Life cycle assessment for the production of MSWI fly-ash based porous glass-ceramics: Scenarios based on the contribution of silica sources, methane aided, and energy

Life cycle assessment for the production of MSWI fly-ash based porous glass-ceramics: Scenarios based on the contribution of silica sources, methane aided, and energy recoveries

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Abstract

Municipal solid waste (MSW) production in the world has increased by 60% in recent years. Incineration of MSW reduces their volume in conjunction with energy recovery. Incineration produces two residues, namely bottom ash (BA) and fly ash (FA), with high concentration of heavy metals and organic pollutants, especially for FA, making them an environmental concern. Vitrification is a costly, highly safe high temperature treatment, ensuring encapsulation of heavy metals. FA vitrification requires a source of silica to be able to get vitrified. In this study, we have proposed valorizing treated (vitrified) FA through the production of porous glass-ceramics, subsequently to MSWI. The entire process, from incineration to glass-ceramics production, was evaluated for several scenarios by Life Cycle Assessment (LCA) using Sima Pro 9.0. Three main scenarios were analysed; each one considering a different silica source: bottom ash (BA), glass cullet (G) and silica sand (S), and for each scenario, three thermal recovery subscenarios were assumed: no thermal recovery used to heat FA prior to vitrification (N), heating FA prior to vitrification using incineration gases thermal recovery (T) and methane-combustion-aided thermal recovery, which exploits methane combustion to further increase the gases temperature (M). Results proved that vitrification was a technically feasible and environmentally-energetically sustainable technology. The result indicates that the most eco-sustainable scenario was using bottom

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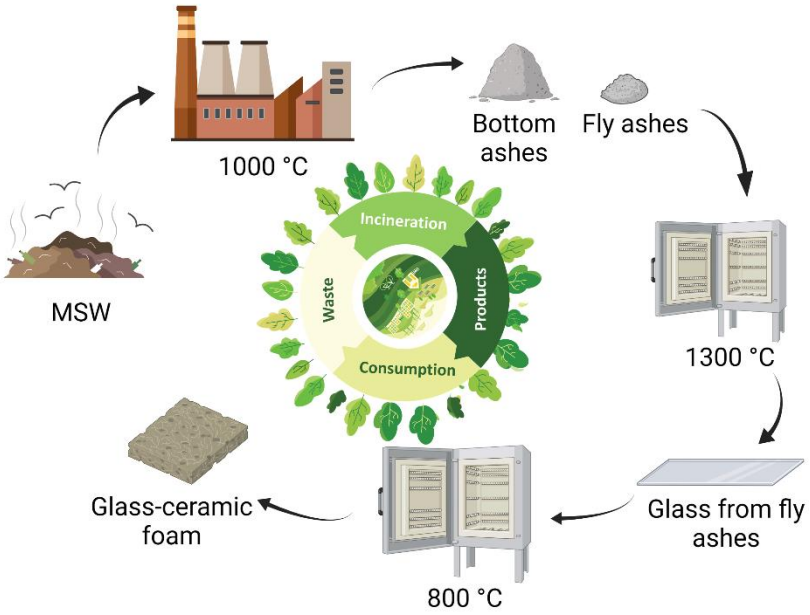
ashes as a silica source together with methane-combustion-aided recovery: 0.467 $kgCO_{2,eq}$, $5.83 \cdot 10^{-8}$ carcinogenic-CTUh and 9.26 MJ required per kg of glass-ceramics produced.

Graphical abstract



Keywords: LCA, fly ash, bottom ash, municipal solid waste, climate change, circular economy

1. Introduction

The growth of population and industrial development, the production of municipal solid waste in the world is expected to increase from 1.3 billion tons in 2015 to 2.2 billion tons in 2025 (Kawai and Tasaki, 2016). The lack of suitable landfill sites and the environmental impact of direct landfilling of waste boosted regional and national organizations toward more sustainable waste management strategies under the new term “circular economy”, suggesting closing the loop of product lifecycle. Recycling is not always an economically viable option, and other strategies like waste-to-energy recoveries are considered for sustainable waste management. There are different waste-to-energy technologies including biological treatment, thermal treatment, landfill gas utilization, and incineration. In the current work, we focus on solid waste incineration for energy recovery (Sharifikolouei and Ferraris, 2021b).

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The residues of incineration are bottom ash and fly ash. Bottom ash (BA) accounts for around 80 wt% of the total incineration residues and is composed of heterogeneous solid granules of broken glass cullet, ceramic, slag/sintered phases, and unburnt materials (Loginova et al., 2019; Xuan et al., 2018). The other incineration residues are fly ashes (FA), in whose composition can widely differ depending on the consumers behavior in the production of solid waste. FA contain soluble salts, high concentration of heavy metals, and organic pollutants such as dioxins. Even though, some heavy metals are also present in BA, heavy metals concentration in FA is higher, classifying them as hazardous waste materials. Some of the most common heavy metals found in FA are Hg, Pb, Zn, Cd, As, Sb, Cu, Sn, Ni, Cr, V (Čarnogurská et al., 2015; Luo et al., 2019).

The management of BA and FA is the major environmental concern due to the possibility of heavy metal leaching. Therefore, they must be treated before landfill or utilization. Treatment of BA and FA introduces a new cost and sometimes new pollutants after the treatment. In the context of resource management, BA and FA have the potential to partially substitute raw materials, especially in the case of construction materials like clinker, cement, concrete, and bricks. According to the European Commission Amending Directive 2018/850, only waste that has been treated can be landfilled (European Commission, 2018). Since the treatment is required to landfill the FA, their valorization through partial substitution of raw materials could recover part of the cost.

One of the safest techniques for encapsulation of heavy metals is vitrification, used for treatment of the most dangerous class of waste materials, radioactive nuclear wastes (Ponsot et al., 2015; Xiao et al., 2008). The disadvantage of vitrification is the cost since it requires a high temperature. Most Japanese incinerators are equipped with direct melting system where fly ash and bottom ash are vitrified in the plant to form slag and vitrified safe products (Shibaike et al., 2005). Therefore, even vitrification could be an affordable treatment option

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depending on how much energy is recovered and if the technology is integrated within the incinerator plant.

Vitrification of bottom ash is feasible due to its high silica content and can be further facilitated by small addition of waste glass (glass cullet). One way to confirm the safety of the vitrified products is the standard EN 12457-2 leaching test (EN 12457-2, 2002). To be classified as suitable for reuse, the leaching tests results need to respect national regulations. As stated by Blasenbauer et al. (Blasenbauer et al., 2020), in the European Union (EU) there is no uniformed regulation for BA reuse. Despite the presence of an EU-emanated directive, each EU Member State may adhere to more stringent regulations, as stated by the directive itself (The Council of the European Union, 2003). Therefore, the exact limits may vary within the EU. In the case of Italy, non-hazardous waste classification for reuse is regulated by two Ministerial Decrees (DM) (Italian Republic, 1998a; Italian Republic, 1998b; Italian Republic, 2006). For EU-widespread, albeit less specific, leaching threshold for classification as landfill-suitable non-hazardous wastes, European Council Decision 2003/33/EC should be referred to. More info on the regulations were provided in the supplementary materials.

Previously, it has been shown that vitrified BA passed the EN12457-2 leaching test, confirming their appropriateness for several industrial applications (Sharifikolouei et al., 2020). On the other hand, FA vitrification is only possible when adequate amount of silica source is used as an additive due to FA low silica and alumina content. The silica source can be simply BA, or other discarded materials such as glass cullet. However, finding the right composition for the successful vitrification of FA is a challenging task because the composition of FA varies greatly depending on the MSW composition.

The silica source is a crucial parameter to reach the FA vitrification sustainability.

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Similarly, high temperature requirement could lead to non-negligible energy consumption. The analysis and comparison of different methods to reduce the energy requirement for reaching vitrification temperatures could be a valuable addition towards less-energy-consuming valorization of FA.

The vitrified BA and FA could be used in isolating bricks made of foamed glass-ceramics. The safety of this approach was proved by conducting the standard leaching test (Rincon Romero et al., 2018).

Life cycle assessment (LCA) is, as defined by ISO 104040 (2006), “an evaluation of inputs, outputs and potential environmental impacts of a product during its lifecycle”, Several circular economy approaches were evaluated by LCA previously, like materials recovery, composting, anaerobic digestion, and recycling. F.Cherubini and co-workers studied alternative scenarios aimed at minimizing the unused material fraction headed to landfill for a MSW in Rome, Italy. (Cherubini et al., 2008). In another survey, conducted for MSW management in Thailand, D Janjareon and co-workers used LCA and MFA (Material flow analysis), (Thushari et al., 2020).

The aim of the present study is to evaluate the environmental sustainability of nine scenarios based on FA valorization and conversion into (foamed) glass-ceramic products through vitrification and heat-treatment process using LCA tools. The LCA is conducted for each of the proposed scenarios according to ISO14040 (2006) and ISO14044 (2006). LCA study can be performed considering different approaches as from cradle to gate, from gate to gate or from cradle to grave, according to the aim and scope of the study and the defined boundary conditions. LCA study consists of four phases: definition of aim and scope of the study, life cycle inventory, life cycle impact assessment and interpretation of data.

