

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

*Original*

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

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6

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9 **Abstract**

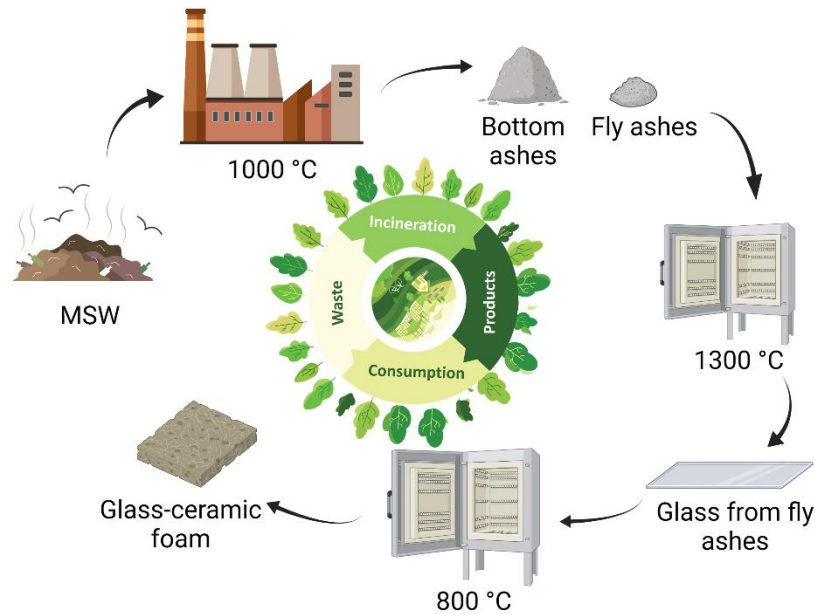
10 Municipal solid waste (MSW) production in the world has increased by 60% in recent years.  
11 Incineration of MSW reduces their volume in conjunction with energy recovery. Incineration  
12 produces two residues, namely bottom ash (BA) and fly ash (FA), with high concentration of  
13 heavy metals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

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27 ashes as a silica source together with methane-combustion-aided recovery: 0.467 kgCO<sub>2,eq</sub>,  
28 5.83·10<sup>-8</sup> carcinogenic-CTUh and 9.26 MJ required per kg of glass-ceramics produced.

## 29 Graphical abstract



30

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

## 33 1. Introduction

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

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44 The residues of incineration are bottom ash and fly ash. Bottom ash (BA) accounts for around  
45 80 wt% of the total incineration residues and is composed of heterogeneous solid granules of  
46 broken glass cullet, ceramic, slag/sintered phases, and unburnt materials (Loginova et al.,  
47 2019; Xuan et al., 2018). The other incineration residues are fly ashes (FA), in whose  
48 composition can widely differ depending on the consumers behavior in the production of  
49 solid waste. FA contain soluble salts, high concentration of heavy metals, and organic  
50 pollutants such as dioxins. Even though, some heavy metals are also present in BA, heavy  
51 metals concentration in FA is higher, classifying them as hazardous waste materials. Some of  
52 the most common heavy metals found in FA are Hg, Pb, Zn, Cd, As, Sb, Cu, Sn, Ni, Cr, V  
53 (Čarnogurská et al., 2015; Luo et al., 2019).

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

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

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

71 Vitrification of bottom ash is feasible due to its high silica content and can be further  
72 facilitated by small addition of waste glass (glass cullet). One way to confirm the safety of the  
73 vitrified products is the standard EN 12457-2 leaching test (EN 12457-2, 2002). To be  
74 classified as suitable for reuse, the leaching tests results need to respect national regulations.  
75 As stated by Blasenbauer et al. (Blasenbauer et al., 2020), in the European Union (EU) there  
76 is no uniformed regulation for BA reuse. Despite the presence of an EU-emanated directive,  
77 each EU Member State may adhere to more stringent regulations, as stated by the directive  
78 itself (The Council of the European Union, 2003). Therefore, the exact limits may vary within  
79 the EU. In the case of Italy, non-hazardous waste classification for reuse is regulated by two  
80 Ministerial Decrees (DM) (Italian Republic, 1998a; Italian Republic, 1998b; Italian Republic,  
81 2006). For EU-widespread, albeit less specific, leaching threshold for classification as  
82 landfill-suitable non-hazardous wastes, European Council Decision 2003/33/EC should be  
83 referred to. More info on the regulations were provided in the supplementary materials.

84 Previously, it has been shown that vitrified BA passed the EN12457-2 leaching test,  
85 confirming their appropriateness for several industrial applications (Sharifikolouei et al.,  
86 2020). On the other hand, FA vitrification is only possible when adequate amount of silica  
87 source is used as an additive due to FA low silica and alumina content. The silica source can  
88 be simply BA, or other discarded materials such as glass cullet. However, finding the right  
89 composition for the successful vitrification of FA is a challenging task because the  
90 composition of FA varies greatly depending on the MSW composition.

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

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

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

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

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

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115 The adopted approach was to simulate the incineration plant condition through Aspen Plus  
116 and conduct its environmental analysis through LCA study considering two methods: ILCD  
117 2011 Midpoint+ method and Cumulative Energy Demand (CED). For the ILCD 2011  
118 Midpoint+ method, the following impact categories were studied according to Morselli et al.  
119 (Morselli et al., 2008): global warming potential and human toxicity. For the CED, the focus  
120 was on the evaluation of the total energy consumption of the process.

