Waste Biomass Valor (2017) 8:1505–1520
DOI 10.1007/s12649-016-9660-8

ORIGINAL PAPER

Comparative Environmental Life Cycle Analysis of Stone Wool Production Using Traditional and Alternative Materials

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Received: 17 March 2016 / Accepted: 16 August 2016 / Published online: 25 August 2016

Abstract The mineral wool sector represents 10 % of the total output tonnage of the glass industry. The thermal, acoustic and fire protection properties of mineral wool make it desirable for use in a wide range of economic sectors especially in the construction industry for the creation of low energy buildings. The traditional stone wool manufacturing process involves melting raw materials, in a coke-fired hot blast cupola furnace, fiberization, polymerization, cooling, product finishing and gas treatment. The use of alternative raw materials as torrefied biomass and sodium silicate, is proposed as an alternative manufacturing process to improve the sustainability of stone wool production, particularly the reduction of 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 processes; process data are incorporated into a LCA model using SimaPro 8 software with the Ecoinvent version 3 life cycle inventory database. The *CML 2000* and *Eco-Indicator99* methods are used to estimate effects on different impact categories. The *Minerals* and *Land use* impacts in Eco-Indicator99 and the *Eutrophication* impact in CML2000 increase between 2 and 4 % for the alternative process instead of the traditional one. Similarly, the ecotoxicity-related impacts increase between 9 and 24 % with the use of the alternative process. However these increases are compensated by concomitant impact decreases in other categories of impact; consequently, the three areas of impact grouped by individual Eco-indicator 99 impacts, show environmental benefits improvements between 6 and 15 % when using the alternative process based on torrefied biomass and silicate instead of the traditional process based on coke and cement use.

Keywords Stone wool · LCA · Alternative materials · Silicate · Torrefied biomass

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Introduction

Fibrous materials may be naturally occurring or synthetically manufactured by thermal or chemical processes. Refractory ceramic fibre, fibre glass and mineral (or stone) wool belong to a class of materials known as synthetic vitreous fibres [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 % 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 mineral wool production directly employed over 21,000 people at 62 installations in 2005. The total volume of rock wool production in EU27 countries between the years 2003 and 2011 is highly variable (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. Typically used raw materials are: (1) igneous rocks such, as diabase, gabbro or basalt; (2) briquettes, made from a blend of various minerals, such as olivine or basalt, diabase and/or gabbro, together with recycled waste stone wool with cement as binder; and (3) limestone added to adjust the viscosity of the melt to the requirements of the spinning process.

Molten material, from 1300 to 1500 °C, gathers 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 fibres and to direct it onto the collection belt to form a mattress. An aqueous phenolic resin solution is sprayed over the fibres. 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 minimize the environmental impact. Water use in the process is generally confined to closed circuit systems.

A set of best available techniques (BAT), with the 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 [7, 11]. An alternative process patented by VL Ambiental Company [12], proposes the use of briquettes formed by waste rock wool agglomerated with torrefied biomass (e.g., conventional biomass, sewage sludge) for production as alternative fuel briquettes. The binder used is a non-fibrous inorganic material such as sodium silicate, which replaces the cement used in the traditional process.

Using a sulphur free binder and a CO_2 neutral biomass fuel has 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].

Life cycle analysis (LCA) is a methodological tool that is used 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 a system to obtain results that show its potential environmental impacts; LCA results can be used to identify strategies for reducing environmental impact and to improve industrial processes to become more environmentally friendly under a cradle to gate approach [14]. The LCA approach has been applied extensively to construction materials and insulation materials, particularly to mineral wool products [15–18].

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

Materials and Methods

Raw Materials and Manufacturing Processes

The raw materials used are the main difference between traditional and alternative manufacturing processes, that is, the use of petroleum coke (petcoke) or metallurgical coke (metcoke) in the traditional process and torrefied biomass in the alternative process. In stone wool the main oxides are silicon dioxide and oxides of alkali earth metals (predominantly calcium and magnesium). Silicon dioxide is principally derived from basalt and blast furnace slag. These raw materials are used in both processes studied. Alkali earth metal oxides are derived from the briquetted recycled material. In traditional briquettes, cement is used as a binder, while in the alternative process, cement is replaced by sodium silicate (Table 1). The composition of 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 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 for the three raw materials.

The process for production of stone wool comprises melting, fiberization, polymerization, cooling, product finishing and gas treatment. A detailed process flow diagram (PFD), built in Aspen software, can be found in Fig. 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 the mass balance analysis.

The stone wool production in the blast oven includes coke, which is used for heating and melting rocks, melting the raw materials and additives (Table 1) and forming fibre on rotating wheels under the influence of a powerful airflow. The product is cured in a polymerization chamber at 200 °C and after cooling, the stone wool is cut to 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 the inputs and energy requirements.

Table 1 Inventory data for the melting stage

Inflow materials	Unit	Traditional		Alternative	SimaPro
		Petcoke	Metcoke		
Basaltic rock	kg	689	689	689	Basalt {RoW}|quarry operation| Alloc Def, S
Blast furnace slag	kg	201	201	201	–
Petcoke	MJ	5056.8	0	0	Petroleum coke {RoW}|petroleum refinery operation| Alloc Def, S
	kg	155	0	0	
Metcoke	MJ	0	5056.8	0	Metallurgical coke, at plant/RNA
	kg	0	167	0	
Torrefied biomass	MJ	0	0	5056.8	–
	kg	0	0	215	
Briquettes					
Traditional recycling of stone wool	kg	204	204	0	–
Alternative recycling of stone wool	kg	0	0	204	–
PAVAL (Aluminium oxide)	kg	93.4	93.4	93.4	–
Electric stell mill slag	kg	89.9	89.9	89.9	–
Traditional fine briquette	kg	117	117	0	–
Alternative fine briquette	kg	0	0	117	–
Traditional rest of stone wool without iron	kg	13.7	13.7	0	–
Alternative rest of stone wool without iron	kg	0	0	13.7	–
Cement	kg	70	70	0	Cement, portland {RoW}|production| Alloc Def, S
Sodium silicate	kg	0	0	70	Sodium Silicate, solid {RoW}| sodium silicate production, solid product| Alloc Def, S
Emissions					
CO_2	kg	537.1	569.1	382.3	CO_2
Iron	kg	23	23	23	Iron
Particulates	kg	0.1	0.1	0.1	Particulates
SO_2	kg	9.73	3.4	0	SO_2
NO_2	kg	1.5	1.5	1.5	NO_2
HCl	kg	0.1	0.1	0.1	HCl
HF	kg	0.02	0.02	0.02	HF
Metals	kg	0.02	0.02	0.02	Metals

