to the common size of the marketed metakaolin.

The computation of the filtration energy consumption is affected by several parameters, among which the particle size is the most important. Alt (2000) provided an estimation of required energy for the filter process in the range [1, 10] kWh per ton of dry material.

2.3.3. Alkaline activator production

The alkaline activator was obtained in two steps. Firstly, the anhydrous sodium hydroxide was dissolved in water with a concentration equal to 10 M. To this aim, an industrial mechanical mixer was used for 12 h at variable speed (≤50 rpm). Afterwards, the sodium hydroxide solution and the sodium silicate were mixed for 5 min at variable speed (<50 rpm). The designed solution mass ratio sodium hydroxide

[1] tc is the american ton (or short ton) which is equivalent to 907.18 metric ton.

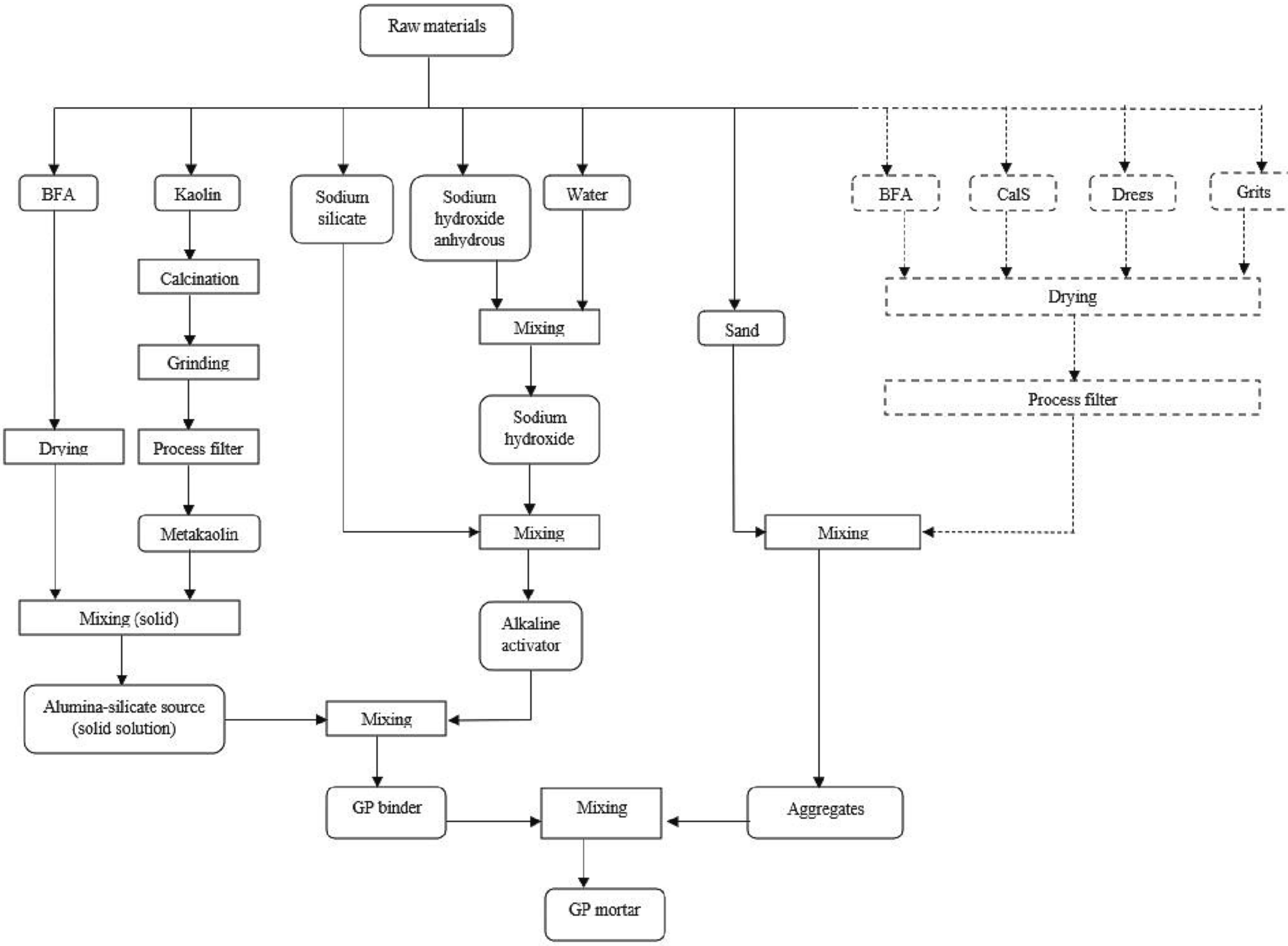

Fig. 2. Flow chart of the GC production system (La Scalia et al.,2021a).