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The adopted approach was to simulate the incineration plant condition through Aspen Plus and conduct its environmental analysis through LCA study considering two methods: ILCD 2011 Midpoint+ method and Cumulative Energy Demand (CED). For the ILCD 2011 Midpoint+ method, the following impact categories were studied according to Morselli et al. (Morselli et al., 2008): global warming potential and human toxicity. For the CED, the focus was on the evaluation of the total energy consumption of the process.

The novelty of the present study is the eco-sustainability design of FA valorization considering and combining technical, energetic and environmental aspects. Moreover, the LCA study was carried out considering primary data collected from an operating municipal incineration plant. In addition to that, while vitrification of municipal solid waste incineration (MSWI) FA – and other similar thermal treatments, were largely studied from a process standpoint, their LCA were not, as stated also by Huang et al. (Huang et al., 2022). Since this is an initial analysis of the process, only core aspects of the process were analyzed, neglecting minor operative steps. Therefore, only the process steps strictly necessary or beneficial to foamed glass-ceramics production were analyzed.

2 Materials and methods:

Life cycle assessment (LCA) was performed with SimaPro 9.0 software based on ISO 14040 (2006) and 14044 (2006). Databases Ecoinvent 3.0 and Agri-Footprint were employed.

2.1 Goal and scope:

The goal and scope of the current study is to evaluate the environmental sustainability and energetic analysis of fly ash (FA) valorization and conversion into glass-ceramic products through vitrification and heat-treatment process. The analysis was based on data from a real MSWI plant located and operating in Turin (Piedmont, Italy), combined with a sequential

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vitrification and heat-treatment processes to produce foamed glass-ceramics encapsulating the heavy metals present in MSWI-FA. From the FA standpoint, the LCA was conducted as cradle to gate.

Vitrification requires a high-silica source, therefore silica-rich materials are usually used to conduct FA vitrification (Sharifikolouei et al., 2021a). BA contain enough silica to be vitrifiable on their own (Sharifikolouei et al., 2021a). Glass cullets and silica sand were shown to be constituted for 64.46% and 99.75% on a mass basis, from silica, respectively. (Sharifikolouei et al., 2021a). However, vitrification requires temperatures ranging from 1100°C to 1500°C (Sharifikolouei et al., 2021a). Moreover, vitrification additives extraction or production could lead, on the long term, to impoverish natural resources. Thus, when possible, solutions to avoid excessive use of raw materials and to reduce the required energy to reach vitrification temperatures should be considered.

Therefore, three main scenarios utilizing internal or external sources of silica inside the plant were evaluated in this study, described in Table 1. The analyzed scenarios aim to compare the use of natural resources, such as silica sand, with the use of waste materials, such as bottom ashes or glass cullets destined to recycling. Each scenario comprehended three subscenarios, aiming to determine how reducing the energy required to reach vitrification temperatures could influence the overall process analysis.

Scenario BA refers to scenarios where bottom ash was used as a silica source for vitrification. The BA were produced inside the boundary conditions; therefore, they are considered as avoided burdens because using BA as a silica source avoids their disposal. Scenario G and Scenario S represent scenarios where glass cullet or silica sand (which were not produced inside the boundaries) were used, as external silica sources. Glass cullets were considered as almost zero-burden wastes, with the sole exception of their transport to the plant being considered. Glass cullets were collected from waste-collection centers in Turin and shipped to

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the plant only in G scenarios, separately from MSW. In the suffix –N subscenarios, FA was not heated through a thermal recovery, therefore not recovering the gases heat in –N subscenarios. In –T subscenarios FA is heated through thermal recovery of a fraction of the incineration gases. Lastly, in –M subscenarios, the thermal recovery used to heat FA was enhanced by methane combustion, further increasing the gases temperature and leading to a higher FA final temperature. Scenarios S temperature is higher than that of scenarios BA and G because the melting point of silica sand is higher than BA or glass cullet fusion temperature (Sharifikolouei et al., 2021a).

Each scenario was analyzed and compared in terms of environmental and energetic sustainability. From now on, each scenario or subscenario will be referred to using the names listed in Table 1. The functional unit (FU) was 1 kg of glass-ceramics production, and all data of inventory were referred to the FU. To keep the analysis as conservative as possible, all the burdens were allocated onto the produced glass-ceramic. In cases where all the outputs of a process steps contributed to the FA-valorizing glass-ceramic production, a mass-basis allocation was used. The mass basis was chosen to use a pertinent physical correlation, broad enough to allow comparing the findings reported in this study with future research. The cut-off method was applied to the pure CO_2 stream co-produced during the glass-ceramics production, due to CO_2 stream contributing for less than 1%, to the total burdens.

The incinerators design suggested by the current study is schematically depicted in Figure 1, which also clarifies the boundary conditions defined inside the plant. A more detailed representation of the boundaries is available in the supplementary materials. As depicted in Figure 1, the three major residues of incineration are FA, BA, and flue gas. BA constitutes 21 wt% of the incinerated wastes and is temporally stocked, to be then sold through a public tender procedure, usually to concrete production industries (Zhang and Zhao, 2014). The incineration gases exit the combustion chamber. FA represent approximately 2wt% of

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incinerated waste and were entrained to the filtration system by the flue gas because of their fine particle size (~60 μm diameter (Rutkowska et al., 2018)). The flue gas was then sent to a heat exchanger to vaporize a water stream, to produce electricity in a vapor turbine. The cooled incineration gas was sent through an electrostatic filter, separating FA, with a removal efficiency calculated to be 99%. Afterwards, FA were stocked, and the gas was sent to a CO_2 capture section, which absorbed CO_2 using a monoethanolamine (MEA) aqueous solution (15.4% weight of MEA). The absorption occurred in an absorption column, meanwhile the CO_2-rich MEA solution was sent to a stripper column, to remove the CO_2 from the aqueous solution through heating. The gases exiting from the stripper column were then sent to a condenser, separating the CO_2 from vapors and steam. The gas exiting the first absorption tower was sent to the gas treatment section. Gas treatment section was not a core part of glass-ceramic production and was the same for all subscenarios, thus it was not included in LCA boundaries. Its inclusion would have resulted in the same burdens for all subscenarios, thus not contributing in highlighting their differences. The captured CO_2 was then used to produce the foaming agent ($CaCO_3$), through reaction with $Ca(OH)_2$. Meanwhile, the stocked FA was sent to a furnace, where the silica source was added. Furnace heating was provided by electricity and the melting-FA-silica-source vitrification batch was heated up to the vitrification temperature, which depends on the used type of silica source.

2.2 Life Cycle Inventory (LCI)

Life Cycle Inventory (LCI) was based on the primary data for both municipal solid waste (MSW) incineration plant and the vitrification process, respectively provided by IREN and Sharifikolouei et al. (Sharifikolouei et al., 2021a). Vaporized water pressure and specific heat are based on the secondary data acquired by technical reports. Although MSW were considered as a zero-burden waste from an LCA standpoint, to model the process, their

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commodity composition was used (Primary data by IREN commodity extract, 2021), which was compared with a reference for North Italy MSW composition (Calabrò and Pagallo, 2020).

Tables 2-A and 2-B describe inventory data. Table 2-A lists the upstream part of the process (steps tied to MSWI). Table 2-B lists the process core steps, strictly tied to foamed glass-ceramic production. While Table 2-A refers to all scenarios, Table 2-B accounts for the different vitrification and thermal recovery scenarios. Due to the different scenarios' energy requirement, the avoided energy for each scenario was different. To avoid considering only the avoided burdens, the outputted energy of this process step was considered coming from an external generation, with the inclusion of avoided energy considering the benefits of generating electricity. Moreover, the avoided burdens in electricity generation were tied to the surplus produced electrical energy, highlighting the importance of different energy requirement among the analyzed scenarios.

Thermal recovery was designed based on (Zheng et al., 2021), comprising a three-crossflow-steps heat exchange system. This system was chosen due to the small quantities treated in this work, which made fluidized bed design irrelevant. On an industrial scale, a fluidized bed exchanger should be adopted. The CO_2 absorption and stripper columns were designed using Aspen Plus, using data from (Batuecas et al., 2021) and (Lin et al., 2011), reaching a CO_2 recovery efficiency of approximately 67 %. ELECNRTL method was used. The electrostatic filter was designed according to (Zheng et al., 2017), using a value of applied tension in accord with (Zhao and Zheng, 2008). The gas velocity through the filter was considered 1.86 m/s, at 200°C, 1atm and 3.72 g/Nm^3 FA load at inlet (Zheng et al., 2017). The vaporizer was designed with Aspen Plus as a tube-in-tube heat exchanger and obtained data agreed with technical reports (TRM S.p.A., 2019). In Table 2-A, BA disposal and recovery through concrete production was reported. Data regarding the BA recovery were taken from Biganzoli

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et al. (Biganzoli et al., 2019). BA disposal consisted in separating metallic components from non-metallic components, using magnetic separators. Afterwards, the remaining BA were subjected to water-washing, to remove BA chlorine compounds and other salts (Biganzoli et al., 2019; Verbinnen et al., 2017). After washing operations, residual unburnt BA components were sent back to the MSWI to be incinerated. The washing operations wastewaters were then treated using a NaOH solution, containing $FeSO_4$ and a cationic polyelectrolyte. The metallic components recovered from BA disposal could have been recovered and treated as avoided burdens; however, their recovery was not included in the LCA. The cationic polyelectrolyte was not included, since its exact composition was not specified in Biganzoli et al.'s work. However, the polyelectrolyte did not represent a crucial contributor to the overall disposal process burdens (Biganzoli et al., 2019).