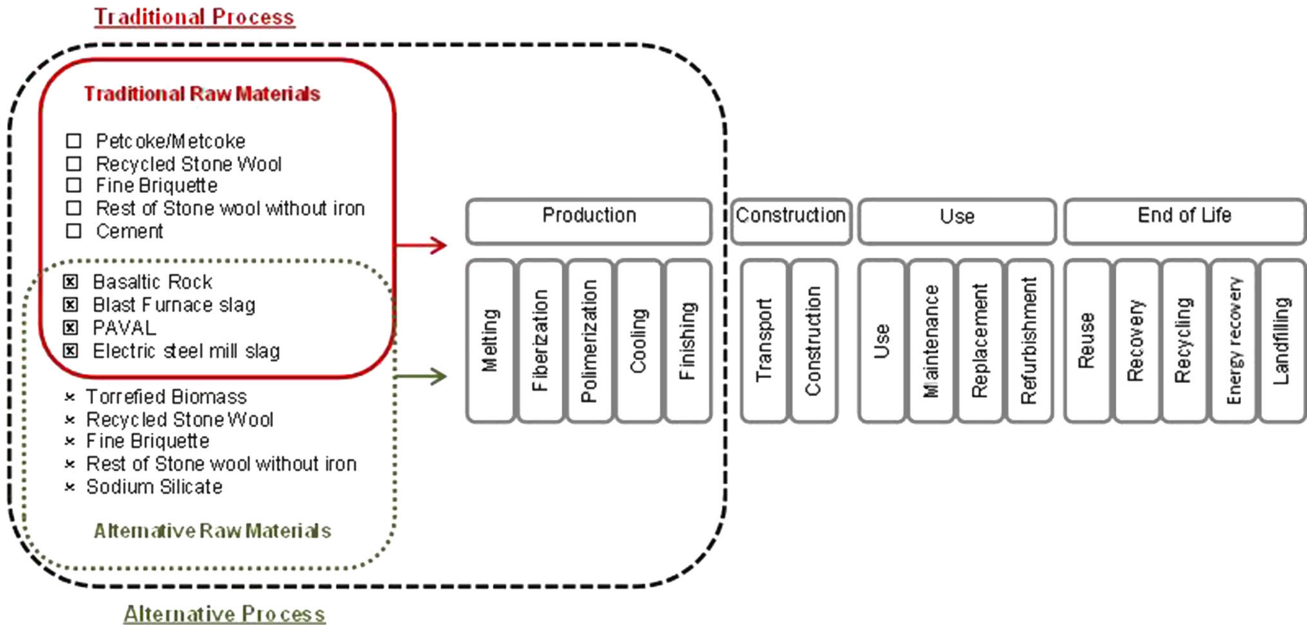
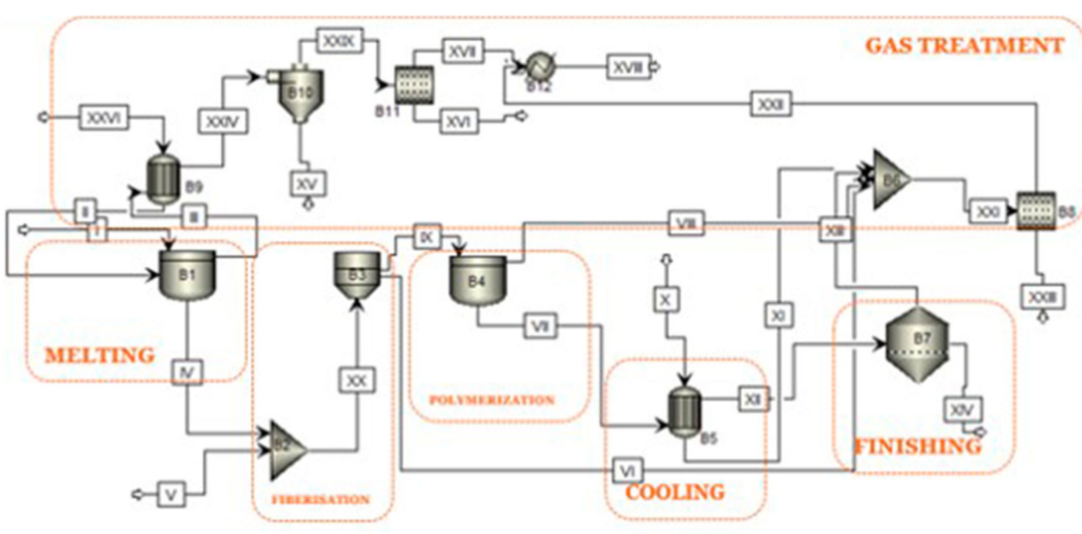


Fig. 1 Flow diagram of the stone wool manufacturing process and equipment list



Name	Equipment	Name	Equipment
B1	Blast oven	B7	Cutting and packing
B2	Mixer	B8	Filter
B3	Rotating wheels	B9	Heat exchanger
B4	Polymerization chamber	B10	Cyclone separator
B5	Cooling	B11	Filter
B6	Mixer	B12	Burner

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

The significant impact of the coke properties and reactivity on the cupola operation during 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 determined before each specific application. The reactivity of metallurgical coke is slightly lower than that of petroleum coke [21]. However, petcoke has a higher sulphur content than metcoke (Table 7, Appendix). On the other hand, sodium silicate is widely used as a raw material in alternative inorganic

Table 2 Inventory data for the fiberization stage

Inflow materials	Unit	Traditional		Alternative	SimaPro
		Petcoke	Metcoke		
Phenolic resin	kg	20	20	20	Phenolic resin {RoW}|production| Alloc Def,S
Ammonia	kg	1.66	1.66	1.66	Ammonia, steam reforming, at plant/RNA
Bakelite	kg	5.82	5.82	5.82	–
Ammonium sulfate	kg	0.964	0.964	0.964	Ammonium sulfate, as N {RoW}|ammonium sulfate production| Alloc Def, S
Silane	kg	0.199	0.199	0.199	Silicon tetrahydride {GLO}| siliconhydrochloration| Alloc Def, S
Polyacrylonitrile (PAN)	kg	3.2	3.2	3.2	–
Emissions					
Phenol	kg	0.4	0.4	0.4	Phenol
Particulates	kg	0.5	0.5	0.5	Particulates
Formaldehyde	kg	0.4	0.4	0.4	Formaldehyde
Ammonia	kg	1.1	1.1	1.1	NH_3
VOC	kg	0.9	0.9	0.9	COV

Table 3 Inventory data for the polymerization stage

Output material	Unit	Traditional		Alternative	SimaPro
		Petcoke	Metcoke		
Particulates	kg	0.1	0.1	0.1	Particulates
NO_2	kg	0.7	0.7	0.7	NO_2
SO_2	kg	0.02	0.02	0.02	SO_2
Phenol	kg	0.03	0.03	0.03	Phenol
Formaldehyde	kg	0.03	0.03	0.03	Formaldehyde
NH_3	kg	0.08	0.08	0.08	NH_3
VOC	kg	0.2	0.2	0.2	COV
CO	kg	0.3	0.3	0.3	CO

Table 4 Inventory data for the cooling stage

Output material	Unit	Traditional		Alternative	SimaPro
		Petcoke	Metcoke		
Emissions					
Particulates	kg	0.1	0.1	0.1	Particulates
Phenol	kg	0.02	0.02	0.02	Phenol
NH_3	kg	0.09	0.09	0.09	NH_3
Formaldehyde	kg	0.02	0.02	0.02	Formaldehyde
VOC	kg	0.04	0.04	0.04	COV

Table 5 Inventory data for the product finishing stage

Output material	Unit	Traditional		Alternative	SimaPro
		Petcoke	Metcoke		
Emissions					
Particulates	kg	0.02	0.02	0.02	Particulates

thermal insulation material and is fundamental in geopolymer technology [22, 23]. The use of torrefied biomass and sodium silicate as alternative materials in the present study has been shown to reduce the carbon and sulphur content of the raw materials and reduce outflow gas emission of carbon dioxide and sulphur dioxide (Table 1).