solution/sodium silicate was set to 1/3, and its LCI was based on the Ecoinvent database. In particular, the sodium hydroxide is manufactured by the chlor-alkali process. Among technologies available for the chlor-alkali process (i.e., membrane, diaphragm, and mercury cells), the mercury cells electrolysis was used in this paper because of its widespread usage in the European chemical plants (Althaus et al., 2007). On an industrial scale, the mixing energy E_{mix} (J) was computed by the equation (5), according to Piccinno et al. (2016).

$$E_{mix} = \frac{N_p \cdot \rho_{mix} \cdot N^3 \cdot id^5 \cdot t}{\eta_{mix}} \quad (5)$$

Table 5 synthetizes the meaning and the value of parameters involved in (5).

Parameters related to the mixer were the ones suggested by Piccinno et al. (2016), while mix densities were calculated considering the solutions properties. Assuming a conservative approach, the rotational speed was 50 rpm.

2.3.4. Aggregates

The aggregates composition depends on the considered formulation (see Table 1). The reference formulation only consists of sand, while the other two include different percentages of waste. LCI of sand is based on the Ecoinvent database. As already mentioned in Section 2.1, wastes derived from the Portuguese paper-pulp industry were considered burden free, as the "cut-off system model" was used. Before being mixed with the sand, wastes were dried for 1 h by a continuous industrial oven at 105 °C in order to force the removal of the residual moisture of raw materials. The heating energy required for the drying process was computed by the equations (1)-(3). The waste specific heat (c_p = 1.246 kJ/(kg·°C) was calculated according to Mehmood et al. (2012) who suggested a method for the calculation of the specific heat of biomass powders based on the constituent weight percentages. The mass of wastes to be dried (M = 6,705 kg) was calculated based on the expected production capacity of the GC manufacturing system (see Section 2.3.1). T_p and T_o values were set to 105 °C and 20 °C respectively. A drying oven with a volume 10% larger than the one of the material to be dried was assumed, and the glass fiber was chosen as insulating material (k = 0.042 W/(m·K); s = 0.010 m; A = 12.58 m^3).

2.3.5. Transport inventory

LCI of transport includes all data about the distance between the raw material suppliers and the GC production site. The GC production plant was assumed to be located where wastes are produced, and the average distance between the production plant and the raw material suppliers was computed, only taking into account the location of the major local market dealers. Table 6 shows the transport inventory for GC mixes.

2.4. Analysed scenarios

Aiming to compare the environmental performance of different power supply, three different scenarios (i.e., S1, S2 and S3) were considered in the present study (Table 7).

In the first scenario (i.e., S1), the overall production system was powered by electricity, and electric ovens were used for the drying (WK

Table 2
Raw material features.

Raw material	Main feature	LCI reference
Kaolin	White clay raw material from which Metakaolin is obtained.	ELCD database
Biomass fly ash (BFA)	Waste primary used to substitute the metakaolin in the binder manufacturing due to its high content of alunimo-silicates. The weight ratio between BFA and metakaolin is 70/30 %, and in some cases, BFA is also used as a filler with other wastes.	Burden free
Grits	Inorganic alkali granular waste stream of the chemical liquor recovery in the wood digestion circuit.	Burden free
Calcareous sludge (CalS)	Inorganic alkali waste stream of the chemical recovery circuit. It is furnished in a powdery sludge whose main component is calcium carbonate.	Burden free
Dregs	Insoluble sludge produced during the chemical liquor clarification that mainly contains carbonates of sodium and calcium, and other compounds deriving from the smelt.	Burden free
Sodium hydroxide anhydrous	Chemical product used to prepare a sodium hydroxide solution in water with a 10 M concentration.	Ecoinvent database
Sodium silicate	Chemical product used to prepare the alkaline activator after mixing with the sodium hydroxide solution. The alkaline activator composition consists of 25% of sodium hydroxide solution and 75% of sodium silicate.	Ecoinvent database
Sand	Silica based natural product used as aggregate in the GP mortar.	Ecoinvent database
Water	Aqueduct water	Ecoinvent database

Table 3
Waste per year produced by the paper mill.