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

130

## 131 **2 Materials and methods:**

132 Life cycle assessment (LCA) was performed with SimaPro 9.0 software based on ISO 14040  
133 (2006) and 14044 (2006). Databases Ecoinvent 3.0 and Agri-Footprint were employed.

134

### 135 **2.1 Goal and scope:**

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

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

143 Vitrification requires a high-silica source, therefore silica-rich materials are usually used to  
144 conduct FA vitrification (Sharifikolouei et al., 2021a). BA contain enough silica to be  
145 vitrifiable on their own (Sharifikolouei et al., 2021a). Glass cullets and silica sand were  
146 shown to be constituted for 64.46% and 99.75% on a mass basis, from silica, respectively.  
147 (Sharifikolouei et al., 2021a). However, vitrification requires temperatures ranging from  
148 1100°C to 1500°C (Sharifikolouei et al., 2021a). Moreover, vitrification additives extraction  
149 or production could lead, on the long term, to impoverish natural resources. Thus, when  
150 possible, solutions to avoid excessive use of raw materials and to reduce the required energy  
151 to reach vitrification temperatures should be considered.

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

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

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

173 Each scenario was analyzed and compared in terms of environmental and energetic  
174 sustainability. From now on, each scenario or subscenario will be referred to using the names  
175 listed in Table 1. The functional unit (FU) was 1 kg of glass-ceramics production, and all data  
176 of inventory were referred to the FU. To keep the analysis as conservative as possible, all the  
177 burdens were allocated onto the produced glass-ceramic. In cases where all the outputs of a  
178 process steps contributed to the FA-valorizing glass-ceramic production, a mass-basis  
179 allocation was used. The mass basis was chosen to use a pertinent physical correlation, broad  
180 enough to allow comparing the findings reported in this study with future research. The cut-  
181 off method was applied to the pure CO<sub>2</sub> stream co-produced during the glass-ceramics  
182 production, due to CO<sub>2</sub> stream contributing for less than 1%, to the total burdens.

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

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190 incinerated waste and were entrained to the filtration system by the flue gas because of their  
191 fine particle size (~60  $\mu\text{m}$  diameter (Rutkowska et al., 2018)). The flue gas was then sent to a  
192 heat exchanger to vaporize a water stream, to produce electricity in a vapor turbine. The  
193 cooled incineration gas was sent through an electrostatic filter, separating FA, with a removal  
194 efficiency calculated to be 99%. Afterwards, FA were stocked, and the gas was sent to a CO<sub>2</sub>  
195 capture section, which absorbed CO<sub>2</sub> using a monoethanolamine (MEA) aqueous solution  
196 (15.4% weight of MEA). The absorption occurred in an absorption column, meanwhile the  
197 CO<sub>2</sub>-rich MEA solution was sent to a stripper column, to remove the CO<sub>2</sub> from the aqueous  
198 solution through heating. The gases exiting from the stripper column were then sent to a  
199 condenser, separating the CO<sub>2</sub> from vapors and steam. The gas exiting the first absorption  
200 tower was sent to the gas treatment section. Gas treatment section was not a core part of glass-  
201 ceramic production and was the same for all subscenarios, thus it was not included in LCA  
202 boundaries. Its inclusion would have resulted in the same burdens for all subscenarios, thus  
203 not contributing in highlighting their differences. The captured CO<sub>2</sub> was then used to produce  
204 the foaming agent (CaCO<sub>3</sub>), through reaction with Ca(OH)<sub>2</sub>. Meanwhile, the stocked FA was  
205 sent to a furnace, where the silica source was added. Furnace heating was provided by  
206 electricity and the melting-FA-silica-source vitrification batch was heated up to the  
207 vitrification temperature, which depends on the used type of silica source.

208

## 209 **2.2 Life Cycle Inventory (LCI)**

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

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215 commodity composition was used (Primary data by IREN commodity extract, 2021), which  
216 was compared with a reference for North Italy MSW composition (Calabrò and Pagallo,  
217 2020).

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

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

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240 et al. (Biganzoli et al., 2019). BA disposal consisted in separating metallic components from  
241 non-metallic components, using magnetic separators. Afterwards, the remaining BA were  
242 subjected to water-washing, to remove BA chlorine compounds and other salts (Biganzoli et  
243 al., 2019; Verbinnen et al., 2017). After washing operations, residual unburnt BA components  
244 were sent back to the MSWI to be incinerated. The washing operations wastewaters were then  
245 treated using a NaOH solution, containing FeSO<sub>4</sub> and a cationic polyelectrolyte. The metallic  
246 components recovered from BA disposal could have been recovered and treated as avoided  
247 burdens; however, their recovery was not included in the LCA. The cationic polyelectrolyte  
248 was not included, since its exact composition was not specified in Biganzoli et al.'s work.  
249 However, the polyelectrolyte did not represent a crucial contributor to the overall disposal  
250 process burdens (Biganzoli et al., 2019).

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

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

268

### 269 **2.3 Life Cycle Impact Assessment (LCIA)**

270 Life cycle impact assessment was performed using ILCD 2011 Midpoint+ and Cumulative  
271 Energy Demand methods. ILCD 2011 Midpoint+ was used to assess climate change (kg CO<sub>2</sub>  
272 equivalent), human toxicity, carcinogenic (CTUh). Morselli et al. (Morselli et al., 2008) have  
273 previously stated that greenhouse gas emission has higher potential impact in thermo-  
274 valorization plants. Cumulative Energy Demand (CED) evaluated the impact of the total  
275 energy consumption of the whole process.