Life Cycle Assessment (LCA)

A life cycle assessment (LCA) was conducted according to standard methodology ISO 14040 and ISO 14044 [24, 25]. The experimental results were incorporated into an LCA model using SimaPro v.8 software with the Ecoinvent v.3

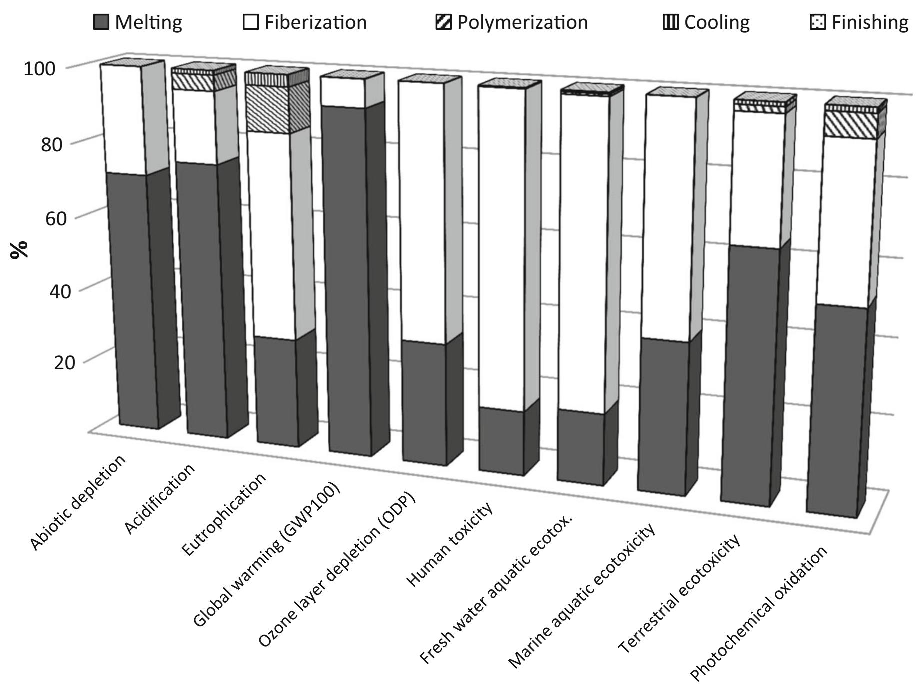


Fig. 3 Characterization of the CML2000 impacts at different stages of the life cycle for the traditional stone wool manufacturing process using metcoke

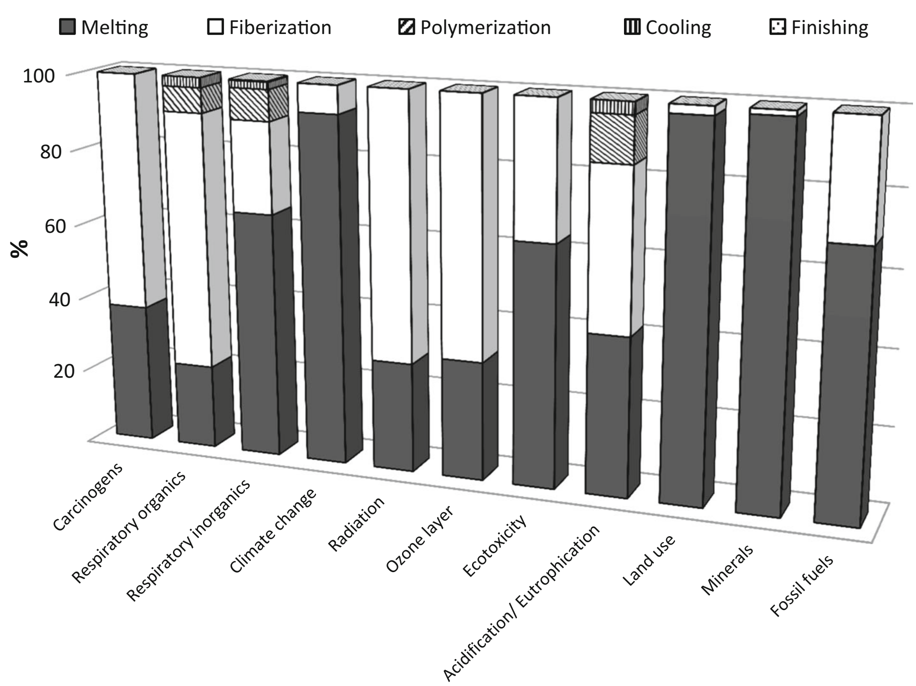


Fig. 4 Characterization of the Eco-Indicator99 impacts at different stages of the life cycle for the traditional stone wool manufacturing process using metcoke

life cycle inventory data base. The *CML 2000* and *Eco-Indicator99* methods were 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 from the production of stone wool using traditional and alternative manufacturing processes.

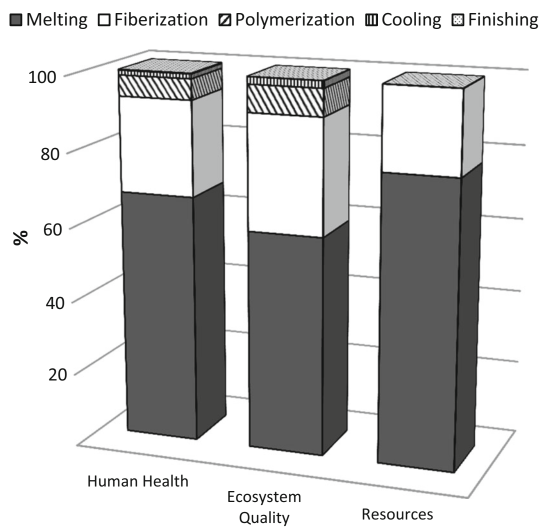


Fig. 5 Areas of protection from Eco-Indicator99 for the traditional stone wool manufacturing process using metcoke

The functional unit selected for this analysis is 1 tonne of final finished product.