Waste	tons/year
Dregs + Grits	4,490
BFA	16,878
Cals	2,234

Table 4
Amount of raw materials for the different formulations of GC.

Raw material	Amount [tons/year]		
BFA	14,000		
MK	6,000		
Sodium hydroxide	1,746		
Sodium silicate	18,333		
Water	4,365		
	Ref − 1	2	3
Sand	133,333	126,666	123,333
Filler	0	6,667	10,000

10,000 model, Nabertherm Italia, Italy) and calcination processes (customized model made by Thermal Engineering, Italy) respectively. In S2, the calcination process was performed by gas ovens (customized model made by Thermal Engineering, Italy), while the drying process of wastes was carried out by means of a boiler (GBP 300 model, Garioni Naval - Svecom Pe S.r.l., Italy) that feeds a suitable oven. On the other hand, the other processes were powered by electricity. Finally, a cogeneration system (CHP) was considered in S3 to exploit the combined production of heat and electricity to meet both the thermal and electrical needs of the remainder processes and plant services, increasing the system's efficiency and reducing the environmental load as a result.

Table 5
Mixing parameters.

Parameter	Meaning	Value
N_p	Dimensionless number depending on the type of mixer	0.79
ρ_{mix}	Mix density	NaOH solution: 1322.8 kg/m^3 Alkaline activator: 2130.7 kg/m^3
N	Rotational speed	50 rpm
id	Impeller diameter	0.373 m
t	Mixing time	NaOH solution: 12 h Alkaline activator: 5 min
n_{mix}	Mixing efficiency	0.90

Table 6
Transport inventory.

Raw material	Average distance
Kaolin	200 km
Biomass fly ash (BFA)	0 km
Grits	0 km
Calcareous sludge (CalS)	0 km
Dregs	0 km
Sodium hydroxide anhydrous	150 km
Sodium silicate	150 km
Sand	50 km

Table 7
Power supply scenarios.

	SCENARIO S1	S2	S3
Power Supply	Electric	Electric + Gas oven + Steam	Cogeneration

In particular, the cogeneration plant was supposed to be equipped by an internal combustion engine, fuelled by natural gas (CG132-12 model, CGT Spa, Italy), with an electrical power produced equal to 515 kW, and electrical and thermal efficiencies of 43.2% and 43.1% respectively. The exhausted gases from the cogeneration plant were used to pre-heat the kaolin, also providing about 50% of the thermal energy required by the calcination process. The remaining energy portion was supplied by an auxiliary gas burner (NG 550 model, CIB Unigas, Italy), while the heat recovered from the lubricating oil circuit was used to power the drying process of wastes deriving from the paper mill.

Since the expected location of the plant is in Portugal, the electric generation mix (i.e. percentages of electricity generated by different energy sources) of Portugal was considered for the LCI of the electric power supply. On the other hand, data inventory of the heat energy needed for the scenarios S2 and S3 was based on the machine data plates. The electricity produced by the cogeneration plant was considered as "avoided product", i.e. a secondary product that generates a useful effect on the environment. The same approach was used for the excess of thermal energy produced by CHP, which can be used for secondary plant services (e.g., heating service).

2.5. Economic analysis

A preliminary economic evaluation was carried out based on Total Capital Investment (TCI, €), Total Operating Cost (TOC, €/year), and Revenues arising from both the energy saving and possible sale of electricity (R, €/year) (the latter only in the cogeneration scenario S3). The economic comparison among the three different scenarios was based on the Net Present Value (NPV), assuming an interest rate of 5% and a duration of the investment of 10 years. By selling the new product, the solution having the lowest NPV indicates the best scenario. For the scenario S1, TCI costs comprised the cost incurred for the ovens used for the calcination and the drying processes, while TOC costs were calculated considering the electric energy. For the scenario S2, TCI included the costs of the gas ovens as well as the cost of the boiler and the oven respectively used in the calcination and drying processes, while TOC costs were computed by considering the annual fuel and electric energy consumption. For the scenario S3, TCI were computed as the sum of costs incurred for the cogeneration system, the auxiliary burner and the ovens used for the calcination and drying process respectively. TOC considered the fuel consumption to power the endothermic engine of the cogeneration system. In S3, a revenue from the self-produced electricity was also considered. TCI and TOC are reported in Table 8 for every scenario.