In all scenarios, about 90.5% of the BA (about 4.75 kg) were sold and then sent to recovery as concrete-production raw material. The remaining 9.5% (about 0.5 kg) was managed according to the scenarios. In BA scenarios, it was used as silica source, representing an avoided burden. In G and S scenarios, it was sent to recovery along with the rest of the BA. Since the disposal of 90.5% of BA was a common data among all scenarios and would not have contributed to the scenarios comparison, it was not included in the LCA. Opposed to that, the disposal of 0.5 kg of BA was considered only for scenarios G and S, where BA was not used as silica source and was entirely shipped to the industry. Representing a difference between scenarios, BA disposal burdens were allocated on glass-ceramic production. Supplementary materials contain more detail regarding the BA disposal and shipment. Similarly, glass cullets and silica sand transport from external sources to the process was considered in G and S scenarios only, respectively. Despite being waste materials, glass cullets disposal was not considered in scenarios BA and S, due to their provenience; glass cullets were not produced inside the process boundaries and were not shipped to the plant alongside the MSW. Glass cullets were

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collected from waste-collection centers in Turin, separately from MSW and only for G scenarios purposes. BA and S scenarios did not include the glass cullets collection, therefore in those scenarios glass cullets disposal was not analyzed.

2.3 Life Cycle Impact Assessment (LCIA)

Life cycle impact assessment was performed using ILCD 2011 Midpoint+ and Cumulative Energy Demand methods. ILCD 2011 Midpoint+ was used to assess climate change (kg CO_2 equivalent), human toxicity, carcinogenic (CTUh). Morselli et al. (Morselli et al., 2008) have previously stated that greenhouse gas emission has higher potential impact in thermo-valorization plants. Cumulative Energy Demand (CED) evaluated the impact of the total energy consumption of the whole process.

2.4 Interpretation of Results

Since vitrification is sensitive to the preparation batch chemical composition, sensitivity analysis was performed to measure and detect possible variation of vitrification response on environmental impacts, focusing on different vitrification batch FA:silica-source mass ratios. The process described in the previous section has FA:silica-source mass ratio of 1:1. Despite different quantity of vitrified FA, the sensitivity analysis maintains the FU previously described. Due to their difficult and expensive disposal, the residual FA will be stocked and used to produce glass-ceramic, once their stocked mass is adequate. Sensitivity scenarios will be referred to, from now on, with their names listed in Table 3.

3 Results and Discussion

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Different sources of silica are considered as vitrification agents, thus the vitrification temperature varies according to the properties of the silica source. Each silica source was mixed with FA and vitrified at the indicated temperature. The vitrified product was then mixed with calcium carbonate and heated up to 800˚C in a heat-treatment furnace leading to its crystallization meanwhile the produced CO_2 gas resulting from calcium carbonate decomposition ($CaCO_3 \rightarrow CO_2 + Ca(OH)_2$), produces a foamed glass-ceramic. The released high purity CO_2 stream here is again captured from the heat-treatment furnace and has added value for its high purity. Inside the MSW incineration plant, a percentage (0.25 wt% for -T subscenarios, 0.1 wt% for -M subscenarios) of the incineration gas could increase the FA temperature before vitrification, saving thermal energy. In -M subscenarios, in addition to incineration gases, methane-combustion gases were used for the thermal recovery as well (0.00864 $kgCH_4$/kg produced glass-ceramic). The methane combustion helped the gases to reach a higher temperature, achieving an even higher temperature for the FA batch, guaranteeing a lower vitrification energy consumption.

For conducting the sensitivity analysis, different FA:silica source mass ratios were employed. Different ratio implies a different vitrification energy requirement, due to the different physical properties of the FA and silica sources. Other consequences of considering a different FA quantity are the mass of incinerated MSW and the subsequential flue gases and BA production.

The LCA takes into consideration as avoided burdens the produced surplus energy sold to other industries or domestic customers.

The glass cullets used in this process were waste glasses from other processes or domestic use, destined to recycling. According to circular economy, the use of raw resources is limited by valorizing waste glass cullets, replacing virgin glass.

3.1 Base scenarios

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313 In Figure 2, for all proposed scenarios, the CO_{2eq} emissions had the same magnitude order,
314 ranging from 0.467 (BA-M scenario) to 0.626 (G-N scenario) $kgCO_{2,eq}$/produced glass-
315 ceramics kg.

316 Considering the silica source, bottom ashes reached the lowest climate change impacts
317 compared to glass cullets and silica sand, reaching climate change impact values equal to
318 0.0478 ± 0.044 and 0.013 ± 0.016 $kgCO_{2eq}$/kg lower than glass cullets and silica sand,
319 respectively.

320 When considering same silica source scenarios, the methane-aided thermal recovery achieved
321 the lowest climate change impacts. M subscenarios reached climate change impact value
322 equal to 0.49±0.03 $kgCO_{2eq}$/kg of glass-ceramics produced, whereas T and N scenarios
323 achieved 0.53±0.02 and 0.598±0.023 $kgCO_{2eq}$/kg, respectively.
324 The energy recovery forms had a non-negligible impact on climate change. The highest
325 vitrification energy requirement (2.92 MJ, G-N scenario) is 1.35 MJ higher than the lowest
326 vitrification energy requirement (1.57 MJ, S-M scenario), making in fact the electric energy
327 influence on overall burdens non-negligible. Combining the silica source and the energy
328 recovery form, the most promising sustainable scenario would be BA-M (bottom ashes as
329 silica source with methane-aided thermal recovery).
330 Similar to climate change burdens, the carcinogenic-emissions-related human cases were of
331 the same magnitude order (Figure 2).
332 Diving into human toxicity analysis, G-M reached the highest emissions, equal to $5.95 \cdot 10^{-8}$
333 CTUh, whereas S-M and BA-M both achieved $5.83 \cdot 10^{-8}$ CTUh. Glass cullet scenarios reached
334 a human carcinogenic toxicity impact equal to $8.69 \cdot 10^{-10} \pm 1.8 \cdot 10^{-9}$ CTUh and $1.03 \cdot 10^{-9} \pm$
335 $1.7 \cdot 10^{-9}$ CTUh higher than the human carcinogenic toxicity impact achieved by BA and silica
336 sand scenarios. Considering the energy recovery form, M subscenarios achieved the lowest
337 human toxicity impacts among the ones considered in the study, reaching average human

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toxicity impact values equal to $5.87 \cdot 10^{-8}$ CTUh ± $5.74 \cdot 10^{-10}$, whereas T and N subscenarios have reached $6 \cdot 10^{-8} \pm 3.18 \cdot 10^{-10}$ CTUh and $6.21 \cdot 10^{-8} \pm 1.46 \cdot 10^{-9}$ CTUh respectively.

Total energy consumption was prioritized over consumption of several distinct energy categories. The total energy consumption had the same magnitude order for all the scenarios (Figure 3). Scenario S-M showed the lowest energy consumption, while G-N scenario exhibited the highest energy consumption. The difference between the highest overall consumption (G-N) and the lowest overall consumption (S-M) was approximately 2.8 MJ, meaning that G-N energy consumption was 30.5 % higher than S-M consumption. On the other hand, G-M energy consumption was 9.7 % higher than that of S-M. The higher G scenarios energy consumption agreed with data reported by Bingham and Hand (Bingham and Hand, 2006), reporting that melting silica-lime glass can require up to 5 MJ per glass kg.

When considering same-silica-source subscenarios, N subscenarios had the highest environmental and energetic impacts amongst N, T and M subscenarios (Figure 2, 3), due to the absence of thermal recovery for FA heating, which obliged heating solely in the electric-heated vitrification furnace.

N subscenarios required the least equipment but the most energy (Figure 3). The higher energy consumption influenced the environmental burdens, making N subscenarios a suitable solution for pre-existent waste-to-energy plants with limited space to add other equipment on site.

T subscenarios burdens were between N and M subscenarios (Figure 2, Figure 3) due to the thermal recovery for FA. Higher starting temperature in the furnace implied less energy required to heat and vitrify the batch. T subscenarios required the installation and maintenance of additional equipment in exchange for both environmental and energetic benefits. Moreover, FA were heated using a negligible fraction of the total gases produced,

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362 leaving the quantity of vaporized water virtually unchanged. Therefore, the net produced
363 electricity in the steam turbine was higher than in N subscenarios. T subscenarios could be a
364 suitable solution for yet-to-build thermo-valorization plants or already existent plants with
365 enough space to add the necessary equipment and pipelines.

