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Comparative environmental life cycle analysis of stone wool production using traditional and alternative materials

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Abstract

The mineral wool sector represents 10 % of the total output tonnage of the glass Industry. Thermal, acoustic and fire protection properties of the mineral wool makes it a product used in a wide range of economic sectors specially in the construction industry for the creation of low energy buildings. The traditional Stone wool manufacturing process involves melting of raw materials, in a coke-fired hot blast cupola furnace, fiberization, polymerization, cooling, product finishing and gas treatment as main stages. The use of alternative raw materials as torrefied biomass and sodium silicate, is proposed as alternative manufacturing process in order to improve sustainability in the Stone wool production, particularly reducing gas emissions (CO_2 and SO_2). The present study adopts a life cycle analysis (LCA) approach to measure the comparative environmental performance of the traditional and alternative stone wool production process; process data are incorporated into a LCA model using SimaPro 8 software with Ecoinvent version 3 life cycle inventory database. *CML 2000* and *Eco-Indicator99* methods are used to estimate effects on different impact categories. The impacts *Minerals* and *Land use* in Eco-Indicator99, and the *Euthrophication* impact in CML2000, increase between 2-4% using the alternative process instead the traditional one. In the same way, all the ecotoxicity related impacts increase between 9-24% with the use of alternative process. However these increases are compensated by impact decreases in other categories of impact; in consequence, the three areas of impact that grouped all individual Eco-indicator 99 impacts, show environmental benefits between 6-15% when using alternative process based on torrefied biomass and silicate, instead traditional process based on coke and cement use.

1. Introduction

Fibrous materials may be naturally occurring or synthetically manufactured by thermal or chemical processes. Refractory ceramic fiber, fiber glass and mineral (or stone) wool, belong to a class of materials known as synthetic vitreous fibers [1]. Mineral wool is typically used in the construction industry for heat insulation, cold and fire protection, and noise insulation [2]. In 2011 traditional mineral wool prevailed in the world thermal insulating materials market with a 52% the market share. The technical, environmental and public health aspects of the insulation materials, play an increasing role in the highly competitive building construction market [3] and more environmentally friendly buildings outlines developing opportunities for improved, new and alternative sustainable insulating materials [4,5].

In Europe the mineral wool production directly employed over 21000 people at 62 installations in 2005. The total volume of rock wool production in EU27 countries between the years 2003 and 2011 shows a great variation in production volumes between years (between 1.95 and 2.5 million tonnes), but the annual production volume showed an average growth rate of 0.91 % as the general trend [6-8].

The most common melting technique for the production of traditional stone wool is the coke-fired hot blast cupola furnace, raw materials that are usually used are: i) rocks, typically formed in volcanos and it could be diabase, gabbro or basalt; ii) briquettes, made from a blend of various minerals, such as olivine or basalt, diabase, gabbro, together recycled waste stone wool and using cement as binder; and iii) limestone added to adjust the viscosity of the melt to the requirements of the spinning process.

The molten material, at between 1300°C to 1500°C, is gathered at the bottom of the furnace and flows out of a notch and along a short trough positioned above the spinning machine. Air is blasted from behind the rotating wheels to attenuate the fibersand to direct them onto the collection belt to form a mattress. An aqueous phenolic resin solution is sprayed over the fibers. The mattress passes through an oven, which dries the product and cures the binder. The product is then cooled and cut to size before packaging. Gases emitted during the production process are cleaned in gas treatment systems to minimise the environmental impact. Water use in the process is generally confined to closed circuit systems.

A set of Best Available Techniques (BAT), with potential for achieving a high level of environmental protection, can be applied to stone wool manufacturing installations; these BAT are focused to avoid, reduce and control dust and gaseous emissions from melting and downstream manufacturing processes. Environmental management systems, process-integrated techniques and end-of-pipe measures, waste minimization and recycling procedures, and techniques for reducing the consumption of raw materials, water and energy, are proposed as BAT [9].