In S2, the cost of the calcination ovens is equal to the one of S1. In fact, the manufacturer stated that the different heating element does not lead to a significant cost variation. As concerns the drying process, ovens used in S2 and S3 should be cheaper than the one of S1. In fact, they are not equipped by the heating element, while being powered by the steam (S2) and the heat recovered from CHP (S3) respectively. However, the same cost of the drying oven used in S1 was pessimistically assumed. The same assumption was considered for the calcination ovens of the scenario S3, whose cost was set equal to the one of calcination ovens of S1 (or S2).

Both the annual electricity and natural gas consumptions were obtained from the energy flows returned by the Simapro software, where the unit costs were set alike the average European prices differentiated by consumption bands for industrial consumers for the year 2020 (ARERA, 2021). The negative value of electricity consumption for the third scenario represents the net quantity of electricity that was assumed to be sold to the public network.

3. Results and discussion:

3.1. GWP comparison between GC and CC productions

The environmental impact of the proposed GC production system was compared with the one of CC characterized by the same resistance class. The compressive mechanical strength of the three formulations analysed (see Table 1) falls within the range [21, 29] MPa (La Scalia et al., 2021a). Therefore, an average LCI related to the production of 1 m^3 of CC with a resistance class equal to 20 MPa was selected for the comparison purpose. Included into the Ecoinvent database, the dataset involved the mean data of the whole manufacturing process to produce ready-mixed concrete. Referring to the scenario S1, Table 9 summarizes the material composition to produce the functional unit (i.e. 1 m^3) of concrete as well as the GWP results for every GC formulation and for the selected CC.

GWP results show that the GC production system proposed by La Scalia et al. (2021a) could provide a lower value (i.e. 22.5%) of CO_2 equivalent emissions than the CC production. Although this result seems to be promising, the environmental benefit may be even higher since the computation of energy consumptions was based on pessimistic assumptions. On the other hand, the GWP score of the three formulations does not show any significant difference for a functional unit of 1 m^3, as the amount of filler used to replace the sand in formulations (2) and (3) is minimal in respect to the total weight. However, the advantage of using paper-pulp wastes as a filler lies in the natural resources saving, if a GC mass production is considered. The formulation (3) saves a quantity of sand of about 100 kg per m^3 of GC produced. Referring to the expected production data (Table 5), the extraction of 10,000 tons of sand could be avoided.

In order to detect the most critical processes of the GC production system, a contribution analysis was performed. The environmental burden of each process was assessed in respect to the overall impact, with the aim of identifying adequate measures to mitigate the environmental impact of the life cycle. Referring to the formulation (3), characterized by the highest amount of waste used, Fig. 3 shows the environmental impact contribution in terms of kg of CO_2 eq released to produce 1 m^3 of GC in the scenario S1.

The sodium silicate production has the most significant contribution on the overall environmental impact. With a GWP value equal to 184.7 kg of CO_2 eq, it represents 72.7% of the total environmental burden, generating about 1 kg of CO_2 eq for every kg of sodium silicate produced. The GWP score of the sodium hydroxide solution is equal to 17.1 kg of CO_2 eq (6.7%), thus representing about 80% of the overall impact along with the sodium silicate contribution. This result is consistent with many previous studies (Salas et al., 2018; Dal Pozzo et al., 2019), which identified the main environmental limitation of GC production in the use of large quantities of alkaline activator. In particular, the sodium silicate manufacturing processes are very energy intensive. As regards the GWP score, the incidence of energy use on its production is higher than 65%.

The environmental impact of sand use consists of 12.7% (32.3 kg of CO_2 eq), mainly represented by sand extraction. Hence, the natural resource extraction is confirmed to be one of the main environmental problems of the construction sector. The environmental load generated by MK production is equal to 6.5% (16.6 kg of CO_2 eq), mainly composed by the contributions of calcination process (6.7 kg of CO_2 eq), kaolin production (6.7 kg of CO_2 eq) and transport (2 kg of CO_2 eq). On the other hand, BFA and other wastes do not have significant environmental load, as their production includes only the impact of the drying process (see Table 2).

Fig. 4 shows the results on the GWP comparison among the three energy supply scenarios (see Table 7).

Table 8
TCI and TOC for every scenario.