366 M subscenarios generally showed the lowest burdens (Figure 2, 3) due to FA entering the
367 vitrification furnace at higher temperature than subscenarios N and T. M subscenarios
368 required undoubtedly less total energy and, thus, showed higher net produced electricity in the
369 turbine, making it a suitable solution for cases like those of T scenarios.

370 Considerations on silica sources and their physical properties investigated differences
371 between scenarios were reported. Considering production or extraction of silica, in the
372 proposed LCA, silica sand showed low burdens per sand kg, related to its extraction. Similar
373 values were reported by Grbeš (Grbeš, 2016). Lower energy is required to be fused and
374 vitrified due to its fusion heat energy (Green and Perry, 2008a); hence, S scenarios had
375 slightly lower energy consumption compared with BA scenarios, leading to comparable
376 burdens between BA and S scenarios. Regarding G scenarios, the higher energy requirement
377 was explained by the glass cullets silica-lime composition, in line with Bingham and Hand's
378 work (Bingham and Hand, 2006), Since both GC and silica sand were transported for a
379 relatively short distance (less than 20 km), their transport had low influence on overall
380 burdens. More details regarding the silica sources transport were provided in the
381 supplementary materials.

382 The human toxicity burdens exhibited agreed with the results of other LCAs on FA
383 vitrification. Pei et al. (Pei et al., 2020), during an LCA of fuel-based vitrification of FA,
384 observed that human toxicity and climate change were the highest impacts among the
385 analyzed categories. Huber et al. (Huber et al., 2018) observed that for FA vitrification in a
386 carbon-fueled furnace, the effects on human health and ecotoxicity were the highest. Huang et

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al. (Huang et al., 2022) and Fruergaard et al. (Fruergaard et al., 2010) observed higher impacts due to FA vitrification on human health.

Climate change impacts of this work differ from those in literature. Pei et al. (Pei et al., 2020) and Fruergaard et al. (Fruergaard et al., 2010) obtained high climate change impacts, while Huber et al. (Huber et al., 2018) obtained relatively low climate change impacts, compared to other FA disposal methods. According to Huber et al., in this work, climate change burdens were not the highest burdens. The differences with Pei et al. and Fruergaard et al. may be explained by use in this work, of a CO_2 capture system, and of an electric-heated vitrification furnace instead of a fuel-heated one. In this work, the CO_2 capture system was demonstrated in Figure 2, 3 to be a major contribute to overall glass-ceramic production. However, even if a considerable amount of energy is required, the overall process burdens showed that CO_2 capture may be beneficial.

The high vitrification energy requirement agreed with other processes of vitrification or similar FA thermal treatments ; according to Huang et al. (Huang et al., 2022), FA vitrification exhibited an energy consumption of 2.16-3.6 MJ per FA kg. Ni et al. (Ni et al., 2012) studied a plasma melting vitrification of MSW FA, which exhibited an energy consumption of approximately 3.6 MJ per kg of FA. Bingham and Hand (Bingham and Hand, 2006) reported that FA thermal treatments require 2 MJ per FA kg. Alhadj-Mallah et al. (Alhadj-Mallah et al., 2015) calculated that melting an FA-biomass mixture may require from 1.65 to 2.65 MJ per kg. The high energy requirement for vitrification adds non-negligible costs to the process, as stated by Sakai and Hiraoka (Sakai and Hiraoka, 2000). Figure 2, 3 demonstrated that the vitrification step was one of the step, alongside CO_2 capture, which contributed the most to the overall burdens of glass-ceramic production.

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410 The reported findings showed BA-M scenario as the most sustainable scenario, closely
411 followed by S-M scenario. Despite some uncertainties on the BA disposal contribution to the
412 overall impacts of G and S scenarios on carcinogenic human toxicity, which may have been
413 underestimated, it can be confidently stated that BA scenarios would represent the lowest
414 carcinogenic emissions, when considering the same subscenario categories. These findings,
415 coupled with the relatively contained differences between the various scenarios impacts
416 showed in Figures 2 and 3, lead to consider BA as the most sustainable scenario, with the
417 occasional use of silica sand or glass cullets as silica sources deemed acceptable, in cases
418 where BA were not available.

419 **3.2 Vitrification untied to incineration burdens**

420 To scrutinize the electric energy production importance, the analysis of the sole vitrification
421 step, considering FA as a zero-burden resource, was performed. The electric energy was
422 considered as gained from external sources. In SimaPro, the external electricity was assumed
423 as a typical Italian electric energy mix, from Ecoinvent 3.0 database.
424 The subsequently listed vitrification has the same name of the scenarios they refer to. The
425 electricity generation burden for each scenario was as follows:
426 BA-N=0.33 $kgCO_{2,eq.}$ (52.8% of vitrification burdens (VB)); BA-T=0.297 $kgCO_{2,eq.}$ (41.2%
427 VB); BA-M=0.391 $kgCO_{2,eq.}$ (41.2% VB);
428 G-N=0.391 $kgCO_{2,eq.}$ (46.5% VB); G-T=0.324 $kgCO_{2,eq.}$ (42% VB); G-M=0.285 $kgCO_{2,eq.}$
429 (36% VB).
430 S-N=0.324 $kgCO_{2,eq.}$ (63.9% VB); S-T=0.264 $kgCO_{2,eq.}$ (59.1% VB); S-M=0.210 $kgCO_{2,eq.}$
431 (46.7% VB)
432 The electricity production burdens were at least 1/3 of total vitrification climate change,
433 proving that electric energy production burdens were not negligible.

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If the ashes cannot be vitrified in the same incineration plant, the electric energy should come from external sources or generated in the vitrification plant. Carrying on the vitrification in the thermo-valorization plant avoids a significant part of the vitrification burdens. Benefits of generating electricity using the incineration gases were underlined by Leme et al. (Leme et al., 2014), stating that a waste-to-energy plant can generate 1.44 MJ per MSW kg as electric energy. The present work agrees with these findings since incineration of 25 kg of MSW generates up to 36 MJ of electric energy.

The above-mentioned considerations underline the benefits of vitrifying the FA in the MSWI plant and the constraints faced for the electric requirements in carrying out vitrification in a separate plant.

3.3 Sensitivity analysis

The sensitivity analysis verified and proved the robustness and consistency of the study and was carried out for climate change and human carcinogenic toxicity, (Figure 4), and for electricity consumption (Figure 5). In this analysis, only thermal recovery was considered as energy recovery form. All BA and G sensitivity scenarios have higher burdens than BA-T and G-T scenarios respectively, for both carcinogenic and climate change burdens. S-60 and S-80 scenarios show higher burdens than S-T, while S-40 burdens were slightly lower than those, for both climate change and carcinogenic toxicity burdens. BA highest climate change burdens were 36.7% higher than BA-T burdens, whereas G and S scenarios highest climate change burdens were 43% and 30.4% higher than the corresponding burdens of G-T and S-T, respectively.

BA scenarios highest carcinogenic toxicity burdens were roughly 10% higher than BA-T corresponding burdens, whereas S-T carcinogenic toxicity burdens were 7.9% lower than S-T

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458 carcinogenic toxicity burdens. G scenarios highest carcinogenic toxicity burdens were
459 roughly 12% higher than G-T burdens.
460 Regarding the energetic consumption, only S-40 presents lower energy consumption than S-
461 T, roughly 1.9% lower (Figure 5). The highest BA and G scenarios energetic consumption
462 were roughly 34.4% and 40.4% higher than BA-T and G-T consumptions, whereas S
463 scenarios highest energetic consumption was 27.2% higher than that of S-T.

464 Scenarios with silica:FA 80:20 achieved the highest burdens, both environmental and
465 energetic, in the cases of BA-80 and S-80. G-80 scenario achieved the highest impacts in all
466 the analyzed categories. Three main reasons explained the high burdens of these scenarios.
467 The first regards silica sand and glass cullet higher specific heat capacity (Green and Perry,
468 2008b; Li et al., 2007) than FA, whereas BA specific heat capacity was like that of FA (Green
469 and Perry, 2008b; Li et al., 2007). Therefore, increasing the amount of silica increases the
470 energy to heat the vitrification batch to the needed temperature, with consequential increase of
471 environmental and energetic burdens. The second reason was that since thermal recovery
472 focused only on FA and steam production, silica entered the vitrification furnace at room
473 temperature, hence higher quantities of silica resulted in a lower starting temperature. The
474 third reason was that in scenarios of silica:FA 80:20 a lesser quantity of MSW was
475 incinerated, thus fewer incineration gases were available. In these scenarios energetic
476 requirements exceeded the turbine energy generation, so a small quantity of energy came
477 from external sources. No electric energy surplus was obtained; thus, no avoided burdens tied
478 to electric energy were present in these scenarios. In the case of G-80, glass cullet had higher
479 fusion heat energy than FA (Green and Perry, 2008a; Kim and Matyáš, 2002; Li et al., 2007),
480 so higher quantity of glass cullet in the vitrification batch required more energy to heat, fuse
481 and vitrify the batch. Moreover, scenarios silica:FA 80:20 required higher quantity of silica

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source, allowing a minor disposed quantity of FA per vitrification batch. Hence these scenarios were not deemed as valid alternatives to the T scenarios.