276

### 277 **2.4 Interpretation of Results**

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

286

## 287 **3 Results and Discussion**

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288 Different sources of silica are considered as vitrification agents, thus the vitrification  
289 temperature varies according to the properties of the silica source. Each silica source was  
290 mixed with FA and vitrified at the indicated temperature. The vitrified product was then  
291 mixed with calcium carbonate and heated up to 800°C in a heat-treatment furnace leading to  
292 its crystallization meanwhile the produced CO<sub>2</sub> gas resulting from calcium carbonate  
293 decomposition ( $\text{CaCO}_3 \rightarrow \text{CO}_2 + \text{Ca(OH)}_2$ ), produces a foamed glass-ceramic. The released  
294 high purity CO<sub>2</sub> stream here is again captured from the heat-treatment furnace and has added  
295 value for its high purity. Inside the MSW incineration plant, a percentage (0.25 wt% for -T  
296 subscenarios, 0.1 wt% for -M subscenarios) of the incineration gas could increase the FA  
297 temperature before vitrification, saving thermal energy. In -M subscenarios, in addition to  
298 incineration gases, methane-combustion gases were used for the thermal recovery as well  
299 (0.00864 kgCH<sub>4</sub>/kg produced glass-ceramic). The methane combustion helped the gases to  
300 reach a higher temperature, achieving an even higher temperature for the FA batch,  
301 guaranteeing a lower vitrification energy consumption.

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

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

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

### 312 **3.1 Base scenarios**

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313 In Figure 2, for all proposed scenarios, the CO<sub>2eq</sub> emissions had the same magnitude order,  
314 ranging from 0.467 (BA-M scenario) to 0.626 (G-N scenario) kgCO<sub>2,eq</sub>/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  $0.0478 \pm 0.044$  and  $0.013 \pm 0.016$  kgCO<sub>2eq</sub>/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  $0.49 \pm 0.03$  kgCO<sub>2eq</sub>/kg of glass-ceramics produced, whereas T and N scenarios  
323 achieved  $0.53 \pm 0.02$  and  $0.598 \pm 0.023$  kgCO<sub>2eq</sub>/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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338 toxicity impact values equal to  $5.87 \cdot 10^{-8}$  CTUh  $\pm$   $5.74 \cdot 10^{-10}$ , whereas T and N subscenarios  
339 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.

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

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

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

357 T subscenarios burdens were between N and M subscenarios (Figure 2, Figure 3) due to the  
358 thermal recovery for FA. Higher starting temperature in the furnace implied less energy  
359 required to heat and vitrify the batch. T subscenarios required the installation and  
360 maintenance of additional equipment in exchange for both environmental and energetic  
361 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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387 al. (Huang et al., 2022) and Fruergaard et al. (Fruergaard et al., 2010) observed higher  
388 impacts due to FA vitrification on human health.

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

399 The high vitrification energy requirement agreed with other processes of vitrification or  
400 similar FA thermal treatments ; according to Huang et al. (Huang et al., 2022), FA  
401 vitrification exhibited an energy consumption of 2.16-3.6 MJ per FA kg. Ni et al. (Ni et al.,  
402 2012) studied a plasma melting vitrification of MSW FA, which exhibited an energy  
403 consumption of approximately 3.6 MJ per kg of FA. Bingham and Hand (Bingham and Hand,  
404 2006) reported that FA thermal treatments require 2 MJ per FA kg. Alhadj-Mallah et al.  
405 (Alhadj-Mallah et al., 2015) calculated that melting an FA-biomass mixture may require from  
406 1.65 to 2.65 MJ per kg. The high energy requirement for vitrification adds non-negligible  
407 costs to the process, as stated by Sakai and Hiraoka (Sakai and Hiraoka, 2000). Figure 2, 3  
408 demonstrated that the vitrification step was one of the step, alongside CO<sub>2</sub> capture, which  
409 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<sub>2,eq.</sub> (52.8% of vitrification burdens (VB)); BA-T=0.297 kgCO<sub>2,eq.</sub> (41.2%  
427 VB); BA-M=0.391 kgCO<sub>2,eq.</sub> (41.2% VB);

428 G-N=0.391 kgCO<sub>2,eq.</sub> (46.5% VB); G-T=0.324 kgCO<sub>2,eq.</sub> (42% VB); G-M=0.285 kgCO<sub>2,eq.</sub>  
429 (36% VB).

430 S-N=0.324 kgCO<sub>2,eq.</sub> (63.9% VB); S-T=0.264 kgCO<sub>2,eq.</sub> (59.1% VB); S-M=0.210 kgCO<sub>2,eq.</sub>  
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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434 If the ashes cannot be vitrified in the same incineration plant, the electric energy should come  
435 from external sources or generated in the vitrification plant. Carrying on the vitrification in  
436 the thermo-valorization plant avoids a significant part of the vitrification burdens. Benefits of  
437 generating electricity using the incineration gases were underlined by Leme et al. (Leme et al.,  
438 2014), stating that a waste-to-energy plant can generate 1.44 MJ per MSW kg as electric  
439 energy. The present work agrees with these findings since incineration of 25 kg of MSW  
440 generates up to 36 MJ of electric energy.