		Scenario S1	Scenario S2	Scenario S3
Calcination ovens		240,000 €	240,000 €	240,000€
Drying oven		60,000 €	60,000 €	60,000 €
Boiler		/	20,500	/
Cogeneration plant		/	/	800,000 €
Auxiliary gas burner		/	/	15,000 €
TIC		300,000 €	320,500 €	1,090,000 €
Electric energy	Consumption	2,767 MWh/year	364 MWh/year	−1,439 MWh/year
	Unit cost	131.7 €/MWh	183.2 €/MWh	153 €/MWh
Natural gas	Consumption	/	250,700 m^3	486,000 m^3
	Unit cost	/	0.507 €/m^3	0.370 €/m^3
TOC	Electric energy	364,413.9 €/year	66,684.8 €/year	−220,167 €/year
	Natural gas	/	127,140.9 €/year	179,917.2 €/year

Table 9
Material composition of each formulation and GWP in the scenario S1.

Component (kg/m^3)	Ref − 1	2	3	CC
BFA	144	150	152	–
Metakaolin	62	65	66	–
Sodium Hydroxide	18	20	21	–
Sodium silicate	189	190	190	–
Water	45	48	48	195
Sand	1370	1300	1270	744
Gravel	–	–	–	1116
Filler (paper pulp wastes)	–	70	105	–
Portland cement	–	–	–	300
Total	1828	1843	1852	2355
GWP (kg CO_2 eq)	256	255	254	328

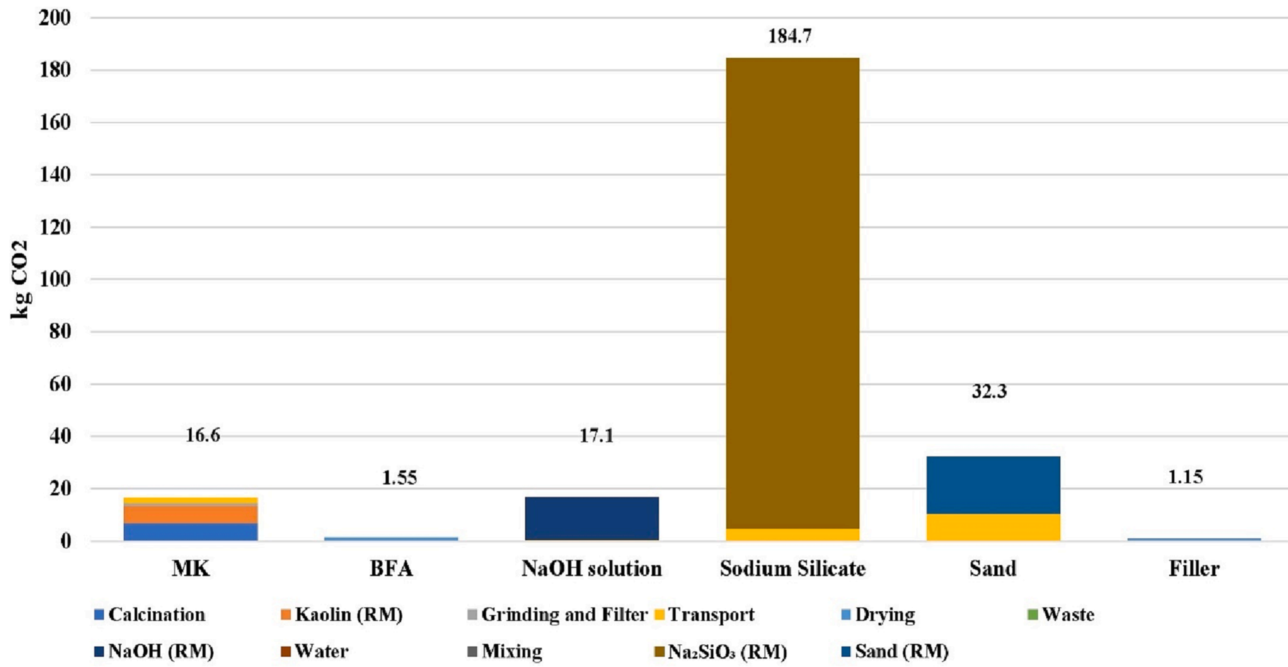

Fig. 3. Contribution analysis for formulation (3) in the scenario S1.