Compared to silica:FA 80:20 scenarios, scenarios "silica:FA 60:40" exhibited burden values closer to those of T scenarios. The silica:FA 60:40 burdens trends were explained by reasons similar to those of scenarios silica:FA 80:20. In scenario silica:FA 60:40, the used silica source is only 20% higher than in T scenarios. Thus, the effect of a lower starting temperature in the furnace and different specific heat capacity had a lower influence on the total burdens. In scenario silica:FA 60:40, the turbine-generated energy, even if lower than in T scenarios, is sufficient to satisfy the energetic requirement of the process and grant a surplus production of electric energy. BA-60, G-60 and S-60 showed higher burdens than, respectively, BA-T, G-T and S-T burdens, due to the increased energy requirement. Moreover, in S-60 scenario, the increase of the used silica source implied higher impacts.

Regarding "silica:FA 40:60" scenarios, G-40 and BA-40 showed higher burdens than G-T and BA-T scenarios, respectively, for all the analyzed burden categories. As opposed to them, S-40 achieved lower burdens than S-T scenario for all analyzed burden categories. The reasons for these trends, however, were not the same reported for scenarios silica:FA 80:20 and 60:40. In scenario silica:FA 40:60, silica source quantities were 20% lower than in T scenarios. Lower energy consumption could therefore be expected. This only happened for the vitrification step, where higher FA quantity implies higher starting temperature of the batch. FA specific heat capacity was lower than that of glass cullet and silica sand, so less energy was required to heat the batch. However, in these scenarios, more wastes were incinerated, leading to a higher energy requirement from the CO_2 capture and the FA removal from flue gases, other than from MSWI, thus leading to higher environmental burdens. Even if a higher quantity of energy was generated, the total process requires more energy than T scenarios, reducing the net produced energy. This led to an increase in environmental and

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energetic burdens in the case of BA-40 and G-40. In the case of S-40, the diminished quantity of silica sand and lower vitrification energy requirement lowered the burdens, contrary to the other two scenarios. Silica sand sole-vitrification-energy requirement decreased enough to achieve an overall lower energy consumption, even if the rest of the process required more energy.

As illustrated in Figures 4 and 5, "silica:FA 40:60" scenarios were the sensitivity scenarios which exhibited the closer impacts to the base T scenarios. Moreover, in cases where BA may not be available to be used as silica source and the chosen silica source were silica sand, it would be advisable to adopt scenario S-40 over scenario S-T. S-40, in fact, did not only showed (slightly) lower burdens, but also allowed to dispose of 0.6 kg of FA/kg of ceramic-glass, versus the disposal of 0.5 kg of FA/kg of ceramic-glass displayed by S-T scenario.

The sensitivity analysis results, coupled with the previous finding regarding BA-M as the most sustainable base scenario, showed BA-40 as the most interesting sensitivity scenario to further analyze. Future studies could expand the system boundaries and include the ceramic-glass utilization life-phase, to determine whether, at industrial scale, disposing of 20 % more FA per vitrification batch would be beneficial, opposed to an increase of approximately 1.8 % of climate change and energy consumption burdens and <1 % of human toxicity burdens. Similar studies could be done on G-40 scenarios, as an alternative in cases where BA may not be available. As already stated, S-40 should instead be preferred over S-T scenario.

4 Conclusions

The aim of the study was assessing the environmental and energetic sustainability evaluation of fly-ash based glass-ceramics production through Life Cycle Assessment, by considering climate change, carcinogenic human toxicity, and cumulative energy demand. Three main

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scenarios were analyzed considering three different silica sources: bottom ashes (BA), glass cullet (G) and silica sand (S) and for each of them three thermal recoveries were assumed no (N), thermal (T) and methane-combustion-aided (M) recoveries. Among these scenarios, G scenarios exhibited the highest environmental and energetic burdens, while BA scenarios the lowest environmental and energetic burdens, when comparing the same subscenario categories. S scenarios exhibited burdens similar, albeit slightly higher, to those of BA. Considering the energy recovery, the methane combustion recovery is the one achieving the lowest environmental and energetic impacts, when comparing the same silica source subscenarios categories. The comparison between the base scenarios and subscenarios demonstrated that energy consumption, thus the energy recovery form, affected the environmental and energetic impacts more than the chosen silica source, showing the importance of solutions aimed to reduce the energetic consumption of the process. However, comparison between subscenarios adopting the same energy recovery form showed how the type of silica source affected the process impacts in a non-negligible way.

Thus, interesting new paths of research could focus on optimizing the energy requirements, or extending the system boundaries, to determine whether it would be beneficial to adopt BA-M scenario, or to adopt a scenario similar to BA-M, using a silica source:FA ratio equal to 40:60.

The result of the study is the eco-sustainability of fly-ash based glass-ceramics production obtained with bottom ashes as silica source and methane-combustion-aided recovery achieving: 0.467 $kgCO_2$, $5.83 \cdot 10^{-8}$ CTUh and 9.26 MJ of energy consumption per kg of glass-ceramics produced.

Acknowledgements

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555 The authors are grateful to TRM S.p.A, Iren group (Torino, Italy) for his valuable technical
556 assistance and preliminary data furnished.
557

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Tables and Figures

Table 1. Scenarios adopted to evaluate the contribution of different silica source for FA vitrification. The glass cullets are external resources which avoid production of glass from raw materials, thus representing a zero-burdens resource. Bottom ashes are produced inside the process boundaries, thus being considered as a zero-burden silica source. The last rows aim to describe the role of each of the three silica sources in all scenarios, including also scenarios where they were not used as silica source. Note that silica sand and glass cullets were external resources introduced in the system specifically to be used as silica source. Therefore, in scenarios where the silica source was different, the specific external resource was not present.

Scenario	**BA**			**G**			**S**		
	BA-N	BA-T	BA-M	G-N	G-T	G-M	S-N	S-T	S-M
Silica source	Bottom ashes	Bottom ashes	Bottom ashes	Glass cullets	Glass cullets	Glass cullets	Silica sand	Silica sand	Silica sand
Incineration gases energy recovery	No recovery	Thermal recovery	Thermal recovery aided by methane combustion	No recovery	Thermal recovery	Thermal recovery aided by methane combustion	No recovery	Thermal recovery	Thermal recovery aided by methane combustion
Origin of silica source	Produced inside process boundaries (zero-burden)	Produced inside process boundaries (zero-burden)	Produced inside process boundaries (zero-burden)	External resources (avoided burdens)	External resources (avoided burdens)	External resources (avoided burdens)	External resource	External resource	External resource
Vitrification temperature, °C	1300	1300	1300	1300	1300	1300	1450	1450	1450
Role of BA	About 9.5% of total production used as silica source; remaining BA sent to disposal			Entire production of BA sent to disposal			Entire production of BA sent to disposal		
Role of GC	Not present in the scenario			Only the sufficient quantity for vitrification was acquired from external soruce; entire quantity of acquired GC used as silica source			Not present in the scenario		
Role of Sand	Not present in the scenario			Not present in the scenario			Only the sufficient quantity for vitrification is acquired from external source; entire quantity of acquired sand used as silica source		

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Table 2-A. Life cycle inventory of upstream part of the process. Only Life Cycle items which contribute to the analyzed categories of impact were reported, with some exceptions. Note that municipal solid waste was assumed to be zero-burden wastes, leading to incineration gases, bottom ashes and municipal solid waste itself being void of emissions. Despite void of emissions, their presence in LCI is explained by them being core parts of the process. MSW were the source of FA and BA, BA were one of the analyzed silica sources and incineration gases were used to generate electricity. Similarly, biogenic CO_2 was assumed as not representing any burden, but was included in the LCI since it is the main product of the CO_2 capture step and a reagent for calcium carbonate production. The rest of the represented items all contribute to the analyzed impact categories.

	Municipal solid waste incineration		**Water vaporization**		**Fly ashes removal**		**CO_2 capture**		**BA disposal through concrete production**	
Flow in	Municipal solid waste, kg	25.5	Incineration gases, kg	180.6	Incineration gases, kg	180.6	Incineration gases, kg	0.16	Transport, truck, >20t, EURO5, 100%LF, empty return; kgkm	60
			Fly ashes, kg	0.505	Fly ashes, kg	0.505	MEA†, kg	0.0546	Iron sulfate {RER}| market for iron sulfate, kg	$6.8 \cdot 10^{-5}$
			Water, kg	54.85			Aqueous solution water†, kg	0.3	Water, deionized, {Europe without Switzerland}| market for water, deionized, kg	0.16
							Make-up water, kg	0.00429	NaOH aqueous solution, 35 wt%, kg	$6.8 \cdot 10^{-8}$
									BA, kg	0.5
Flow out	Incineration gases, kg	180.6	Incineration gases, kg	180.6	Incineration gases, kg	180.6	Incineration gases, kg	0.129	Unburnt materials, kg	0.0125