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

444

### 445 **3.3 Sensitivity analysis**

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

456 BA scenarios highest carcinogenic toxicity burdens were roughly 10% higher than BA-T  
457 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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482 source, allowing a minor disposed quantity of FA per vitrification batch. Hence these  
483 scenarios were not deemed as valid alternatives to the T scenarios.

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

494 Regarding “silica:FA 40:60” scenarios, G-40 and BA-40 showed higher burdens than G-T  
495 and BA-T scenarios, respectively, for all the analyzed burden categories. As opposed to them,  
496 S-40 achieved lower burdens than S-T scenario for all analyzed burden categories. The  
497 reasons for these trends, however, were not the same reported for scenarios silica:FA 80:20  
498 and 60:40. In scenario silica:FA 40:60, silica source quantities were 20% lower than in T  
499 scenarios. Lower energy consumption could therefore be expected. This only happened for  
500 the vitrification step, where higher FA quantity implies higher starting temperature of the  
501 batch. FA specific heat capacity was lower than that of glass cullet and silica sand, so less  
502 energy was required to heat the batch. However, in these scenarios, more wastes were  
503 incinerated, leading to a higher energy requirement from the CO<sub>2</sub> capture and the FA removal  
504 from flue gases, other than from MSWI, thus leading to higher environmental burdens. Even  
505 if a higher quantity of energy was generated, the total process requires more energy than T  
506 scenarios, reducing the net produced energy. This led to an increase in environmental and

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

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

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

526

## 527 **4 Conclusions**

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

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

545 Thus, interesting new paths of research could focus on optimizing the energy requirements,  
546 or extending the system boundaries, to determine whether it would be beneficial to adopt BA-  
547 M scenario, or to adopt a scenario similar to BA-M, using a silica source:FA ratio equal to  
548 40:60.

549 The result of the study is the eco-sustainability of fly-ash based glass-ceramics production  
550 obtained with bottom ashes as silica source and methane-combustion-aided recovery  
551 achieving: 0.467 kgCO<sub>2</sub>, 5.83·10<sup>-8</sup> CTUh and 9.26 MJ of energy consumption per kg of glass-  
552 ceramics produced.

553

## 554 **Acknowledgements**

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557

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725 **Tables and Figures**

726 *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*  
 727 *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*  
 728 *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*  
 729 *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*  
 730 *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 source; 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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733 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  
 734 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  
 735 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  
 736 analyzed silica sources and incineration gases were used to generate electricity. Similarly, biogenic CO<sub>2</sub> was assumed as not representing any burden, but was included in  
 737 the LCI since it is the main product of the CO<sub>2</sub> capture step and a reagent for calcium carbonate production. The rest of the represented items all contribute to the analyzed  
 738 impact categories.

	Municipal solid waste incineration		Water vaporization		Fly ashes removal		CO <sub>2</sub> capture		BA disposal through concrete production	
<b>Flow in</b>	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 <sup>†</sup> , kg	0.0546	Iron sulfate {RER}  market for iron sulfate, kg	6.8·10 <sup>-5</sup>
			Water, kg	54.85			Aqueous solution water <sup>†</sup> , 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	6.8·10 <sup>-8</sup>
<b>Flow out</b>	Incineration gases, kg	180.6	Incineration gases, kg	180.6	Incineration gases, kg	180.6	Incineration gases, kg	0.129	BA, kg	0.5
									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 <sub>2</sub> , kg	0.011	Treated wastewaters, kg	0.16
	Bottom ashes, kg	5.3	Steam, kg	54.85			Flue gases containing Fossil CO <sub>2</sub> , kg	0.0074	Treated BA, kg	0.448
							MEA vapor, kg	2.9·10 <sup>-4</sup>	Ferrous-magnetic materials, kg	0.039
<b>Energy required to carry out the process step</b>	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**

<b>Flow in</b>	Steam, kg										
<b>Flow out</b>	Expanse steam, kg										
	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
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**Energy required to carry out the process step**

<b>Avoided burdens</b>	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

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739 †□ The item does not contribute to mass balances. The item is the recirculated in the CO<sub>2</sub> capture system, thus being not part of the system mass balance.

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741 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  
 742 of the process, and were thus included in the LCI, despite being considered as near zero-burden.