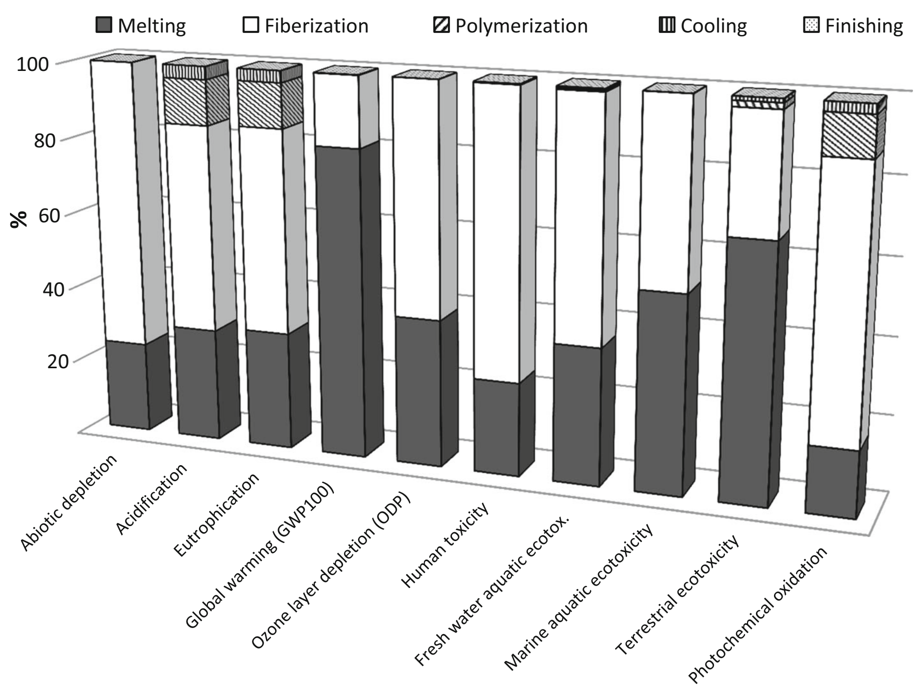
System Boundaries

The system boundaries determine which unit processes should be included in the LCA study. Defining system boundaries is partly based on a subjective choice that is 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 changes between the two processes, because the products obtained in both processes have the same technical and environmental properties. Thus, this work limited the application of life cycle analysis to the extraction of raw materials and 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.

Inventory Analysis

The life cycle inventory involves the collection of the necessary data using specific methods. These data were then analysed comparatively with studies from the literature and software databases, involving materials, energy and fuels. Each stage in the stone wool manufacturing process is analysed. These production stages are melting of

Fig. 6 Characterization of the CML2000 impacts at different stages of the life cycle for the alternative stone wool manufacturing process using petcoke



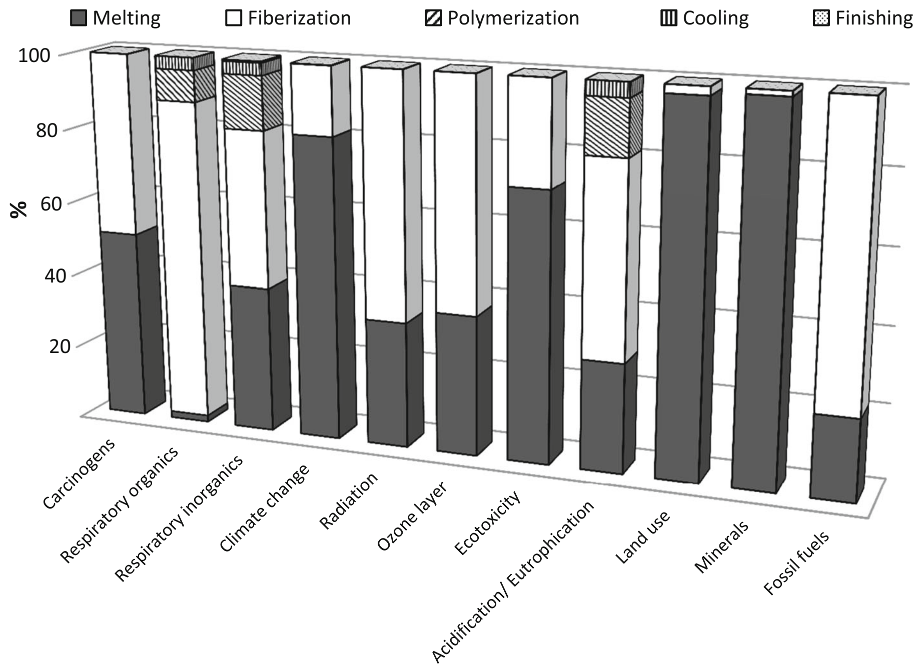


Fig. 7 Characterization of the Eco-Indicator99 impacts at different stages of the life cycle for the alternative stone wool manufacturing process using petcoke

raw materials, fiberization of the melt, polymerization, cooling, and product finishing. Data needed for the inventory were obtained from the Integrated Environmental Authorisation of the company Rockwool Peninsular 2005 [19]. Air emission data are the emission limit values authorized to this company for the minority compounds studied; for carbon dioxide and sulphur oxides, the data are the stoichiometric quantities assuming that all of the carbon and sulphur from the raw materials (coke, biomass and cement) completely react.

The inventory generated for the life cycle study is shown in Tables 1, 2, 3, 4, 5 and "Appendix Table 7". These tables show the input and output materials and the gas emissions for the traditional stone wool manufacturing 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 account for the impacts related to its production. In Table 1, the collected inventory data for melting stage for both processes of manufacturing stone wool are shown. Table 2 refers to the inventory data for the fiberization stage where the inflows are similar for traditional and alternative processes. The inventory data for the polymerization stage is shown in Table 3. This step is entirely controlled by outputs in the form of emissions to the atmosphere, which are identical in both traditional and alternative processes. The inventory data for the cooling stage are summarized in Table 4, showing no differences

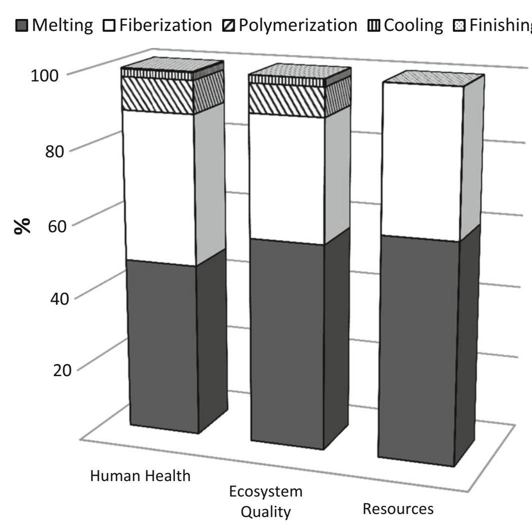


Fig. 8 Areas of protection from Eco-Indicator99 for the alternative stone wool manufacturing process using petcoke

between the outflows (gas emissions) of the studied processes. Finally, Table 5 gives the inventory data for the product finishing consisting of particulate emissions generated due to the cutting process of the final product.