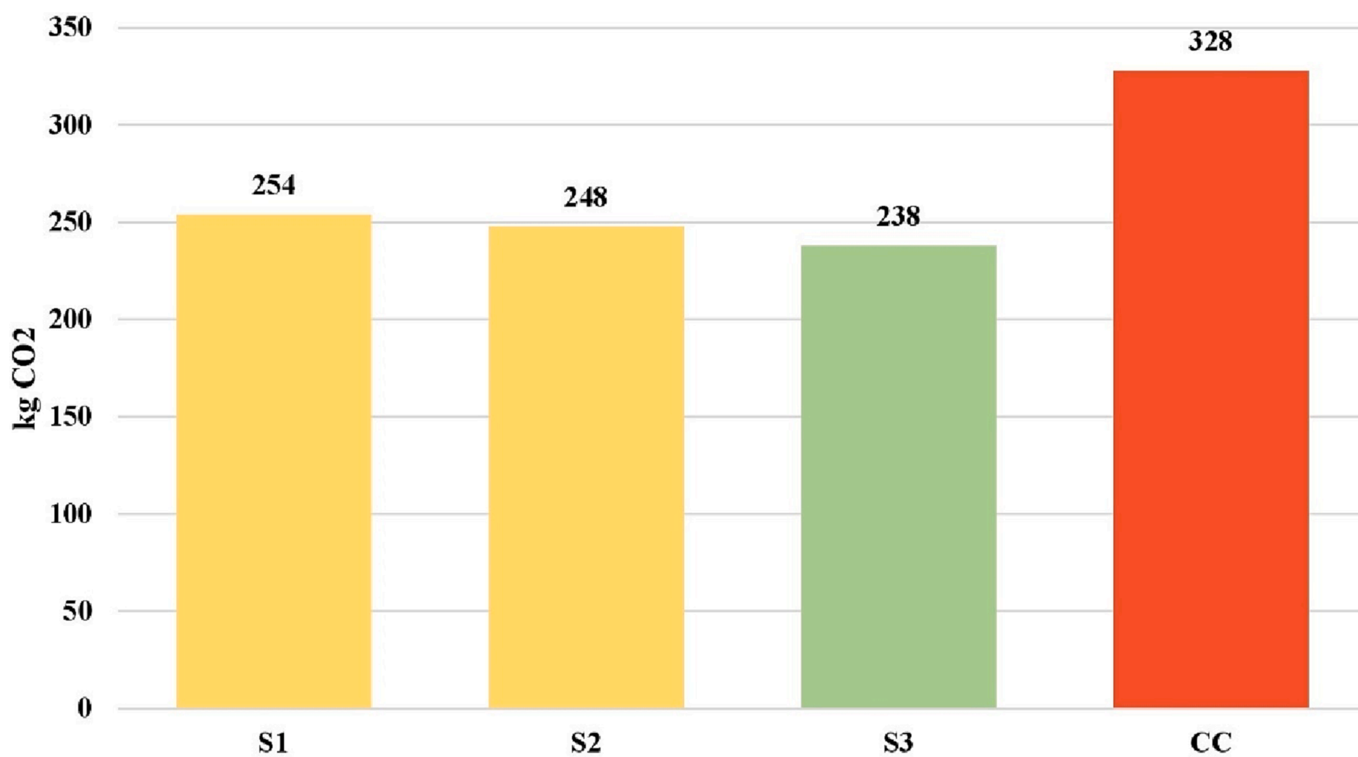

Fig. 4. GWP indicator of the three case scenarios.

As regards the scenario S2, the environmental advantage obtained is not noteworthy. The GWP indicator of S2 is lower by 6 kg of CO_2 eq (i.e. 2.36%) than S1. On the other hand, S3 provides a further reduction of the carbon footprint, corresponding to 6.30% in respect to scenario S1. Referring to S3, the obtained results show a potential reduction of greenhouse gas emissions equal to 27% (i.e. 90 kg of CO2 eq.) compared with the production of CC. Despite the results may seem meaningless when referring to the functional unit chosen (i.e. 1 m^3), the advantages provided by the GC production must to be analysed on a mass production scale. The environmental benefits and the economic convenience of the GC production plant become remarkable when referring to the annual production capacity assumed (Table 4). As aforementioned, the waste use in the formulation (3) could avoid the extraction of 10,000 tons of sand per year and 16,280 tons of kaolin per year respectively (see Table 4). Furthermore, the cogeneration plant could also offer a substantial economic advantage in terms of energy savings, owing to the simultaneous production of electrical and thermal energy. Aiming to highlight the potential economic advantage provided by the scenario S3 (i.e. power supply with cogeneration), an economic comparison among the three scenarios was performed and detailed in the following section.