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	Fly ashes, kg	0.505	Fly ashes, kg	0.505	Fly ashes, kg	0.5	Flue gases containing Biogenic CO_2, kg	0.011	Treated wastewaters, kg	0.16
	Bottom ashes, kg	5.3	Steam, kg	54.85			Flue gases containing Fossil CO_2, kg	0.0074	Treated BA, kg	0.448
							MEA vapor, kg	$2.9 \cdot 10^{-4}$	Ferrous-magnetic materials, kg	0.039
Energy required to carry out the process step	Electricity, mid tension, MJ	6.290	Heat from incineration gases, MJ	182.65	Electricity, mid tension, MJ	6.91	Electricity, mid tension, MJ	0.0124	Electricity, Italian mix, mid tension, MJ	0.0133
							Heat, from steam, in chemical industry {RER}, MJ	0.516		
Avoided burdens										

	Electricity production in turbine									
Flow in	Steam, kg						54.85			
Flow out	Expanse steam, kg						54.85			
	Electricity, mid tension, MJ	Scenario BA-N	Scenario BA-T	Scenario BA-M	Scenario G-N	Scenario G-T	Scenario G-M	Scenario S-N	Scenario S-T	Scenario S-M

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		16.41	15.93	15.55	16.63	16.13	15.84	16.13	15.68	15.28
Energy required to carry out the process step										
Avoided burdens	Electricity, Italian mix, mid tension, MJ	Scenario BA-N	Scenario BA-T	Scenario BA-M	Scenario G-N	Scenario G-T	Scenario G-M	Scenario S-N	Scenario S-T	Scenario S-M
		5.85	6.68	6.87	5.79	6.48	6.58	6.08	6.93	7

739 † The item does not contribute to mass balances. The item is the recirculated in the CO_2 capture system, thus being not part of the system mass balance.

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Table 2-B. Life cycle inventory of vitrification and glass-ceramic foam production core steps. Similarly to MSW in Table 2-A, bottom ashes and glass cullets were core parts of the process, and were thus included in the LCI, despite being considered as near zero-burden.

	Thermal recovery				**Vitrification**				**$CaCO_3$ production**		**Glass-ceramic foam production**	
					Scenarios BA							
		N	T	M		N	T	M				
Flow in	Incineration gases, kg	-	0.45	0.18	Fly ashes, kg	0.5	0.5	0.5	Biogenic CO_2, kg	0.0088	Fly ash glass, kg	1
	Fly ashes, kg	-	0.5	0.5	Bottom ashes, kg	0.5	0.5	0.5	$Ca(OH)_2$, kg	0.0148	$CaCO_3$, kg	0.02
	Methane, kg	-	-	$8.64 \cdot 10^{-3}$								
Flow out	Incineration gases, kg	-	0.45	0.41	Fly ash glass, kg	1	1	1	$CaCO_3$, kg	0.02	Glass-ceramic foam, kg	1
	Fly ashes, kg	-	0.5	0.5					H_2O (vapor), kg	0.0036	Pure CO_2, kg	0.0088
Consumed Energy	Heat from incineration gases, MJ	-	0.503	0.68	Electricity, mid tension, MJ	2.7	2.22	1.84			Electricity, mid tension, MJ	0.5
Avoided products												
					Scenarios G							
		N	T	M		N	T	M				
Flow in	Incineration gases, kg	-	0.45	0.18	Fly ashes, kg	0.5	0.5	0.5	Biogenic CO_2, kg	0.0088	Fly ash glass, kg	1

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	Fly ashes, kg	-	0.5	0.5	Glass cullets, waste for reuse, kg	0.5	0.5	0.5	$Ca(OH)_2$, kg	0.0148	$CaCO_3$, kg	0.02
	Methane, kg	-	-	$8.64 \cdot 10^{-3}$								
Flow out	Incineration gases, kg	-	0.45	0.41	Fly ash glass, kg	1	1	1	$CaCO_3$, kg	0.02	Glass-ceramic foam, kg	1
	Fly ashes, kg	-	0.5	0.5					H_2O (vapor), kg	0.0036	Pure CO_2, kg	0.0088
Consumed Energy	Heat from incineration gases, MJ	-	0.503	0.503	Electricity, mid tension, MJ	2.92	2.42	2.13			Electricity, mid tension, MJ	0.5
Avoided products												
					Scenarios S							
		N	T	M		N	T	M				
Flow in	Incineration gases, kg	-	0.45	0.18	Fly ashes, kg	0.5	0.5	0.5	Biogenic CO_2, kg	0.0088	Fly ash glass, kg	1
	Fly ashes, kg	-	0.5	0.5	Silica sand, from near Turin, kg	0.5	0.5	0.5	$Ca(OH)_2$, kg	0.0148	$CaCO_3$, kg	0.02
	Methane, kg	-	-	$8.64 \cdot 10^{-3}$								
Flow out	Incineration gases, kg	-	0.45	0.41	Fly ash glass, kg	1	1	1	$CaCO_3$, kg	0.02	Glass-ceramic foam, kg	1
	Fly ashes, kg	-	0.5	0.5					H_2O (vapor), kg	0.0036	Pure CO_2, kg	0.0088
Consumed Energy	Heat from incineration gases, MJ	-	0.503	0.503	Electricity, mid tension, MJ	2.42	1.97	1.57			Electricity, mid tension, MJ	0.5
Avoided products												

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745 *Table 3. Sensitivity analysis scenarios. Thermal recovery is considered for all these scenarios.*

Scenario	Subscenario	Silica Source	Silica source: FA mass ratio	Vitrification Temperature
Scenario BA	BA-40	Bottom Ash	40:60	1300˚C
	BA-60		60:40	
	BA-80		80:20	
Scenario G	G-40	Glass cullet	40:60	1300˚C
	G-60		60:40	
	G-80		80:20	
Scenario S	S-40	Silica sand	40:60	1450˚C
	S-60		60:40	
	S-80		80:20	

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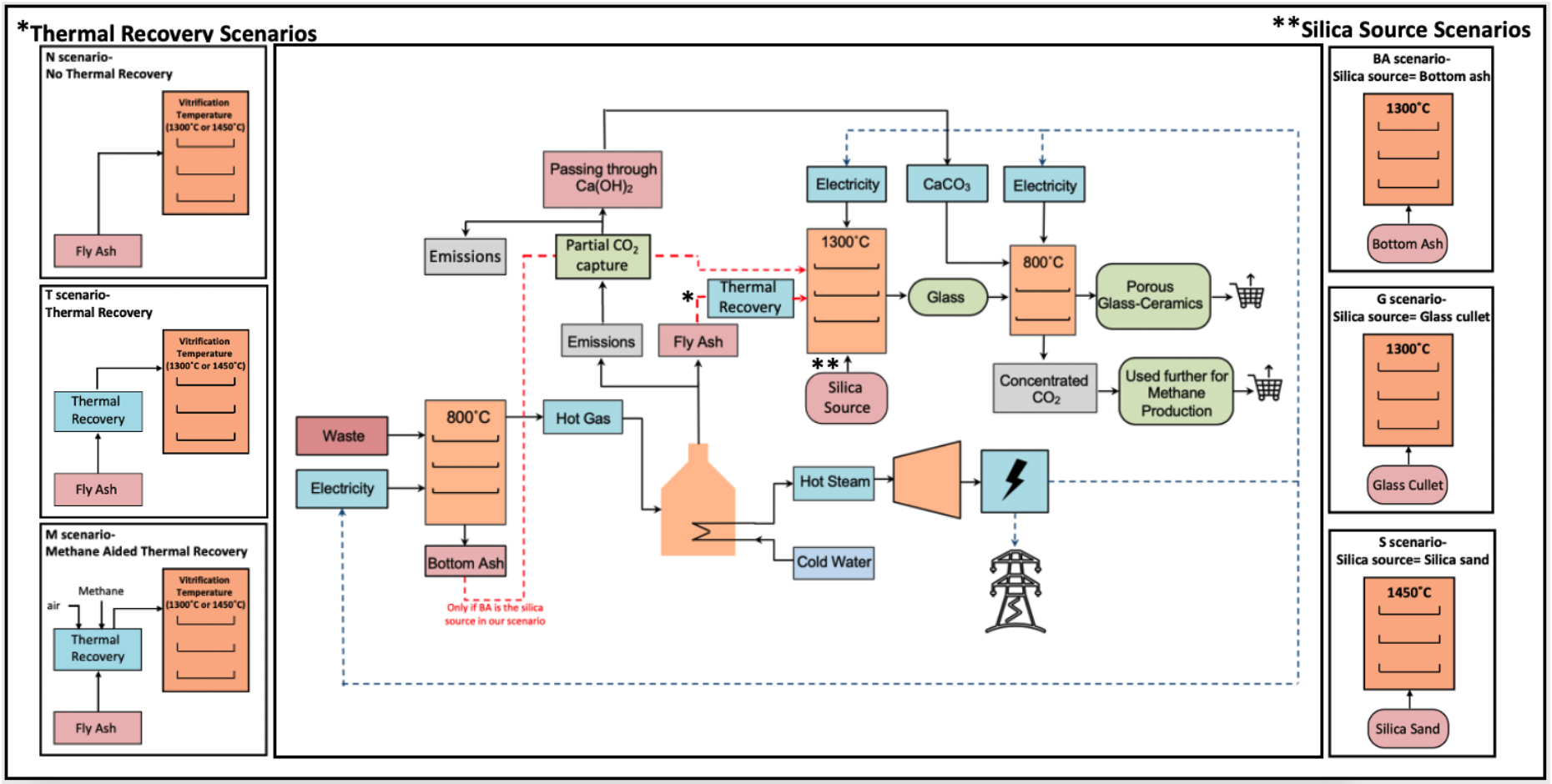