		Thermal recovery			Vitrification			CaCO <sub>3</sub> production		Glass-ceramic foam production		
Scenarios BA												
		N	T	M				N	T	M		
<b>Flow in</b>	Incineration gases, kg	-	0.45	0.18	Fly ashes, kg	0.5	0.5	0.5	Biogenic CO <sub>2</sub> , 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) <sub>2</sub> , kg	0.0148	CaCO <sub>3</sub> , kg	0.02
	Methane, kg	-	-	8.64·10 <sup>-3</sup>								
<b>Flow out</b>	Incineration gases, kg	-	0.45	0.41	Fly ash glass, kg	1	1	1	CaCO <sub>3</sub> , kg	0.02	Glass-ceramic foam, kg	1
	Fly ashes, kg	-	0.5	0.5					H <sub>2</sub> O (vapor), kg	0.0036	Pure CO <sub>2</sub> , kg	0.0088
<b>Consumed Energy</b>	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
<b>Avoided products</b>												
Scenarios G												
		N	T	M				N	T	M		
<b>Flow in</b>	Incineration gases, kg	-	0.45	0.18	Fly ashes, kg	0.5	0.5	0.5	Biogenic CO <sub>2</sub> , 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) <sub>2</sub> , kg	0.0148	CaCO <sub>3</sub> , kg	0.02
	Methane, kg	-	-	8.64·10 <sup>-3</sup>								
<b>Flow out</b>	Incineration gases, kg	-	0.45	0.41	Fly ash glass, kg	1	1	1	CaCO <sub>3</sub> , kg	0.02	Glass-ceramic foam, kg	1
	Fly ashes, kg	-	0.5	0.5					H <sub>2</sub> O (vapor), kg	0.0036	Pure CO <sub>2</sub> , kg	0.0088
<b>Consumed Energy</b>	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
<b>Avoided products</b>												
<b>Scenarios S</b>												
		N	T	M		N	T	M				
<b>Flow in</b>	Incineration gases, kg	-	0.45	0.18	Fly ashes, kg	0.5	0.5	0.5	Biogenic CO <sub>2</sub> , 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) <sub>2</sub> , kg	0.0148	CaCO <sub>3</sub> , kg	0.02
	Methane, kg	-	-	8.64·10 <sup>-3</sup>								
<b>Flow out</b>	Incineration gases, kg	-	0.45	0.41	Fly ash glass, kg	1	1	1	CaCO <sub>3</sub> , kg	0.02	Glass-ceramic foam, kg	1
	Fly ashes, kg	-	0.5	0.5					H <sub>2</sub> O (vapor), kg	0.0036	Pure CO <sub>2</sub> , kg	0.0088
<b>Consumed Energy</b>	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
<b>Avoided products</b>												

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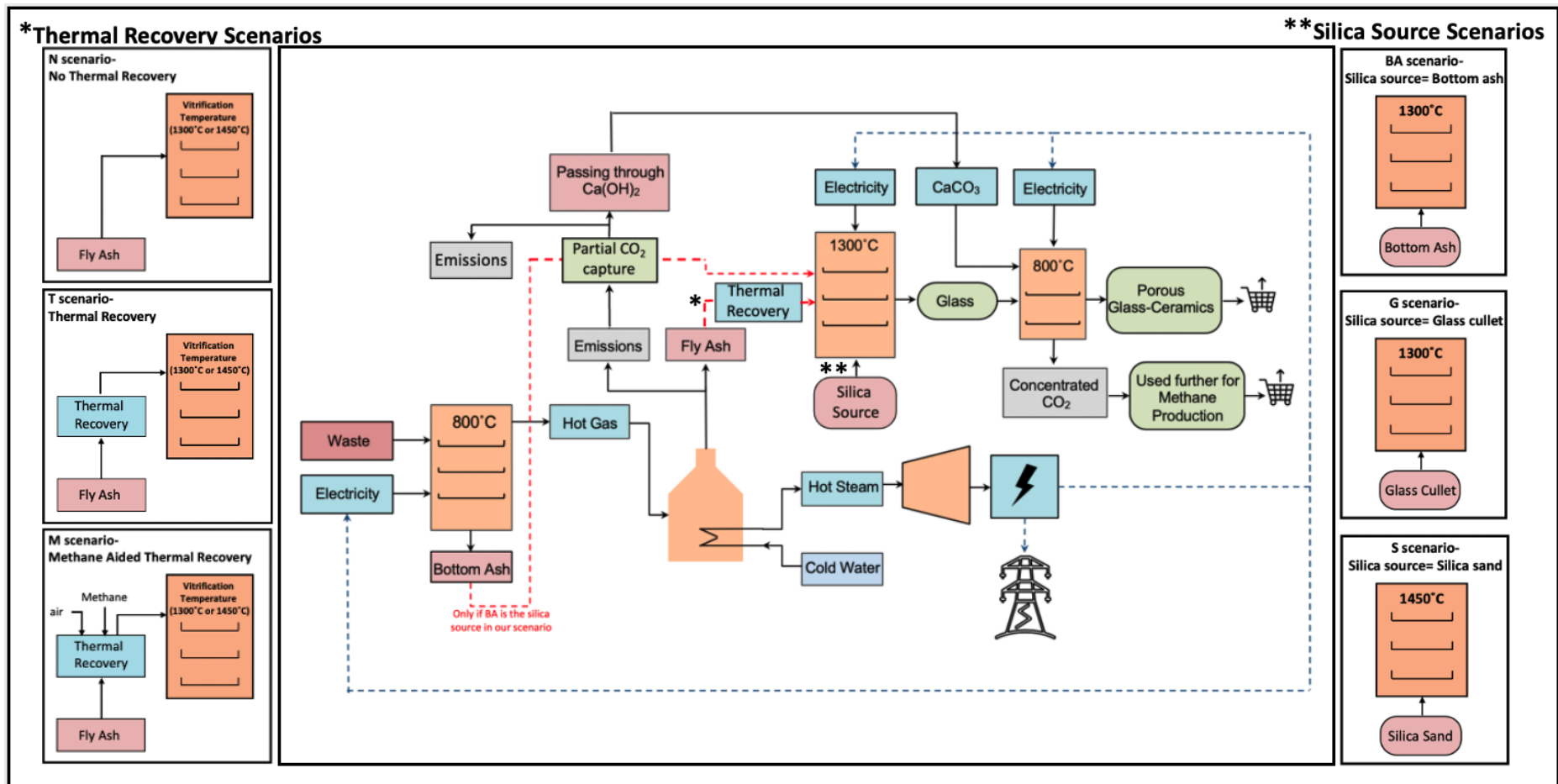
*Table 3. Sensitivity analysis scenarios. Thermal recovery is considered for all these scenarios.*