In the "Appendix", the specific composition of the materials that were used to calculate the stoichiometric gaseous emissions, and the composition of the different waste flows used as raw materials are compiled in "Appendix Tables 7 and 8". The data shown in "Appendix Tables 7 and 8" are based on the amount of 1 kg of raw material shown in the first column, labelled raw materials (RM).

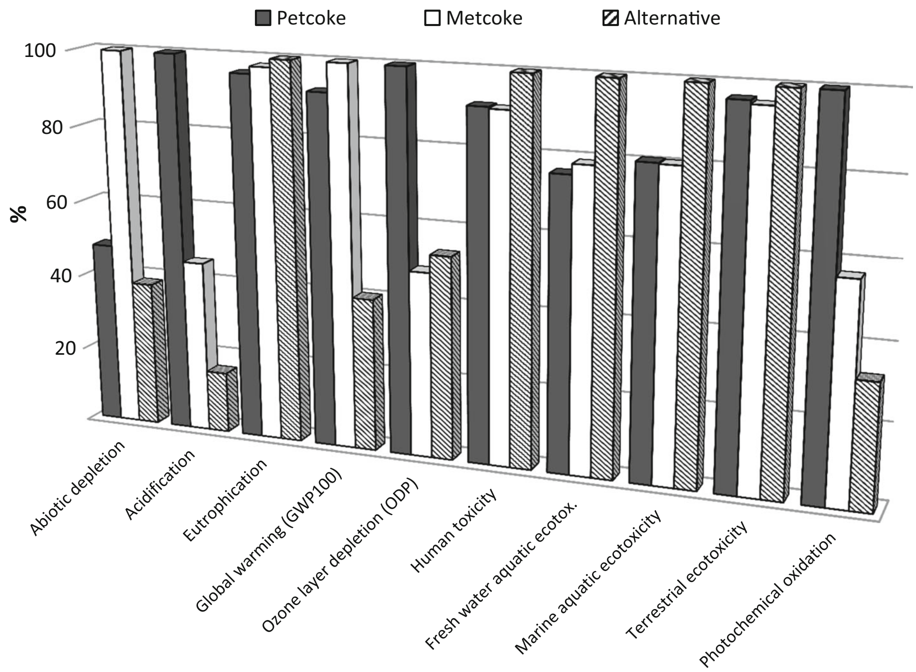


Fig. 9 Comparison of CML2000 impacts for lifecycles of both traditional and alternative stone wool manufacturing processes. (The results are normalized to the case with the highest impact)

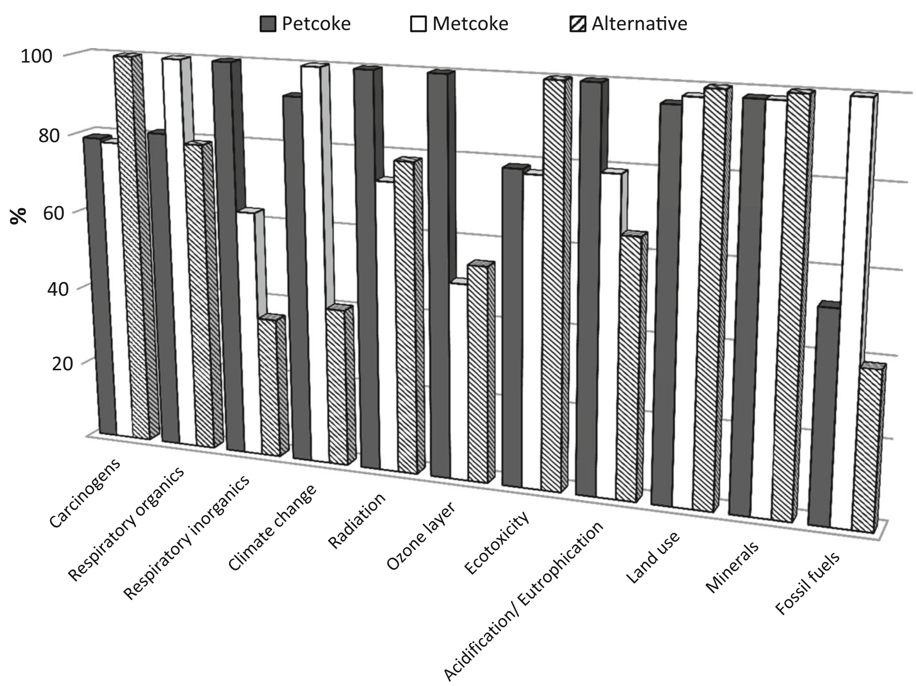


Fig. 10 Comparison of Eco-Indicator99 impacts for lifecycles of both traditional and alternative stone wool manufacturing processes. (The results are normalized to the case with the highest impact)

Impact Assessment

The purpose of the life cycle impact assessment is to evaluate the quantity and significance of the potential environmental impacts of a defined system throughout its whole life cycle. For this study, 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 (Fig. 2). The methods applied for the impact assessment are twofold: (1) the CML 2000 method, developed using the mid-point approach, which is widely used in the construction sector that assesses the effect on ten categories of impact, and (2) the *Eco-Indicator 99* method, developed using the end-point approach, which assesses the effect on eleven categories of impact and is

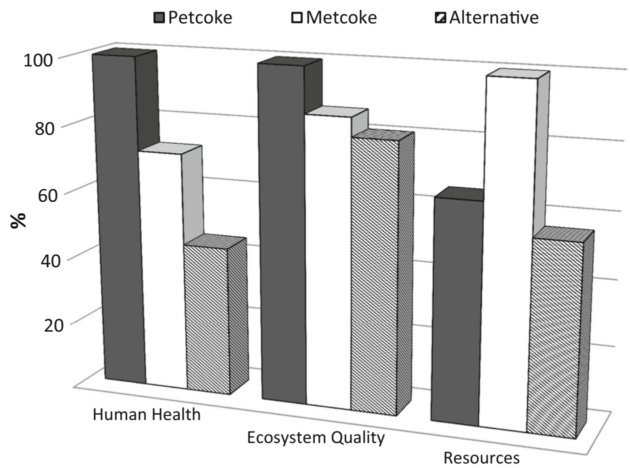


Fig. 11 Comparison of damage assessments from Eco-Indicator99 impacts for lifecycles of both traditional and alternative stone wool manufacturing processes (The results are normalized to the case with the highest impact)

more commonly used in an environmental background; it allows for the characterization of the effect on three categories of impact: *human health, ecosystem quality and resources,* denoted as "Areas of Protection (AoP)".