Figure 1. The incinerators design suggested by the current study for the production of foamed glass-ceramics. The boundary conditions are clear in this figure

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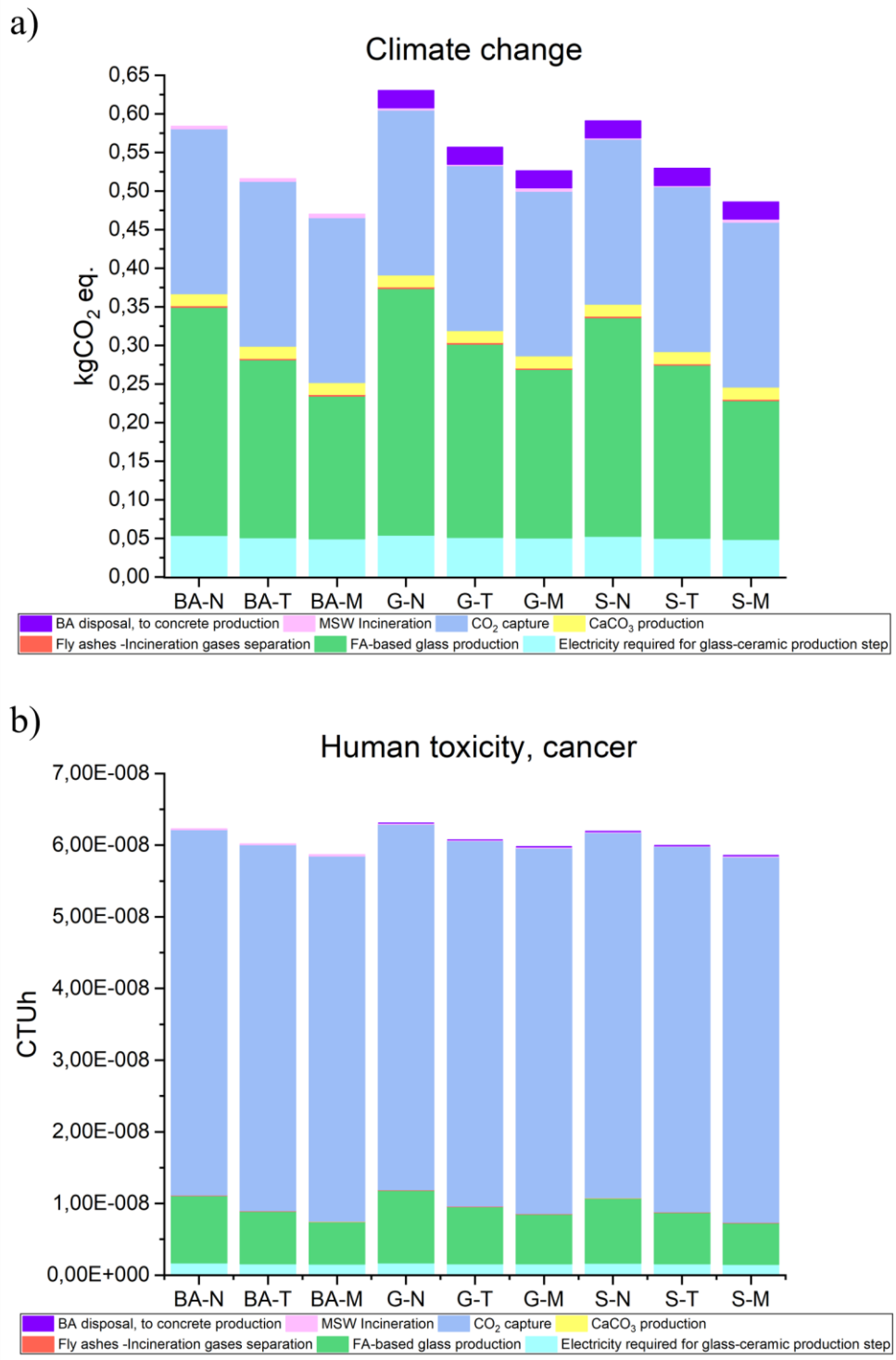

Figure 2 Evaluation of a) climate change and b) human toxicity categories for all studied scenarios; BA-N: bottom ash as a silica source, no thermal recovery; BA-T: bottom ash as a silica source + thermal recovery; BA-M: bottom ash as a silica source + thermal recovery aided by methane combustion; G-N: glass cullet as a silica source, no thermal recovery; G-T: glass cullet as a silica source + thermal recovery; G-M: glass cullet as a silica source + thermal recovery aided by methane combustion.; S-N: silica sand as a silica source, no thermal recovery; S-T: silica sand as a silica source + thermal recovery; S-M: silica sand as silica source + thermal recovery aided by methane combustion. The data refer to production of 1 kg of ceramic-glass.

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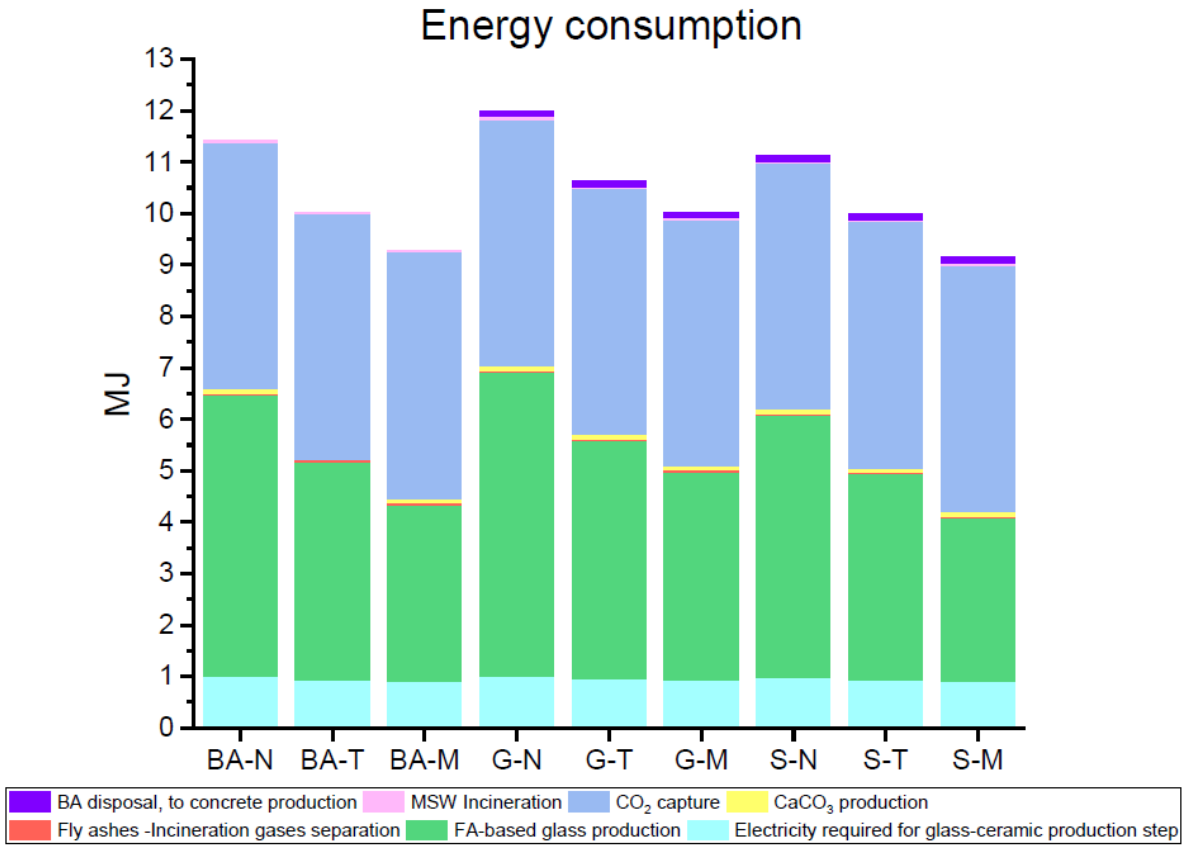

Figure 3 Energy consumption in all scenarios: BA-N: bottom ash as a silica source, no thermal recovery; BA-T: bottom ash as a silica source + thermal recovery; BA-M: bottom ash as a silica source + thermal recovery aided by methane combustion; G-N: glass cullet as a silica source, no thermal recovery; G-T: glass cullet as a silica source + thermal recovery; G-M: glass cullet as a silica source + thermal recovery aided by methane combustion.; S-N: silica sand as a silica source, no thermal recovery; S-T: silica sand as a silica source + thermal recovery; S-M: silica sand as silica source + thermal recovery aided by methane combustion. The data refer to production of 1 kg of ceramic-glass.

