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Environmental Assessment of Different Cement Manufacturing Processes Based on Emergy and Ecological Footprint Analysis

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Abstract

Due to its high environmental impact and energy intensive production, the cement industry needs to adopt more energy efficient technologies to reduce its demand for fossil fuels and impact on the environment. Bearing in mind that cement is the most widely used material for housing and modern infrastructure, the aim of this paper is to analyse the Emergy and Ecological Footprint of different cement manufacturing processes for a particular cement plant. There are several mitigation measures that can be incorporated in the cement manufacturing process to reduce the demand for fossil fuels and consequently reduce the CO_2 emissions. The mitigation measures considered in this paper were the use of alternative fuels and a more energy efficient kiln process. In order to estimate the sustainability effect of the aforementioned measures, Emergy and Ecological Footprint were calculated for four different scenarios. The results show that Emergy, due to the high input mass of raw material needed for clinker production, stays at about the same level. However, for the Ecological Footprint, the results show that by combining the use of alternative fuels together with a more energy efficient kiln process, the environmental impact of the cement manufacturing process can be lowered.

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Keywords: Sustainable cement production; Cement industry; Mitigation scenario, Emergy; Ecological Footprint

1. Introduction

Climate change problems are addressed by two major international agreements: the 1992 United Nations Framework Convention on Climate Change (UNFCCC) and the 1997 Kyoto Protocol (IPCC, 2013). The ultimate objective of these agreements is to stabilise greenhouse gas - GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the global climate system. The latest report from the scientific panel on anthropogenic global warming indicates that substantial and joint global action is required to reduce carbon dioxide - CO_2 emissions. Meaning the longer we wait to address this issue, the more difficult, technologically challenging and expensive it becomes (IPCC, 2014).

It is well known that over 80 % of global CO_2 emissions are caused by transport activities and industry due to this reason, there is a need to decarbonize transport and industrial production (Klemeš et al., 2012). In 2008, the electricity and heat generation sector was responsible for 41 %, transport sector for 22 %, and industry for 20 % of anthropogenic CO_2 emissions (Benhelal et al., 2013). From these 20 % of global CO_2 emissions related to industry, the cement industry accounts for approximately a quarter of total CO_2 emissions in industry (Marques and Neves-Silva, 2015). This means that cement industry as an energy intensive industrial sector, alone generates approximately 5 % of anthropogenic CO_2 in the world, and this figure is given in several studies (Mikulčić et al., 2013a; Usón et al., 2013). Due to its significant environmental impact, over the past decades several CO_2 emissions mitigation measures have appeared. The main objective of these measures is environmental conservation in terms of reducing CO_2 emissions.

In recent years, there have been numerous studies worldwide discussing energy conservation policies, estimating the CO_2 mitigation potential, and considering technology evaluation for the cement industry. Some of these studies investigated the effect of mitigation measures at the global level, such as the study conducted by the International Energy Agency - IEA (IEA, 2009). However, the majority of these studies evaluated the environmental impact of cement production at national and regional levels. The effect of mitigation measures on the regional level, like those in the European Union - EU were analyzed in Pardo et al. (2011) and Moya et al. (2011). The United States' cement industry was analysed in the study by Xu et al.

(2013). However due to the rapid economic growth and vast urbanization, the majority of the studies related to the cement industry are for the developing countries like China (Li et al., 2014; Wang et al., 2014; Xu et al., 2014), South Africa (Swanepoel et al., 2014), Turkey (Ekincioglu et al., 2013), Iran (Ostad-Ahmad-Ghorabi and Attari, 2013), India (Morrow et al., 2014), Thailand (Hasanbeigi et al., 2010), and Vietnam (Nguyen and Hens, 2013). The reason for these is most easily seen in Table 1 where the global cement production for 2012 is given. Table 1 shows that the vast majority of cement production is located in developing countries, especially in Asia. The importance of cement production in these developing economies can also be observed when comparing the annual CO_2 emissions from cement production in industrialised countries and developing countries. In the EU, the cement industry contributes to about 4.1 % of total CO_2 emissions (Mikulčić et al., 2013b). This share varies from one EU country to another, in EU's most developed country Germany, this share is even lower, and the cement industry accounts for 2.9 % of Germany's CO_2 emissions (Brunke and Blesl, 2014). This is similar for the cement industry in United States, where cement production is responsible for about 2 % of total CO_2 emissions (Worrell and Galitsky, 2008). Whereas in China, the world's largest cement producing country and the world's largest emitter of GHG emissions, 15 % of total CO_2 emissions are related to cement production (Chen et al., 2014; Wang et al., 2013). All of these studies stated that there is a great challenge in attempting to approach sustainability in the cement industry. Due to this reason and the increased social awareness in fighting climate changes, eco-labelling of companies, products, lifestyle, services, etc., is becoming an element of decision making (Čuček et al., 2012a).