Results and Discussion

For the traditional process that uses metcoke as a raw material, and using the CML2000 method, the results obtained show that all effects for all categories are not good for the environment (Fig. 3). The stages that generates the greatest impacts in most of the impact categories analysed are the melting and fiberization stages. This is because during these steps most of the materials used in the process are introduced and involve a greater extraction of natural resources, which has a greater impact on the *Abiotic depletion* category. Furthermore, coke and cement are fed

Table 6 Comparison of the CML2000, Eco-Indicator99 and damage assessment impacts for lifecycles of both traditional and alternative stone wool manufacturing processes

Impact category	Unit	Traditional		Alternative	(%)	
		Petcoke	Metcoke		Petcoke	Metcoke
CML2000						
Abiotic depletion	kg Sb eq	2.22	4.63	1.77	−9	−61
Global warming (GWP 100)	kg CO_2 eq	1310	1410	568	−52	−59
Acidification	kg SO_2 eq	26.3	11.9	4.21	−84	−29
Photochemical oxidation	kg C_2H_4 eq	1.31	0.74	0.43	−67	−24
Eutrophication	kg PO_4^- eq	0.97	0.99	1.01	4	2
Terrestrial ecotoxicity	kg 1,4-DB eq	1.8	1.78	1.86	3	4
Ozone layer depletion ($\times 10^{-5}$)	kg CFC-11 eq	1.07	0.52	0.57	−47	5
Human toxicity	kg 1,4-DB eq	376	374	412	9	9
Marine aquatic ecotox. ($\times 10^{4}$)	kg 1,4-DB eq	9.7	9.67	12	19	19
Fresh water aquatic ecotox.	kg 1,4-DB eq	48.4	50.1	63.4	24	21
Eco-Indicator99						
Fossil fuels	MJ surplus	339	649	253	−13	−61
Climate change ($\times 10^{-4}$)	DALY	2.74	2.96	1.19	−52	−59
Respiratory inorganics ($\times 10^{-4}$)	DALY	15.8	9.9	5.65	−64	−27
Respiratory organics ($\times 10^{-6}$)	DALY	2.76	3.4	2.69	−3	−21
Acidification/eutrophication	PDF $\times$ m^2 y	55.3	43.8	35.9	−35	−14
Minerals	MJ surplus	252	251	256	2	2
Land use	PDF $\times$ m^2 y	18.5	18.9	19.3	4	2
Ozone layer ($\times 10^{-9}$)	DALY	11.5	5.73	6.28	−45	4
Radiation ($\times 10^{-7}$)	DALY	3.53	2.59	2.77	−22	5
Carcinogens ($\times 10^{-4}$)	DALY	1.81	1.79	2.29	21	22
Ecotoxicity	PAF $\times$ m^2 y	95	93	121	21	22
Damage assesment						
Resources	MJ surplus	590	900	508	−9	−44
Human health ($\times 10^{-4}$)	DALY	20.3	14.7	9.17	−55	−27
Ecosystem quality	PDF $\times$ m^2 y	83.3	72	67.2	−19	−6

at the melting stage, generating 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, the fiberization stage generates the greatest effects in *Human toxicity* (82.7 %), *Fresh water aquatic ecotoxicity* (80.1 %), *Ozone layer depletion* (67.2 %) and *Marine aquatic ecotoxicity* (60.1 %) categories, mainly due to the phenolic resin introduced at this stage as an additive. *Eutrophication*, *Terrestrial ecotoxicity* and *Photochemical oxidation*, are impacts that come from more than two process stages.

The impacts obtained with Eco-Indicator99 are also not good for the environment for all categories (Fig. 4). Melting and the fiberization stages generates the greatest effects in most of the impact categories analysed. Melting has an effect particularly in the *Minerals* (98.6 %), *Land use* (97.7 %), *Climate change* (92.6 %), *Fossil fuels* (69.6 %) and *Ecotoxicity* (63.9 %) categories, while fiberization has the greatest effect on the *Radiation* (70.9 %), *Ozone layer* (68.5 %) and *Carcinogens* (63.0 %) categories. *Respiratory organics, Respiratory inorganics* and *Acidification/Eutrophication* categories come from all stages of the production process.

For the damage assessment based on areas of protection from Eco-Indicator99, all of the effects are negative for the environment (Fig. 5). The stage with the greatest negative effects is the melting stage, reaching 77.7 % of the impact in *Resources;* this process stage consumes most of the raw materials used in manufacturing and is the main stage generating flue gas emissions. Thus, in the *Human Health* and *Ecosystem quality* areas of protection, this stage produces the greatest impacts, followed by the fiberization stage.

The results of the traditional process using petcoke do not show many differences (between 0 and 15 %) in any impact category compared to those for the process using metcoke; however, the melting and fiberization process stages interchange as the main responsible stages for *Abiotic depletion* and *Ozone layer depletion* in CML2000 and *Fossil fuels* in Eco-Indocator99. The impacts remain negative in the same studied categories of impact; the melting and the fiberization stages are still responsible the greatest impacts in different categories for the CML2000, Eco-Indicator 99 and Areas of Protection, as discussed in the methodologies (Figs. 12, 13 and 14 of the "Appendix").

Assessment of the alternative stone wool manufacturing process with the CML2000 method shows that the fiberization stage dominates the negative effects generated in most of the impact categories analysed (Fig. 6). The effects in impact categories, such as *Abiotic depletion* and *Human toxicity*, are mainly generated at this stage, with contributions of 76.0 and 75.1 %, respectively. The melting stage has an important impact contribution to the *Global warming* category (81.3 %).

The melting stage also generates the greatest effects in four impact categories, *Ecotoxicity* (72.0 %), *Climate change* (81.6 %), *Land use* (97.8 %) and *Minerals* (98.6 %) (Fig. 7), when analysed by the Eco-indicator99 method. In addition to the melting stage, the fiberization stage is important in the *Respiratory organics, Fossil fuels, Radiation* and *Ozone layer* categories, with contributions of 86.5, 78.2, 66.2 and 62.5 %, respectively. The impact category *Carcinogens* is equally divided between the melting and fiberization stages. However, all of the process stages contribute effects in the *Respiratory inorganics* and *Acidification/Eutrophication* impact categories. The finishing stage only contributes to one category of impact (*Respiratory inorganics*) with a low value of 0.56 %.

The four production stages dominate the effects in the *Human health* and *Ecosystem Quality* areas, while only the melting and fiberization production stages have influences in the *Resources* impact area (Fig. 8).