Alternative raw materials derived from mineral wastes can play an important role in manufacture of mineral wool [10]. Several methods have been developed to return fine rock wool production waste and to recycle mineral wool waste to the manufacturing process through briquetting mineral wool waste with a binder material [11,7]. An alternative process patented by VL Ambiental company [12], proposes the use of briquettes formed by waste rock wool for production process agglomerated with torrefied biomass (conventional biomass, sewage sludge) as alternative fuel briquetted. The binder used is a not fibrous inorganic material such as sodium silicate, which replaces the cement used in the traditional process.

Using a sulphur free binder and a biomass fuel as CO_2 neutral, have the advantage of reducing both the emissions of CO_2 and SOx. In addition to the low nitrogen content of biomass, the fuel nitrogen in biomass is converted to NH radicals during combustion providing an in situ thermal DeNOx source and can also result in lower NOx levels [13].

The life cycle analysis (LCA) is a methodological tool to measure the environmental impact of a product, process or system throughout its life cycle. It is based on the collection and analysis of the inputs and outputs of the system to obtain results that show its potential environmental impacts; LCA results can be used in order to be able identify strategies for reducing impact and to improve industrial processes obtaining a more environmentally-friendly process under a cradle to gate approach [14]. LCA approach has been applied extensively to construction materials and to insulation materials, particularly to mineral wool products [15-18].

The main objective of the present study is to adopt a LCA approach to measure the comparative environmental performance of the different stages of traditional and alternative stone wool production processes. Process flow diagram is build and the mass and energy balance are made. A comparative LCA is applied to both processes determining the inventory analysis and impact assessment.

2. Materials and methods

2.1 Raw materials and manufacturing processes.

Raw materials are the main difference between the traditional process (using petroleum coke (petcoke), and metallurgical coke (metcoke) as two different industrial options) and alternative (using torrefied biomass) process of manufacturing. In stone wool the main oxides are silicon dioxide and oxides of alkali earth metals (predominantly calcium and magnesium). The silicon dioxide is derived principally from basalt and blast furnace slag. These raw materials are used in both processes studied. The alkali earth metal oxides are derived from the briquetted recycled material. In the traditional briquettes, cement is used as binder, while in the alternative process the cement is replaced by sodium silicate (Table 1). The composition of the traditional raw materials is obtained from the Integrated Environmental Authorisation of the company Rockwool Peninsular 2005 [19]. The amount of biomass needed is greater (215 kg) than the petcoke (155 kg) and metcoke (167.8 kg) due to a lower heat capacity of the biomass (5618 kcal/kg) versus petcoke (7792.3 kcal/kg) and metcoke (7200 kcal/kg). The manufacturing steps, equipment and energetic requirements are the same with the three raw materials.

The process for production of stone wool comprises melting, fiberization, polymerization, cooling, product finishing and gas treatment as main sections. A detailed process flow diagram (PFD), building in Aspen software, can be found in Figure 1. This PFD is the same for traditional and alternative process with only differences in the inputs (selected raw materials) and outputs (emissions) variables from mass balance analysis.

Fig. 1 *Flow diagram of the stone wool manufacturing process and equipment list.*

The stone wool production in the blast oven includes coke used for heating and melting the rocks, melting the raw materials and additives (Table 1) and fibers formation on to rotating wheels under the influence of a powerful airflow. The product is cured in a polymerisation chamber at 200 ºC and after cooling, the stone wool is cut into the desired dimensions and packaged in polyethylene foil. The flue gas treatment system includes cooling and particle separation before burner systems. Off-cuts and other mineral wool scraps are recycled back into the production process, which further reduces inputs and energy requirements.

Significant impact of the coke properties and reactivity on the cupola operation in stone wool production has been reported [20]. With a more reactive coke less heat is lost to the cooling water and therefore coke can be saved. The coke reactivity must be previously determined for each specific application. The reactivity of metallurgical coke is slightly lower than that of petroleum coke [21]. However, the petcoke has higher Sulphur content than metcoke (Table 2, Appendix). On the other hand, sodium silicate is being widely used as raw material in alternative inorganic thermal insulation material and is fundamental in the geopolymer technology [22-23]. The use of torrified biomass and sodium silicate as alternative material in the present work reduces the carbon and sulphur content of the raw materials and make possible the reduction of the process outflow gas emission of carbon dioxide and sulphur dioxide (Table 1).