Over the years, Ecological Footprint has arisen as a simple, yet effective tool that can serve as an indicator of environmental impact, and eco-labelling (Cagiao et al., 2011; Čuček et al., 2012b). However, Huijbregts et al. (2008) in their study show that the usefulness of the Ecological Footprint as a stand-alone indicator for the environmental impact is limited. Based on their observations, they concluded that the Ecological Footprint should be used together with other indicators to estimate in detail the impact of human activities on the environment. This observation was even more highlighted recently by Rugani et al. (2013), where it was concluded that the use of the Carbon Footprint in combination with other single-issue indicators would be recommended to increase transparency and impacts coverage.

As cement manufacturing is an energy intensive process, Emergy was used as an indicator for sustainability in some studies. Pulselli et al. (2008) in their study through an Emergy evaluation assessed the sustainability of building materials, including cement. Zhang

et al. (2011) showed that Emergy analysis provides results that measure the resource input in the cement industry. These results can be further used for process performance analysis. Liu et al. (2014) used emergy analysis and evaluated the environmental effect of using sewage sludge as an alternative raw material or fuel in clinker production. The study showed that the use of emergy accounting may provide quantitative metrics of eco-industrial sustainability. In a recent study by Jamali-Zghal et al. (2013), Emergy and Carbon Footprint were used together to study to which extent, replacing fossil fuel with biomass for heating is an environmentally friendly solution. In relation to this study, Andrić et al. (2014) using the same approach for electricity production determined the maximum supply distance of biomass that allows the co-firing of coal and biomass to be more environmentally efficient than the pure coal combustion. The study showed that the Carbon Footprint and Emergy method are used together to cover all, or at least most, of the significant aspects of the electricity production process that may influence the environment.

To date, to the knowledge of the authors, there have been no studies that used the Emergy and Ecological Footprint together as environmental indicators, to investigate the sustainability of cement manufacturing processes. For that reason in this study, in order to help cement manufactures to operate in a more environmental friendly way, and to assess which manufacturing process is more sustainable, the environmental impact of four different cement manufacturing processes is estimated. Actual cement plant data is used in order to correctly study the impact of different processes. The results shown in this study highlight potential modifications and improvements in the manufacturing process, regarding its sustainability.

2. Methodology

Sustainability is essentially about finding ways to meet the material and energy needs of human society within the limits of planet Earth over the long term (WCED, 1987). In the case of manufacturing activities, sustainability goes beyond pollution prevention by extending the time frame and the functional scope of the analysis. Extending the time frame implies that processes must be capable of functioning in an environmentally acceptable manner for a very long time. Extending the functional scope of the analysis means that the manufacturing activity must be able to function without seriously impairing the natural processes of the environment in which it is imbedded. These natural processes include things such as waste dissipation, nutrient cycling, oxygen production, and many others. For these processes to function there are some conditions that must be maintained such as having: (1) as small of a

footprint on the environment as possible and (2) as small of an appropriation of the energy resources of the environment as possible. These two are not necessarily the only two issues of concern. But they are important for technological processes, and they can be expressed quite generally as will be shown shortly. They also can inherently incorporate many specific sustainability issues such greenhouse gas emissions, land use, and water depletion.