The comparative LCA results of both studied processes are shown in Figs. 9, 10, 11 and Table 6. Comparing these results shows that the use of metallurgical coke (S: 0.7 %) and petroleum coke (S: 2.8 %) in the traditional stone wool production process and the alternative production process have similar effects on the categories *Eutrophication*, *Human toxicity* and *Terrestrial ecotoxicity*. However, the alternative process decreases the effects in the *Photochemical oxidation, Acidification, Global warning and Abiotic depletion* impacts by between 24 and 61 % for metcoke and increases *Ozone layer depletion, Marine aquatic ecotoxicity and Fresh water aquatic ecotoxicity* between 5 and 21 % with the CML2000 method. The effects on *Minerals* and *land use* impacts are similar in all processes when analysed using the Eco-Indicator99 method. The alternative process decreases the effects on *Acidification/Eutrophication, Respiratory organics, Respiratory inorganics, Climate change* and *Fossil fuels* impacts studied between 14 and 61 % for metcoke, while the effects on *Ozone layer, Radiation, Carcinogens* and *Ecotoxicity* impacts increase between 4 and 22 % for metcoke. The alternative process reduces all of the areas of protection by between 6 and 44 % (Table 6) as studied by Eco-Indicator99. The impact reductions obtained using the alternative process are more significant when compared to using petroleum coke instead of metallurgical coke.

Conclusions

The melting stage, which occurs in a blast cupola furnace and the fiberization stage are the most intensive steps in the stone wool manufacturing process due to resources extraction and consumption and pollutant emissions. Minimization of the environmental impact of the final product can be promoted by a combined strategy of material recycling and selection of raw materials with a low sulphur content. The alternative rock wool manufacturing process, in which torrefied biomass is used in place of coke and sodium silicate is used instead of cement, is able to reduce both the emissions of CO_2 and SO_2. The impact categories *Minerals* and *Land use* in Eco-Indicator99 and the *Eutrophication* impact in CML2000 increase between 2 and 4 % for the alternative process compared to the traditional process. However, with the use of the alternative process, the ecotoxicity-related impacts increase between 9 and 24 %. These increases are compensated for by decreases in other impact categories; in consequence, the three impact areas composed of individual Eco-indicator 99 impacts show environmental benefits between 6 and 15 % when using the alternative process with torrefied biomass, instead of the 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 both traditional and alternative processes, make the LCA results more representative of real life cases, and are a fruitful direction for future work.

Appendix

Detailed Inventory Data of Materials Introduced in the Melting and Fiberization Stage

See Tables 7 and 8.

Table 7 Detailed inventory data of materials introduced for the melting process stage

RM	Inflow materials	Unit	Traditional		Alternative	SimaPro
			Petcoke	Metcoke		
Blast furnace slag						
	Silicon	kg	0.142	0.142	0.142	Si
	Aluminum	kg	0.106	0.106	0.106	Al
	Calcium	kg	0.286	0.286	0.286	Ca
	Magnesium	kg	0.055	0.055	0.055	Mg
	Chlorine	kg	0.002	0.002	0.002	Cl
	Fluorine	kg	0.001	0.001	0.001	F
	Oxygen	kg	0.408	0.408	0.408	O
Basaltic rock						
	Silicon	kg	0.205	0.205	0.205	Basalt {RoW}|quarry operation| Alloc Def, S
	Aluminum	kg	0.021	0.021	0.021	
	Iron	kg	0.095	0.095	0.095	
	Manganese	kg	0.0015	0.0015	0.0015	
	Magnesium	kg	0.206	0.206	0.206	
	Calcium	kg	0.025	0.025	0.025	
	Sodium	kg	0.0045	0.0045	0.0045	
	Potassium	kg	0.0016	0.0016	0.0016	
	Phosphorus	kg	0.00043	0.00043	0.00043	
	Titanium	kg	0.0048	0.0048	0.0048	
	Oxygen	kg	0.43517	0.43517	0.43517	
Electric stell mill slag						
	Iron	kg	0.341	0.341	0.341	Fe
	Calcium	kg	0.196	0.196	0.196	Ca
	Silicon	kg	0.054	0.054	0.054	Si
	Aluminum	kg	0.028	0.028	0.028	Al
	Magnesium	kg	0.034	0.034	0.034	Mg
	Manganese	kg	0.027	0.027	0.027	Mn
	Oxygen	kg	0.32	0.32	0.32	O

Table 7 continued

RM	Inflow materials	Unit	Traditional		Alternative	SimaPro
			Petcoke	Metcoke		
Stone wool						
	Silicon	kg	0.22	0.22	0.2209	Si
	Aluminum	kg	0.061	0.061	0.06	Al
	Iron	kg	0.043	0.043	0.039	Fe
	Calcium	kg	0.12	0.12	0.117	Ca
	Magnesium	kg	0.073	0.073	0.0703	Mg
	Titanium	kg	0.0135	0.0135	0.0135	Ti
	Sodium	kg	0.0082	0.0082	0.0115	Na
	Potassium	kg	0.014	0.014	0.0195	K
	Phosphorus	kg	0.0068	0.0068	0.0068	P
	Oxygen	kg	0.4405	0.4405	0.4415	O
Cement						
	Calcium	kg	0.45	0.45	0	Cement, portland {RoW}|production| Alloc Def, S
	Silicon	kg	0.1	0.1	0	
	Aluminum	kg	0.029	0.029	0	
	Iron	kg	0.025	0.025	0	
	Magnesium	kg	0.015	0.015	0	
	Potassium	kg	0.008	0.008	0	
	Sodium	kg	0.007	0.007	0	
	Sulfur	kg	0.006	0.006	0	
	Oxygen	kg	0.36	0.36	0	
Sodium silicate						
	Silicon	kg	0	0	0.23	Sodium Silicate, solid {RoW}| sodium silicate production, solid product| Alloc Def, S
	Sodium	kg	0	0	0.377	
	Oxygen	kg	0	0	0.23	
Coke						
	Carbon	kg	0.949	0.925	0	Petroleum coke {RoW}|petroleum refinery operation| Alloc Def, S Metallurgical coke, at plant/RNA
	Nitrogen	kg	0.011	0	0	
	Hydrogen	kg	0.003	0.00089	0	
	Sulfur	kg	0.028	0.007	0	
Torrefied biomass						
	Carbon	kg	0	0	0.485	C
	Hydrogen	kg	0	0	0.055	Hydrogen, liquid, syntheses gas, at plant/kg/RNA
	Oxygen	kg	0	0	0.46	O
Paval						
	Aluminum	kg	0.529	0.529	0.529	Al
	Oxygen	kg	0.471	0.471	0.471	O

Table 8 Detailed inventory data of materials introduced for the fiberization stage