2.2 Life cycle assessment (LCA)

The Life Cycle Assessment (LCA) has been conducted according to standard methodology ISO 14040 and ISO 14044 [24,25]. The experimental results were incorporated into a LCA model using SimaPro v.8 software with Ecoinvent v.3 life cycle inventory data base. *CML 2000* and *Eco-Indicator99* methods have been used to estimate effects on different impact categories. According to the standards, LCA methodology is divided into four steps:

Goal and scope definition

The objective of the study is to evaluate and compare the environmental impacts generated by the stone wool traditional and alternative manufacturing processes. The functional unit selected for this analysis is 1 tonne of final finished product.

System boundaries

The system boundaries determine which unit processes to be included in the LCA study. Defining system boundaries is partly based on a subjective choice, made during the scope phase when the boundaries are initially set. Figure 2 shows the different steps of the life cycle of the traditional and alternative Stone wool products. In this figure, the production, use and end of life stages are represented. Only the raw materials used and the production of the Stone wool implies changes between the two processes, because the products obtained in both processes have the same technical and environmental properties. For that, this work has limited the application of the life cycle analysis to the extraction of raw materials and the industrial production of stone wool. In the studied industrial process, coke (petcoke and metcoke), biomass, raw materials consumptions and the gas emissions, are taken into account.

Fig 2. *System boundaries of the stone wool product life cycle*

Inventory analysis

The life cycle inventory involves the collection of the necessary data using specific methods that were analysed comparatively with studies from literature and software databases, involving materials, energy and fuels. Each stage in the manufacturing process of stone wool is analysed. These production stages are melting of raw materials, fiberization of the melt, polymerization, cooling, and product finishing. Data needed for the inventory have been obtained from the Integrated Environmental Authorisation of the company Rockwool Peninsular 2005 [19]. Data of air emissions are supposed to be the emission limit values authorized to this company for the minority compounds studied, and for carbon dioxide and sulphur oxides, the stoichiometric quantities supposing that all carbon and Sulphur of the raw materials (coke, biomass and cement) completely react.

The inventory generated to carry out the analysis of life cycle under study is shown in Tables 1-6. In these Tables are gathered the Input and Output Materials and the gas emissions for the stone wool manufacturing traditional process using petcoke and metcoke, and for the alternative process studied. The last column of the inventory tables refers to the nomenclature used by the software to introduce the inputs and outputs. It can be seen that the inputs are materials (products and wastes) and the outputs are gaseous emissions. All products used as raw materials have a Simapro reference to take into account the impacts related to its production. In Table 1 are collected inventory data of melting stage for both process of manufacturing stone wool; Table 3 refers to the inventory data of fiberization stage where inflows are similar for traditional and alternative processes; the inventory data of the polymerization stage is shown in Table 4. This step is entirely controlled by outputs in the form of emissions to the atmosphere being identical in traditional and alternative processes. Inventory data of the cooling stage is summarized in Table 5, showing no differences between the outflows (gas emissions) of studied processes; finally, Table 6 gives the inventory of the product finishing consisting of particulate emissions generated due to the cutting process of the final product.

Table 1. *Inventory data of melting stage*

Table 3. *Inventory data of fiberization stage*

Table 4. *Inventory data of polymerization stage*

Table 5. *Inventory data of cooling stage*

Table 6. *Inventory data of product finishing stage*

In the appendix, Tables 2 and 7 gathered the specific composition of those materials that have been used to calculate the stoichiometric gaseous emissions, and the composition of the different waste flows used as raw materials. Data shown in Tables 2 and 7 are based on the amount of 1 kg of raw material showed in the first column labelled as RM (Raw Materials).