3.2. Economic assessment

Disregarding the overall cost needed for the plant construction and the revenue arising from the GC sale, the performed economic analysis is focused on the comparison of costs related to the three investigated scenarios. Fig. 5 shows the resulting NPV, based on TIC and TOC data summarised in Table 8.

Based on the assumption of selling 100% of excess electricity produced by CHP, S3 is clearly the most convenient scenario with approximately 780,000€ of NPV, resulting in a costs reduction of 75% and 57% compared with S1 and S2 respectively. In real situations, it would be impossible to feed the public network by the total amount of electrical energy produced by CHP. Therefore, a sensitivity analysis was performed on the percentage of electricity sold to evaluate its impact on NPV. The sale price was assumed equal to the cost one (ARERA, 2021) for all electricity production bands. The sensitivity analysis results are represented in Fig. 6, where three different percentage of electricity sold are considered (i.e. 0%, 50%, 100%).

If the electricity produced in excess by CHP is not fed into the network, S3 has a higher NPV than S2. Therefore, the installation of the CHP system is not economically viable unless the excess energy produced is used to power the primary production system (i.e. the paper mill). In that case, the economic revenue will be represented by the avoided purchasing of electricity necessary for the primary production. On the other hand, if the 50% of excessed electricity is sold, NPV of S3 is lower than the one S2. The percentage of electricity sold that makes the two NPVs of S2 and S3 equal is 39%. With this recognition, the S3 scenario is cheaper than S2 when the percentage of electricity sales exceeds 39%, while the ideal situation is represented by the selling of the 100% of electricity, as previously said.

4. Conclusions

Among industrial sectors, the construction one has widely recognized as highly polluting in terms of greenhouse gas emissions, natural resources depletion, soil erosion and high-water consumption. The production of building materials represents one of the main critical issue in the construction industry since it encompasses some very energy-intensive processes. Therefore, the aim of the present paper was to evaluate the life cycle impact assessment of the industrial production of a greener building material (i.e. the Geopolymer Concrete - GC) than the Conventional Concrete (CC). Based on LCA results, the Global Warming Potential (GWP) indicator demonstrated a lower greenhouse gas emission of the proposed GC production in respect to the CC manufacturing process. On the other hand, no significant difference was observed in the GWP scores of the three GC formulations analysed, when referring to the functional unit. Nevertheless, the usage of the innovative GC formulations on industrial scale would avoid the extraction of a large amount of sand and kaolin per year. The contribution analysis demonstrated that the main limitation to GC development is represented by the large use of sodium silicate in the alkaline activator manufacturing process. To reduce the GC environmental impact, a solution could be represented by an electrical generation mix based on renewable resources or by a reduction of the sodium silicate use, with negative effects on GC compressive strength. Finally, the economic assessment showed that the coupled production of thermal and electrical energy by a cogeneration system could provide an important cost reduction.

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CRediT authorship contribution statement

Adelfio Luca: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Giallanza Antonio:** Supervision, Formal analysis, Writing – original draft, Writing – review & editing. **La Scalia Giada:** Supervision, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **La Fata Concetta Manuela:** Supervision, Writing – original draft, Writing – review & editing. **Micale Rosa:** Supervision, Formal analysis, Writing – original draft, Writing – review & editing.