RM	Inflow materials	Unit	Traditional		Alternative	SimaPro
			Petcoke	Metcoke		
Phenolic resin						
	Carbon	kg	0.677	0.677	0.677	Phenolic resin {RoW}|production| Alloc Def, S
	Hydrogen	kg	0.065	0.065	0.065	
	Oxygen	kg	0.258	0.258	0.258	
Bakelite						
	Carbon	kg	0.794		0.794	C
	Hydrogen	kg	0.052	0.052	0.052	Hydrogen, liquid, syntheses gas, at plant/kg/RNA
	Oxygen	kg	0.154	0.154	0.154	O
NH_3						
	Nitrogen	kg	0.823	0.823	0.823	Ammonia, steam reforming, at plant/RNA
	Hydrogen	kg	0.177	0.177	0.177	
Ammonium sulfate						
	Nitrogen	kg	0.212	0.212	0.212	Ammonium sulfate, as N {RoW}|ammonium sulfate production| Alloc Def, S
	Hydrogen	kg	0.061	0.061	0.061	
	Sulfur	kg	0.242	0.242	0.242	
	Oxygen	kg	0.485	0.485	0.485	
Silane						
	Silicon	kg	0.875	0.875	0.875	Silicon tetrahydride {GLO}| siliconhydrochloration| Alloc Def, S
	Hydrogen	kg	0.128	0.128	0.128	
PAN						
	Carbon	kg	0.679	0.679	0.679	C
	Hydrogen	kg	0.057	0.057	0.057	Hydrogen, liquid, syntheses gas, at plant/kg/RNA
	Nitrogen	kg	0.264	0.264	0.264	N

Characterization of the Impacts for Traditional Stone Wool Manufacturing Process Using Petcoke

The following figures are the result of analyzing the traditional process of manufacturing stone wool with CML200, Eco-Indicador99 and damage assessment methods (Figs. 12, 13, 14).

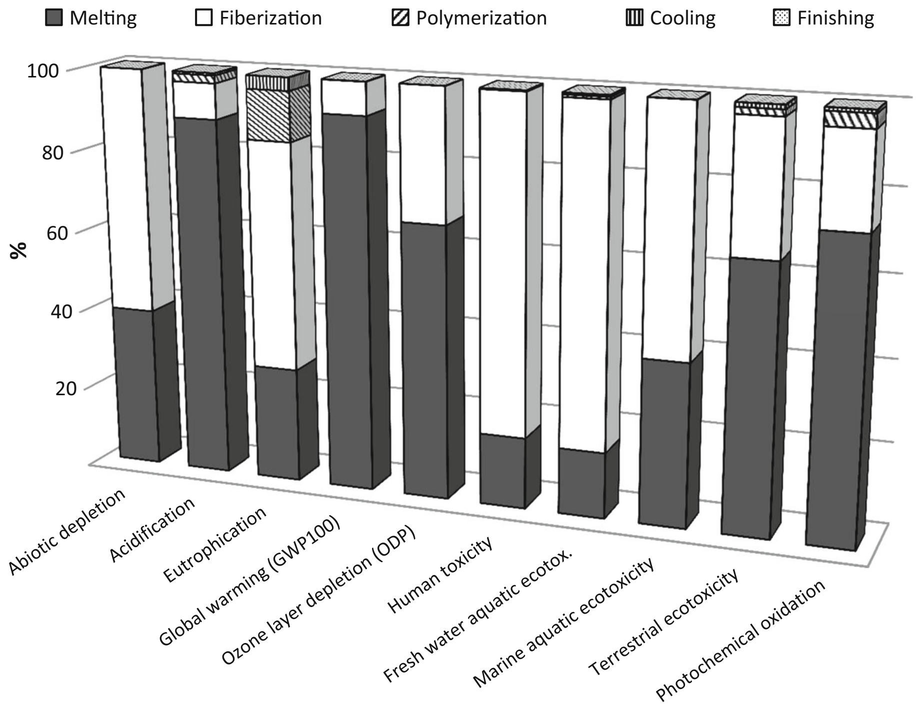


Fig. 12 Characterization of the CML2000 impacts at different stages of the life cycle for the traditional stone wool manufacturing process using petcoke

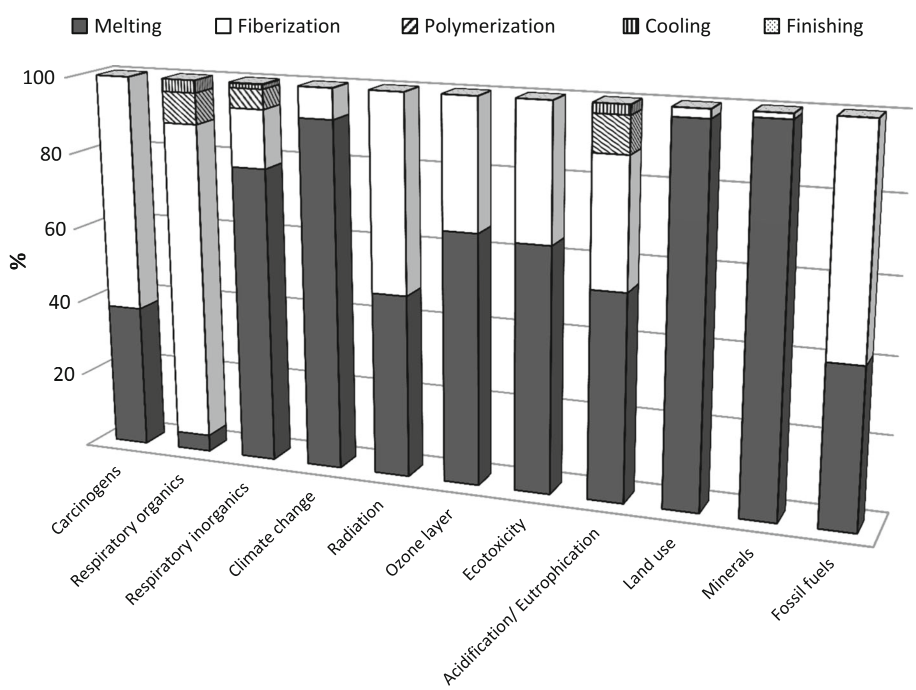


Fig. 13 Characterization of the Eco-Indicator99 impacts at different stages of the life cycle for the traditional stone wool manufacturing process using petcoke

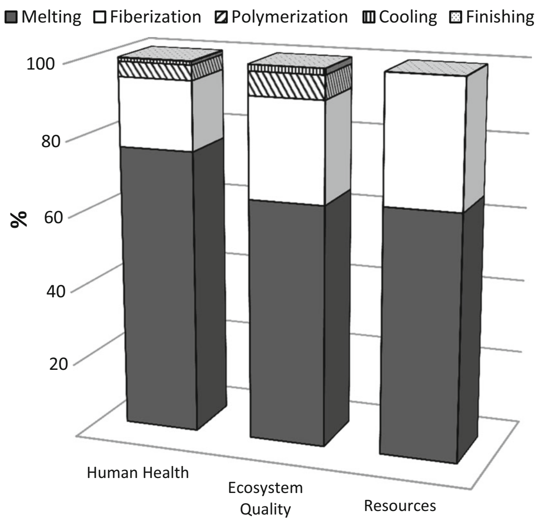


Fig. 14 Areas of protection from Eco-Indicator99 for the traditional stone wool manufacturing process using petcoke

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