Impact assessment

The life cycle impact assessment is oriented to evaluate the quantity and significance of the potential environmental impacts of a defined system throughout its whole life cycle. For this study, the LCA is conducted based on the cradle to gate approach including the raw materials extraction. The study begins with the input of materials to the production system and ends with the product output of the system (Figure 2). The methods applied for the impact assessment are two: (i) the CML 2000 method, developed using the mid-point approach, widely used in the construction sector that assesses the impact on ten categories of impact; (ii) the *Eco-Indicator 99* method, developed using end-point approach, that assesses the impact on eleven categories of impact and is more commonly used in an environmental background; it allows the characterization of the impact on three categories of impact, *human health, ecosystem quality and resources,* denoted as "Areas of Protection (AoP)".

3. Results and discussion

For the traditional process with metcoke as raw material, and using CML2000 method, the results obtained show that all impacts caused for all categories are not good for the environment (Figure 3). Melting and Fiberization are the stages that generates the greatest impacts in most of the impact categories analysed. This is because most of the materials used in the process are introduced in these steps involving a greater extraction of natural resources which is transferred to a greater impact on the category *Abiotic depletion*. Furthermore, coke and cement are feed at Melting stage, with generation of CO, CO_2, NO_2, C_2H_4, SO_2, metals and HF emissions, which directly influence impact categories such as *Global warming* (92.5%) and *Acidification* (75.2%). On the other hand, Fiberization stage generates the greatest impacts in the categories *Human toxicity* (82.7%), *Fresh water aquatic ecotoxicity* (80.1%), *Ozone layer depletion* (67.2%) and *Marine aquatic ecotoxicity* (60.1%), mainly due to the phenolic resin introduced at this stage as additive. *Eutrophication*, *Terrestrial ecotoxicity* and *Photochemical oxidation*, are impacts coming from more than two process stages.

Fig. 3 Characterization of the CML2000 impacts at different stages of the life cycle for stone wool traditional manufacturing process using metcoke

The impacts obtained with Eco-Indicator99 are also not good for all categories (Figure 4). Also the Melting and the Fiberization stages are that generates the greatest impacts in most impact categories analysed. Melting has impact specially in *Minerals* (98.6%), *Land use* (97.7%), *Climate change* (92.6%), *Fossil fuels* (69.6%) and *Ecotoxicity* (63.9%). Fiberization in *Radiation* (70.9%), *Ozone layer* (68.5%) and *Carcinogens* (63.0%). *Respiratory organics*, *Respiratory inorganics* and *Acidification/Eutrophication* impact coming from all categories.

Fig. 4 Characterization of the Eco-Indicator99 impacts at different stages of the life cycle for stone wool traditional manufacturing process using metcoke

Looking the damage assessment based on areas of protection from Eco-Indicator99, all impacts are not good for the environment (Figure 5). Melting stage is predominant in all categories reaching 77.7% of impact in *Resources;* this process stage consume most of the raw materials used in the manufacture and it’s the main stage generating flue gas emissions. This fact implies that in the areas of protection *Human Health* and *Ecosystem quality* this stage produces great impacts, followed by the fiberization stage.

Fig. 5 Areas of Protection from Eco-Indicator99 for stone wool traditional manufacturing process using metcoke

The results of the traditional process using petcoke have not many differences (between 0% and 15%) from those seen using metcoke in any impact category; an interexchange between the Melting and Fiberization process stages occurs as main responsible stage of the *Abiotic depletion* and *Ozone layer depletion* in CML2000 and *Fossil fuels* in Eco-Indocator99. The impacts remain not good in the same studied categories of impact; the Melting and the Fiberization stages remain generating the greater impacts in different categories for the CML2000, Eco-Indicator 99 and Areas of Protection discussed methodologies (Figures 6, 7 and 8 of the Appendix).

Assessment of the alternative process of stonewool manufacturing with CML2000 method shows that Fiberization stage dominates the not good effects generated in most of the impact categories analyzed (Figure 9). Impact categories like *Abiotic depletion* and *Human toxicity,* are generated mainly by this stage, with contributions of 76.0% and 75.1% respectively. Melting stage has an important impact contribution to the *Global warming* (81.3%).