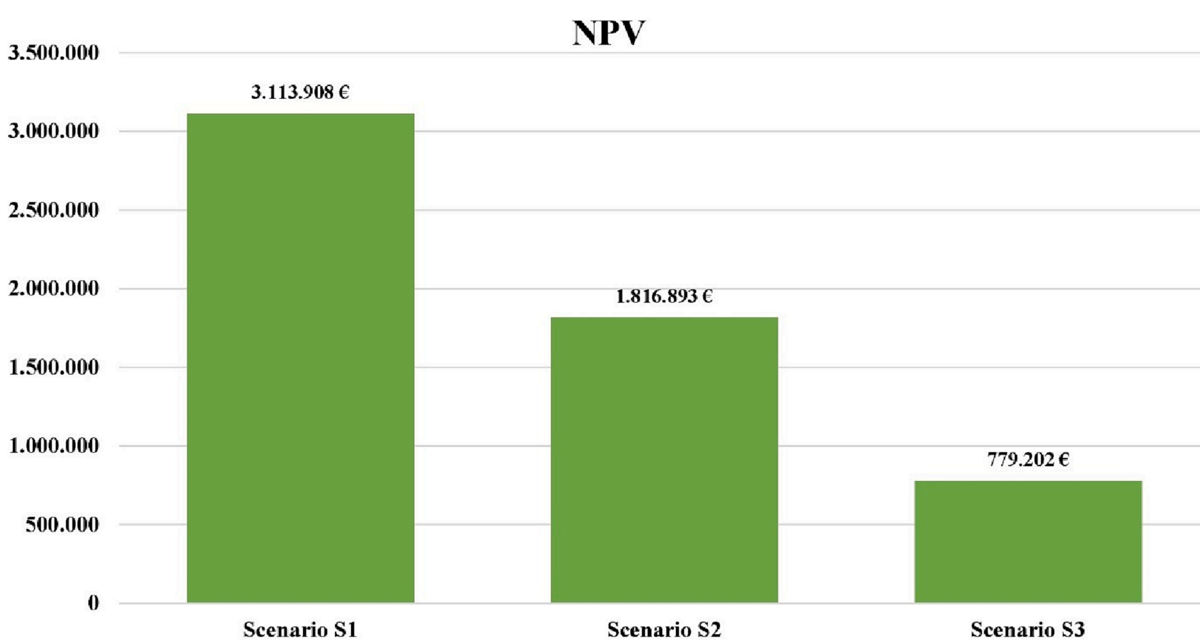

Fig. 5. Economic assessment results.

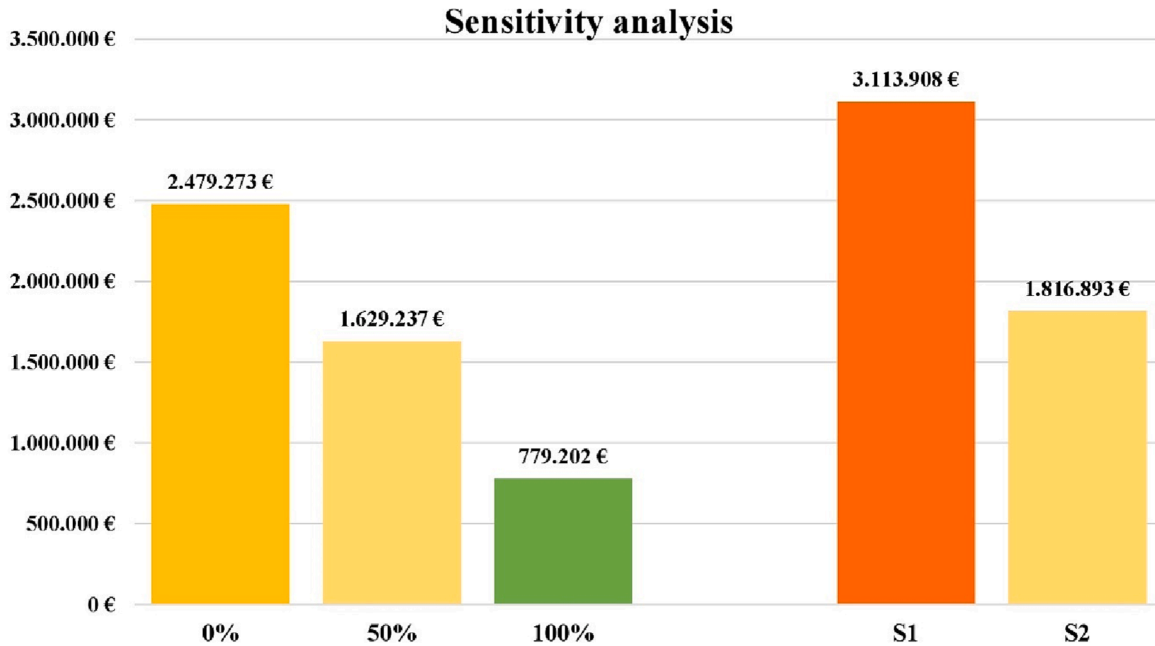

Fig. 6. NPV of S3 for different percentages of electricity sold.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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