<b>Scenario</b>	<b>Subscenario</b>	<b>Silica Source</b>	<b>Silica source: FA mass ratio</b>	<b>Vitrification Temperature</b>
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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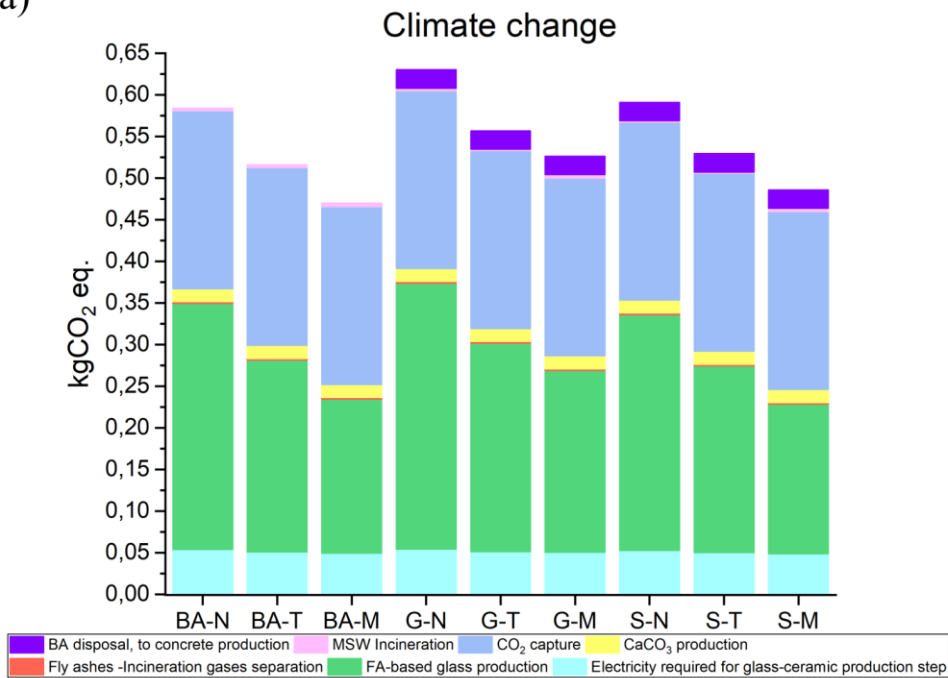
Figure 1. The incinerators design suggested by the current study for the production of foamed glass-ceramics. The boundary conditions are clear in this figure

749

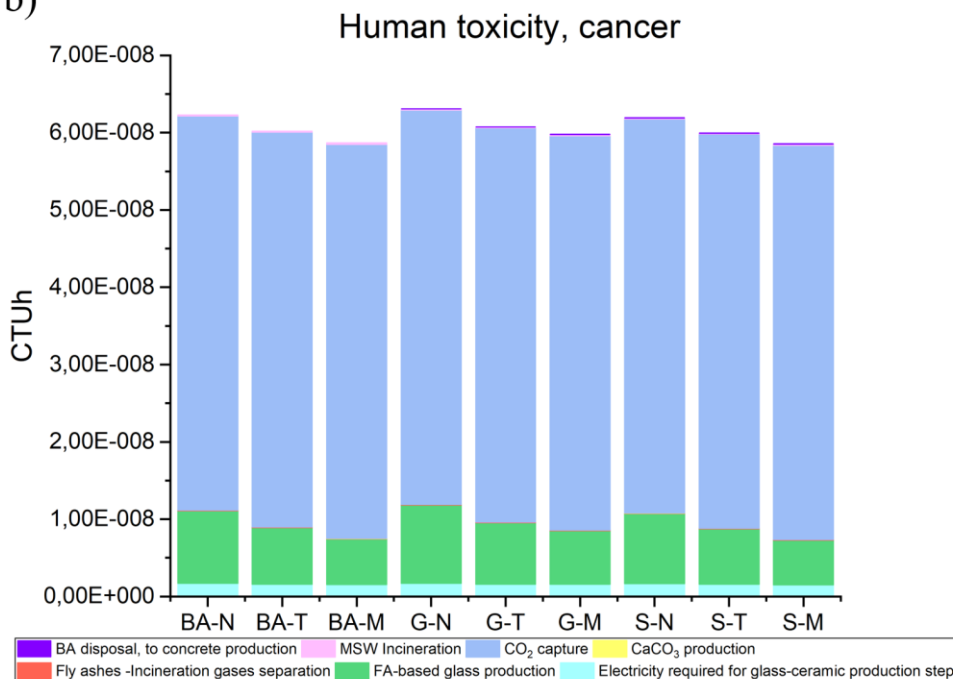
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a)



b)