It is very important, however, that environmental issues not be ported from one media or area to another. For example, reducing energy consumption at the cost of increased water usage, thus reducing one kind of environmental impact only to increase another. To mitigate this problem, we use integrated sustainability metrics where many effects across the life-cycle are incorporated into common measures. Hence, we account for the use of land with the Ecological Footprint – EF (Wackernagel and Rees, 1996) and for energy resources using Emergy Analysis - Em (Odum and Nilsson, 1996) as will be discussed further in the following sections. The application of Ecological Footprint (Vance et al., 2013) and Ecological Footprint and Emergy Analysis (Vance et al., 2015) to the design of energy supply chains can be found in the literature.

Ecological Footprint and Emergy Analysis speak to sustainability because, when comparing two options, the more sustainable one is the one with the smallest Ecological Footprint and the lowest input of Emergy. Further, for an option to be considered more sustainable, it must meet both criteria simultaneously. In mathematical form the criteria indicate that option one is more environmentally sustainable than option two when: $EF_1 \leq EF_2$ and $Em_1 \leq Em_2$.

2.1. Emergy

Emergy is generally meant to represent the sum total of the thermodynamic work done in producing a product or maintaining an operation using solar energy along with tidal and geothermal energy as energy sources. Note that solar energy input is by far the largest contributor to Emergy. For purposes of this work, Emergy is the sum of the total thermodynamic work done in producing a specific mass of cement. Emergy is expressed in solar energy Joules or seJ. The conversion factor between different kinds of energy in Joules or J and Emergy in seJ is called a transformity. The application of Emergy theory also known as Energy Systems Theory is often known as Emergy accounting. In essence, Emergy accounting tries to transform all mass and energy flows into solar energy Joules.

Transformities are in general very specific to the material, e.g. the seJ of, for example, a kilogram of a particular type of coal. For practical use, it is easier to rely on unit Emergy

values which can often be found in the literature (Rugani et al., 2011). These are proportionality constants which convert a defined unit of a substance or a form of energy produced at a specific location by a particular process into the equivalent seJ. For example, the unit Emergy value of hard wood in Europe is approximately $1.16 \cdot 10^{14}$ seJ/m^3 where the unit of wood is meters cube (Rugani et al., 2011). Unit Emergy values aggregate most of the contributions from the lifecycle of the product or process, and they differ in that respect from transformities which do not attempt to integrate the over life-cycle. For a product, for example cement, the Emergy is calculated from the expression,

$$Em_{CP} = \sum_{m} Em_{m,CP} + \sum_{e} Em_{e,CP} \qquad (1.)$$

where Em_{CP} is the Emergy in seJ needed to produce cement "C" by process "P," $Em_{m,CP}$ is the Emergy of material input m in seJ into process "P", $Em_{e,CP}$ is the Emergy of energy input "e" in seJ into process "P", and the sum "m" is taken over all of the material inputs and the sum "e" is taken over all energy inputs into the process.

The Emergy of each material input is computed from,

$$Em_{m,CP} = b_{m,S} \bullet K_{m,S} \qquad (2.)$$

where $b_{m,S}$ is the unit Emergy in seJ of one kilogram of input "m" obtained or produced from source "S", and $K_{m,S}$ is the necessary number of kilograms of input "m". Input "m" can be any material input needed, including manufactured products, e.g. chemicals, metals, waste, or agricultural products, e.g. wood, agricultural residue. However, care must be taken to match as closely as possible the actual process under study to the process used to derive the unit Emergy values. This includes matching as well as possible the geographical location, raw materials and their sources, technology used, etc.

When the input is a type of energy, the form of the expression is the same, but the interpretation of the terms is now different. For example,

$$Em_{e,CP} = b_{e,S} \bullet K_{e,S} \qquad (3.)$$

where $b_{e,S}$ is the unit Emergy in seJ of one kilowatt hour of energy of form "e" obtained or produced from source "S", and $K_{e,S}$ is the necessary number of kilowatt hours of energy "e". The energy "e" can be any form of energy, e.g. electricity, heat, mechanical energy, generated by any process, e.g. solar electricity, thermo-electric generation, and waste heat. However,

again, care must be taken to match as closely as possible the energy generation processes to geographical location, raw materials and their sources, technology used, etc.