Fig. 9 Characterization of the CML2000 impacts at different stages of the life cycle for stone wool alternative manufacturing process

With Eco-indicator99 method also the melting stage generates the greatest impacts in four impact categories such as *Ecotoxicity* (72.0%), *Climate change* (81.6%), *Land use* (97.8%) and *Minerals* (98.6%) (Figure 10). Besides the melting stage, fiberization stage is important in the categories like *Respiratory organics, Fossil fuels, Radiation* and *Ozone layer,* with a contribution of 86.5%, 78.2%, 66.2% and 62.5 % respectively. The impact *Carcinogens* is divided fifty-fifty between Melting and Fiberization stages. *Respiratory inorganics* and *Acidification/Eutrophication* impact coming from all process stages. The stage of finishing only contributes to one category of impact (*Respiratory inorganics*) with a low value of 0.56%.

Fig. 10 Characterization of the Eco-Indicator99 impacts at different stages of the life cycle for stone wool alternative manufacturing process

Damage assessment by the three areas of protection is dominated by the four production stages in *Human health* and *Ecosystem Quality* areas and only Melting and Fiberization production stages have influence in *Resources* impact area (Figure 11).

Fig. 11 Areas of Protection from Eco-Indicator99 for stone wool alternative manufacturing process

The comparative LCA results of both studied processes are showed in Figure 12-14 and Table 8. Comparative results shown the use of metallurgical coke (S: 0.7%) and petroleum coke (S: 2.8%) in the traditional stone wool production, and the alternative production process. *Eutrophication*, *Human toxicity* and *Terrestrial ecotoxicity* impacts are similar for all processes. However, the alternative process decreases *Photochemical oxidation, Acidification, Global warning and Abiotic depletion* impacts studied for metcoke between the 24% and 61% and increases *Ozone layer depletion, Marine aquatic ecotoxicity and Fresh water aquatic ecotoxicity* between the 5% and 21% with CML2000 method. *Minerals* and *land use* impacts are similar in all processes using Eco-Indicator99 method. The alternative process decrease *Acidification/Eutrophication, Respiratory organics, Respiratory inorganics, Climate change* and *Fossil fuels* impacts studied for metcoke between 14% and 61% and increases *Ozone* *layer, Radiation, Carcinogens* and *Ecotoxicity* impacts studied for metcoke between 4% and 22%. Alternative process reduces all areas of protection, studied as damage assessment of Eco-Indicator99, between 6% and 44% (Table 8). The impact reductions obtained using alternative process, are more important in comparison to using petroleum coke than using metallurgical coke.

Fig. 12 Comparative of CML2000 impacts for both lifecycles manufacturing stone wool using traditional and alternative process (The results are normalized to the case with the highest impact)

Fig. 13 Comparative of Eco-Indicator99 impacts for both lifecycles manufacturing stone wool using traditional and alternative process (The results are normalized to the case with the highest impact)

Fig. 14 Comparative Damage assessment from Eco-Indicator99 for both lifecycles manufacturing stone wool using traditional and alternative process (The results are normalized to the case with the highest impact)

Table 8 Comparative of the CML2000, Eco-Indicator99 and Damage assessment impacts for lifecycles manufacturing stone wool using traditional and alternative process

4. Conclusions

Melting stage in blast cupola furnace and Fiberization stage are the most intensive step in the stone wool manufacturing process due to the resources extraction and consumption and the pollutant emissions. The minimization of the environmental impact of the final product can be allowed by a combined strategy of material recycling and selection of raw material with a low content of sulphur in this stage. Using the rock wool manufacturing alternative process, where torrefied biomass instead coke and sodium silicate instead cement are used, is able to reduce both the emissions of CO_2 and SO_2. The impacts *Minerals* and *Land use* in Eco-Indicator99, and the *Euthrophication* impact in CML2000, increase between 2-4% using the alternative process instead the traditional one. In the same way, all the ecotoxicity related impacts increase between 9-24% with the use of alternative process. However these increases are compensated by impact decreases in other categories of impact; in consequence, the three areas of impact that grouped all individual Eco-indicator 99 impacts, show environmental benefits between 6-15% when using alternative process based on torrefied biomass, instead traditional process based on coke use. The modeling, simulation and optimization of the stone wool manufacturing process, and the use of real emission data for traditional and alternative processes, making the LCA results more representative for real life cases, are suggested as future work.

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