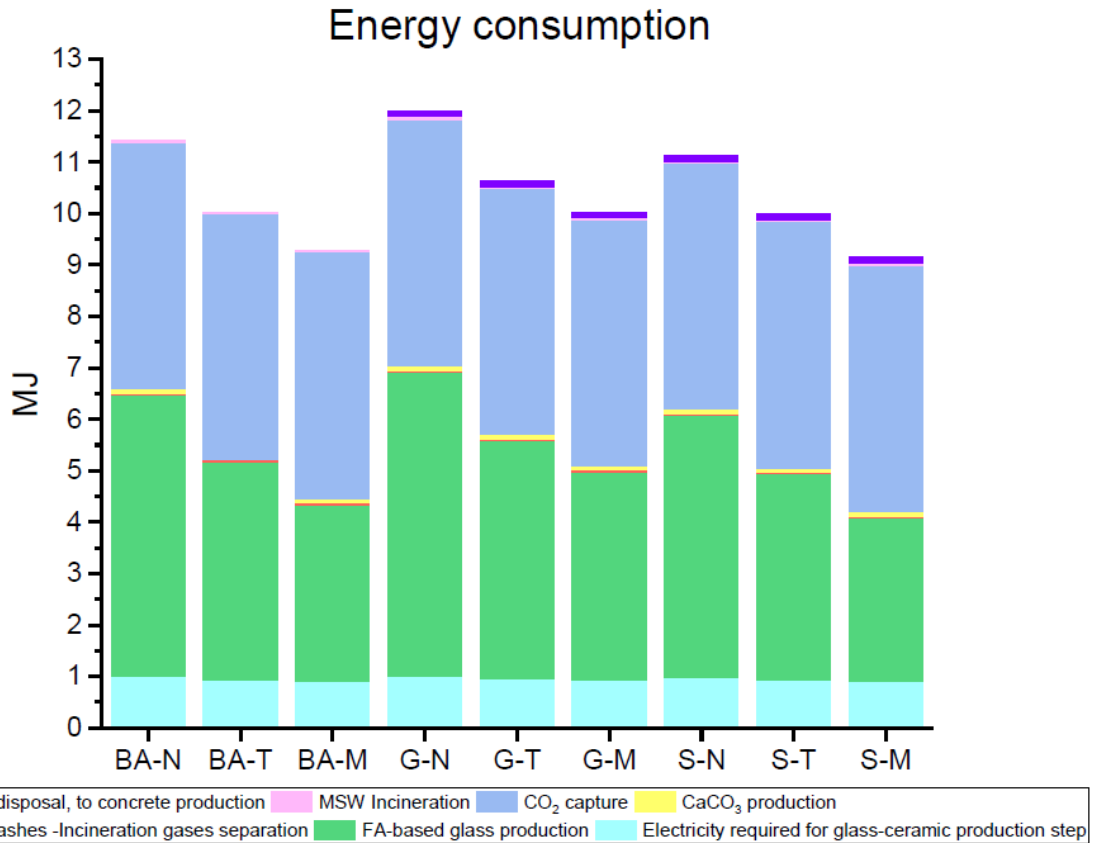


750

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

\*F. Barracco e F. Demichelis contributed equally to this work

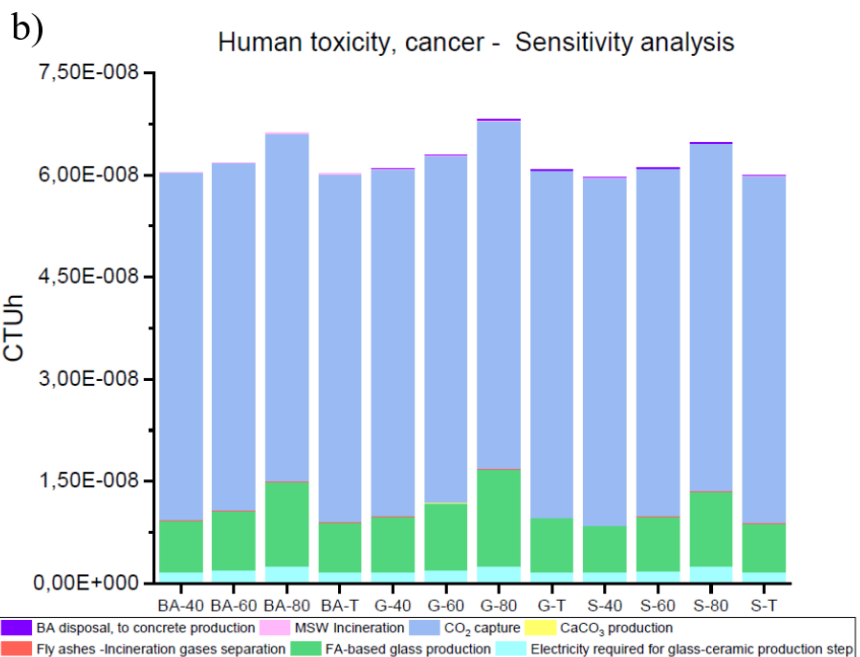
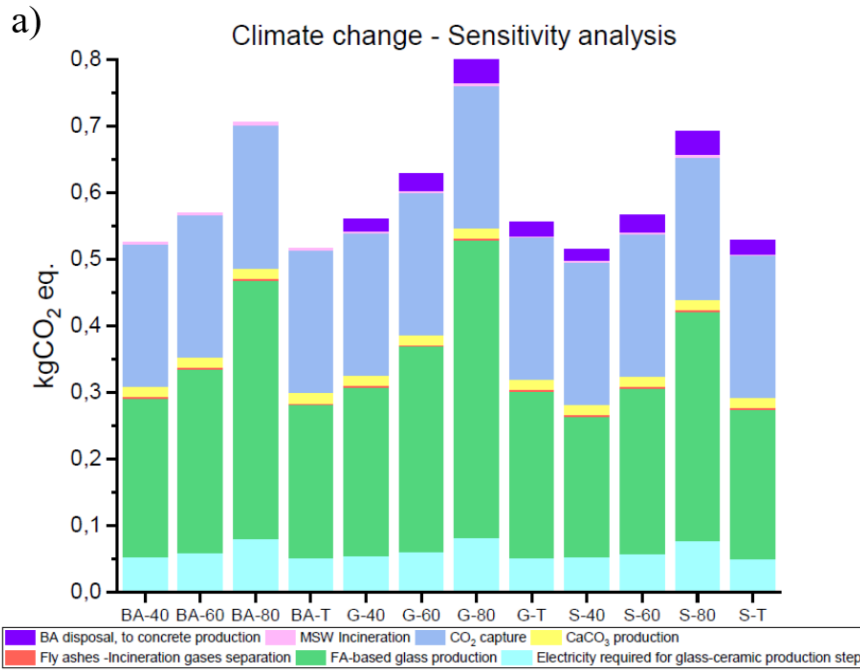
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759