2.2. Ecological Footprint

Ecological Footprint theory attempts to estimate the area needed to support a given human population or human activity such as a manufacturing process. This is the area needed to provide the required resources and dissipate the resulting waste. Ecological Footprint is measured in global hectares or gHa. For this purpose the required land area is divided into six kinds of land: arable land, forest land, pasture land, sea, energy land, and built land. The procedure to compute the Ecological Footprint is basically to estimate the amount of land area needed for each type of land and sum them up to obtain the Ecological Footprint. As Emergy accounting attempts to estimate the solar energy Joules corresponding to different products or to maintain processes, the Ecological Footprint tries to estimate the area in global hectares needed for producing different products or maintaining different processes.

As already mentioned, cement production is an energy intensive process, and the dominant component of the Ecological Footprint is due to the area needed to absorb the carbon dioxide emitted by the process. It is assumed that the carbon dioxide is absorbed by forest and the ocean. Hence, the Ecological Footprint EF_C for cement production is calculated from:

$$EF_C = \frac{P_C \bullet \left(1 - S_{Ocean}\right)}{Y_C} \bullet EQF \qquad (4.)$$

where P_C is the kilograms of carbon dioxide emitted by the cement production process, S_{Ocean} is the fraction of the carbon dioxide sequestered by the ocean, Y_c is the average global yield of forest land sequestration in kilograms per hectare, and EQF is the equivalence factor. This factor has units of maximum productivity of forest land sequestration in kilograms divided by the average productivity of all land types in kilograms as well. It is used to convert hectares of forest land to global hectares (Ewing et al., 2010; Galli, 2015). Lastly, it is assumed that the ocean can sequester about 28 % of the carbon dioxide so that S_{Ocean}=0.28. Global yields Y_c and equivalence factors can be obtained from the Global Footprint Network – GFN (GFN, 2008; GFN, 2015) or from the literature (Hopton and White, 2012).

3. Mitigation scenarios

Due to the energy intensity involved in cement manufacture, we focus on mitigation efforts that reduce CO_2 emissions. However, for the reduction in CO_2 emissions to represent an

improvement towards sustainability, the aforementioned criteria of reducing the Ecological Footprint and Emergy input must also be met. There are different effective mitigation measures to reduce CO_2 emissions from cement manufacturing (Mikulčić et al., 2013b): (1) carbon capture and storage (CCS) technology; (2) reduction of clinker to cement ratio with the addition of different additives; (3) improving the energy efficiency of the kiln process; and (4) replacing fossil fuels with alternative fuels of predominately biomass origin. As most of the named measures are to a large extent affected by environmental policy and legal frameworks, the integration of these measures will only be possible under incentives and policies that foster the deployment of these measures in cement manufacturing. This applies in particular to carbon CCS technology due to its high cost.

The projected cement production of a particular cement plant is presented through four different scenarios. The first scenario, business-as-usual or BAU, can be considered as a reference scenario since the actual cement plant Emergy and Ecological Footprint are calculated. The other three are mitigation scenarios that integrate appropriate measures that will lower the fuel consumption and lessen CO_2 emissions from cement production.

In these four scenarios an assumption was made that the same amount of cement is produced with the same hydraulic quality, meaning that the reduction of clinker to cement ratio with the addition of different additives is not considered as a mitigation measure in these scenarios. The improvement of the energy efficiency of the kiln process, and the replacement of fossil fuels with alternative fuels of predominately biomass origin are the two mitigation measures considered in the four scenarios. In this study, the CO_2 emissions from the cement production have been calculated according to the IPCC methodology (IPCC, 2001).

3.1. Business as usual scenario

The BAU scenario is based on the exploitation of existing resources, needed for stable cement production. The studied cement plant uses a dry kiln with a four stage preheating tower. The specific thermal energy consumption of this cement plant is 3.67 GJ/t clinker. The BAU scenario does not include the implementation of any mitigation measure beyond those already in use. This scenario represents a reference level for the Emergy and Ecological Footprint analysis. This includes alternative fuels, such as discarded tyres, already used in the production process. The list of fuels can be found in Table 2.