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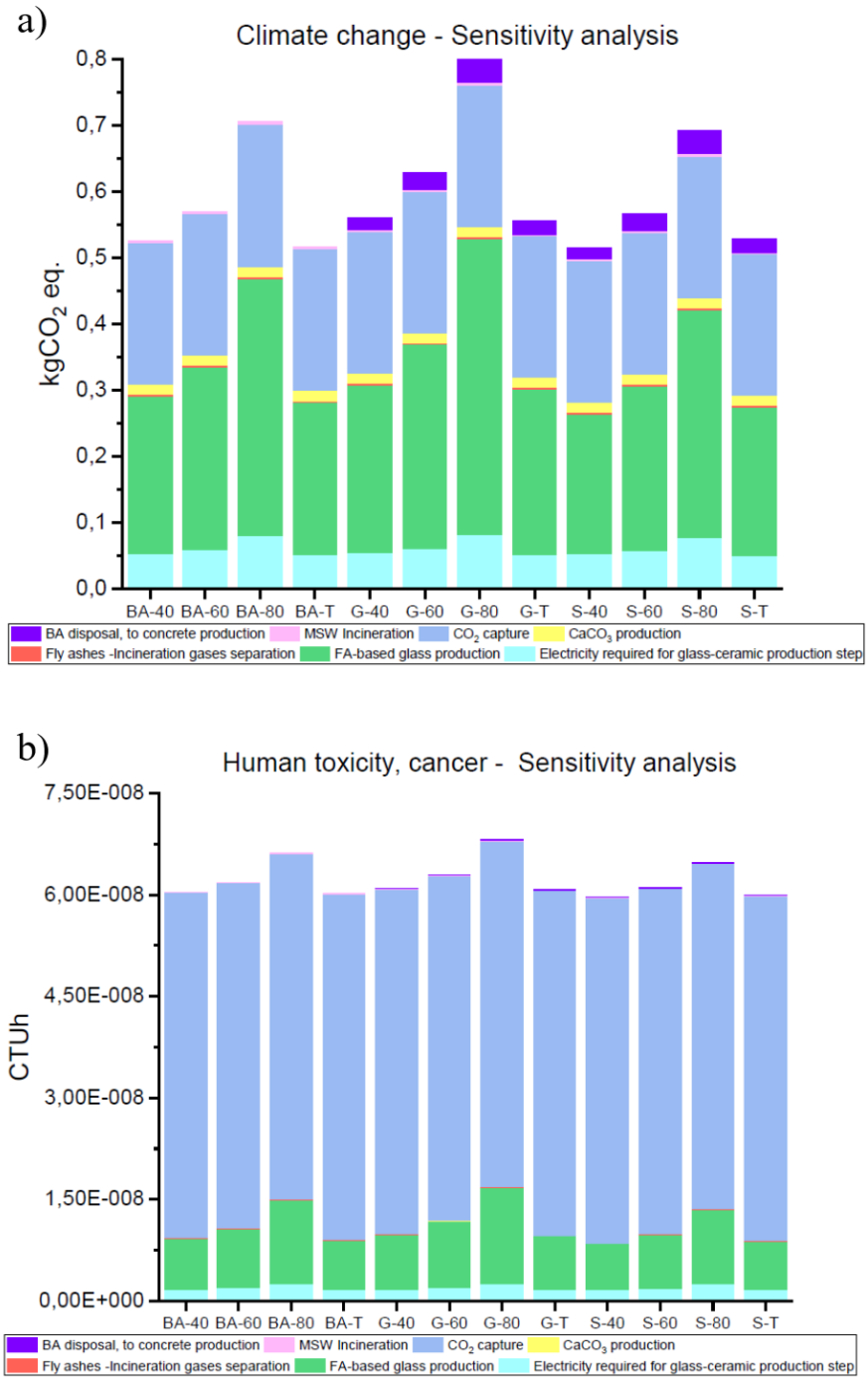

Figure 4 Sensitivity analysis on a) climate change and b) human toxicity. BA-40: bottom ash as a silica source, FA:silica source ratio 60:40; BA-60: bottom ash as a silica source, FA:silica source ratio 40:60; BA-80: bottom ash as a silica source, FA:silica source ratio 20:80.; BA-T: bottom ashes as silica source, fly ashes heated through thermal recovery; G-40: glass cullet as a silica source, FA:silica source ratio 60:40; G-60: glass cullet as a silica source, FA:silica source ratio 40:60; G-80 glass cullet as a silica source, FA:silica source ratio 20:80; G-T: glass cullet as a silica source, fly ash heated through thermal recovery; S-40: silica sand as a silica source, FA:silica source ratio 60:40; S-60: silica sand as a silica source, FA:silica source ratio 40:60; S-80: silica sand as a silica source, FA:silica source ratio 20:80; S-T: silica sand as a silica source, fly ash heated through thermal recovery. The data refer to production of 1 kg of ceramic-glass.

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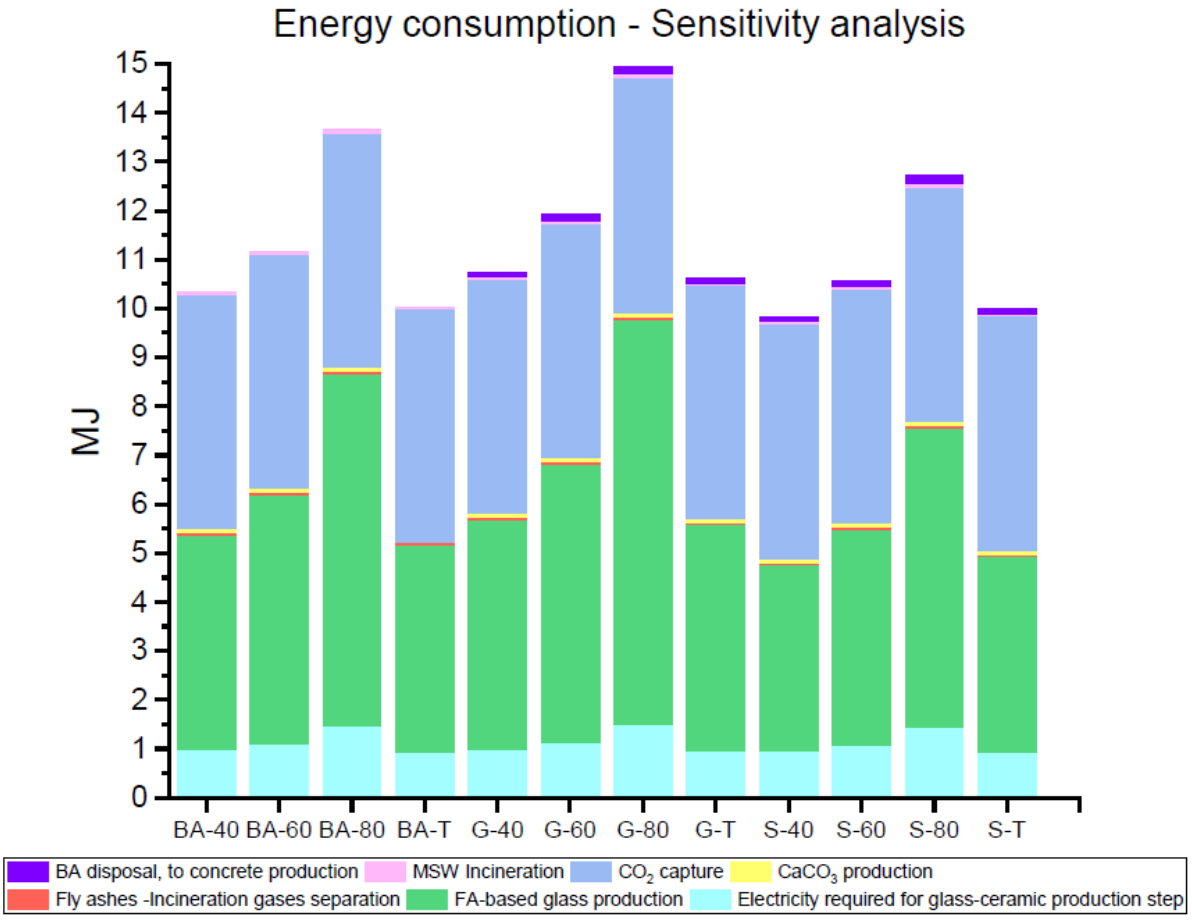

Figure 5 sensitivity analysis on the total energy consumption. BA-40: bottom ash as a silica source, FA:silica source ratio 60:40; BA-60: bottom ash as a silica source, FA:silica source ratio 40:60; BA-80: bottom ash as a silica source, FA:silica source ratio 20:80.; BA-T: bottom ashes as silica source, fly ashes heated through thermal recovery; G-40: glass cullet as a silica source, FA:silica source ratio 60:40; G-60: glass cullet as a silica source, FA:silica source ratio 40:60; G-80 glass cullet as a silica source, FA:silica source ratio 20:80; G-T: glass cullet as a silica source, fly ash heated through thermal recovery; S-40: silica sand as a silica source, FA:silica source ratio 60:40; S-60: silica sand as a silica source, FA:silica source ratio 40:60; S-80: silica sand as a silica source, FA:silica source ratio 20:80; S-T: silica sand as a silica source, fly ash heated through thermal recovery. The data refer to production of 1 kg of ceramic-glass.

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