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

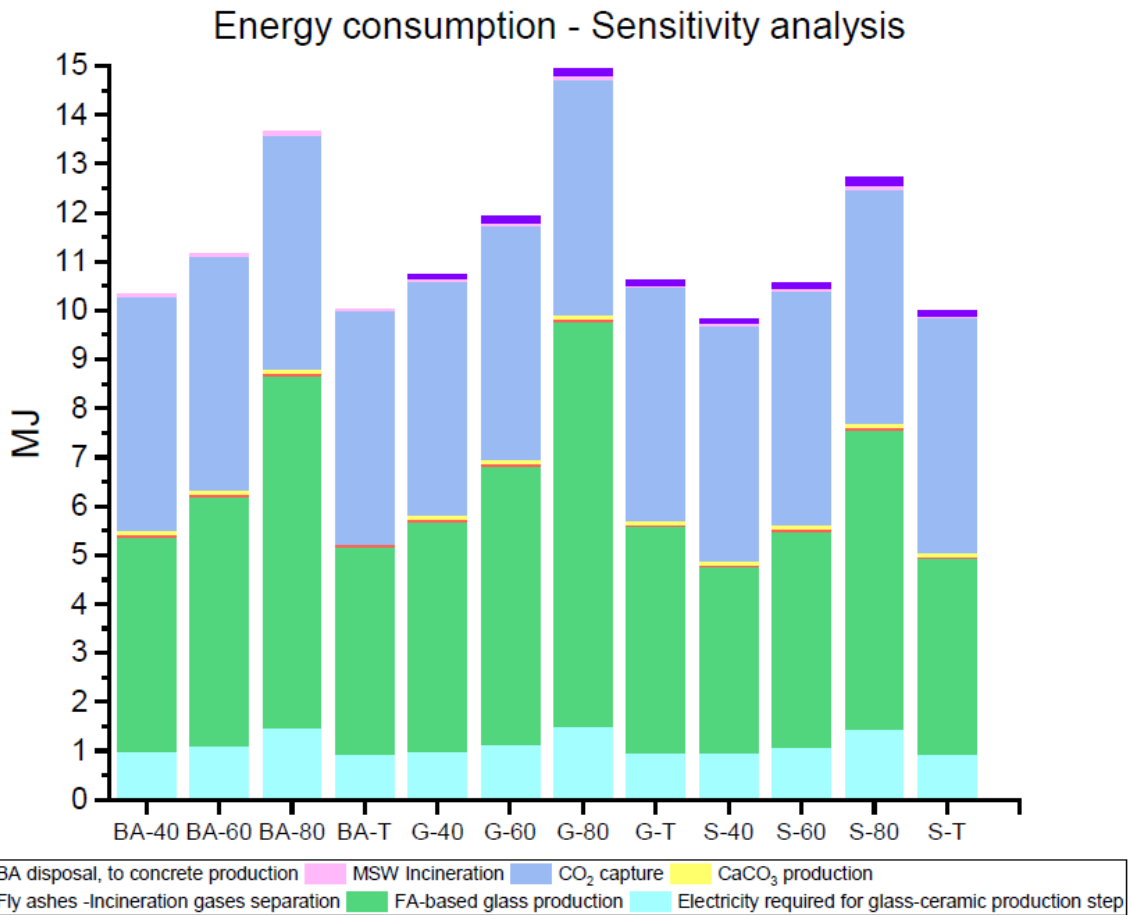
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769 Figure 4 Sensitivity analysis on a) climate change and b) human toxicity. BA-40: bottom ash as a silica source,  
 770 FA:silica source ratio 60:40; BA-60: bottom ash as a silica source, FA:silica source ratio 40:60; BA-80: bottom  
 771 ash as a silica source, FA:silica source ratio 20:80.; BA-T: bottom ashes as silica source, fly ashes heated  
 772 through thermal recovery; G-40: glass cullet as a silica source, FA:silica source ratio 60:40; G-60: glass cullet  
 773 as a silica source, FA:silica source ratio 40:60; G-80 glass cullet as a silica source, FA:silica source ratio  
 774 20:80; G-T: glass cullet as a silica source, fly ash heated through thermal recovery; S-40: silica sand as a silica  
 775 source, FA:silica source ratio 60:40; S-60: silica sand as a silica source, FA:silica source ratio 40:60; S-80:  
 776 silica sand as a silica source, FA:silica source ratio 20:80; S-T: silica sand as a silica source, fly ash heated  
 777 through thermal recovery. The data refer to production of 1 kg of ceramic-glass.

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