3.2. Scenario 1 – Energy Efficient Kiln Process

This first scenario assumes the inclusion of the most energy efficient kiln process in the cement manufacturing industry. Currently, the most energy efficient technology for cement

production is a dry rotary kiln process with a multi-stage preheater and a cement calciner, which has a specific energy consumption of 3 GJ per ton of clinker (Mikulčić et al. 2015). Here as in the BAU scenario, alternative fuels already used are included.

3.3. Scenario 2 – Alternative Fuel

In this second scenario, the assumption is made that the fraction of thermal energy produced by alternative fuels is 30 %. The value of 30 % is chosen since no major capital investments are needed to substitute fossil fuels with alternative fuels up to this level. The alternative fuel considered in this scenario, in addition to those already used, is solid recovered fuel (SRF). SRF is defined as solid fuels prepared from non-hazardous waste materials intended for firing in industrial furnaces. The assumption is made that 60 % of SRF is of biogenic origin, i.e. CO_2 neutral (Mikulčić et al. 2014).

3.4. Scenario 3 – Alternative Fuel and Efficient Kiln

In this third scenario both the energy improvement of the kiln process and the use of increased share of SRF are considered. An assumption is made that the most energy efficient kiln process together with 30 % of thermal energy fraction produced by SRF is used in the manufacturing process.

4. Results and discussion

In Table 2 the actual plant data and the corresponding calculated Emergy values for the BAU scenario are shown. The unit Emergy values listed in the table were taken from literature (Rugani et al. 2011). It can be observed that 60 % of input Emergy ends up in the final product, i.e. cement. Furthermore, from the table, it can be seen that the biggest contributor (~ 44 %) to the input Emergy of the overall cement manufacturing process comes from the high and low grade marl. This is due to their large input mass - several orders of magnitude higher than of other input materials - and relatively large unit emergy values. In Table 3 the Emergy values for three mitigation scenarios are shown. As already discussed, it can be observed that Emergy values do not differ much. This presents a challenge to sustainability improvements because marl, a calcium carbonate sedimentary rock which contains variable amounts of clays, is not easy to substitute in cement production. This brings up the possibly obvious but very important point that when attempting to improve the sustainability of the process by reducing the input of emergy, one has start with the numerically largest contribution, then the second largest, and so on down. This focuses

attention on the inputs that really matter. For instance, taking the otherwise intuitive step of reducing the input of coal and petrol coke is likely to lead only to a modest reduction in Emergy input, because the total Emergy values of both are almost two orders of magnitude smaller than the total Emergy input. Lastly, it should be noted that the calculated Emergy of cement corresponds well to the value reported in the literature (Pulselli et al. 2008) giving credence to our calculation procedure.

In Table 4 the calculated masses of different fuels for all four scenarios are given. For the BAU scenario, the actual mass of the used fuels is given. For three other scenarios, masses of the fuels were calculated according to the previously specified assumptions. Again, Scenario 1 involves the use of the most efficient kiln process in the industry, Scenario 2 involves the production of 30 % of the thermal energy from alternative fuels, and Scenario 3 uses an efficient kiln and alternative fuels both exactly as in Scenarios 1 and 2. As expected, the thermal energy needed is reduced only by the use of a more efficient kiln process. However, the consumption of coke and coal is significantly reduced by both the use of the more efficient kiln process and alternatives fuels, with the greatest reduction in Scenario 3 where both are combined. Compared to BAU, Scenario 3 reduces thermal energy needs by -18 %, the thermal energy produced from coke by -32 %, and the thermal energy produced from coal by -32 % as well. This is significant, because under the assumption that alternative fuels are carbon neutral, this represents very roughly a 1/3 reduction in carbon dioxide emissions. Alternative fuels are often, in any case, low value materials with low economic value and not too many other uses. Hence, their use in this application is probably environmentally and economically advantageous (Benhelal et al., 2013; Andrić et al., 2014).

In Table 5 the CO_2 emissions and the Ecological Footprint for all four scenarios are shown. As can be seen the Ecological Footprint, as opposed to the Emergy, is a better indicator of the influence that different cement manufacturing processes have on the environment. This probably indicates the fact that for cement production the ecological footprint is dominated by the land area required to sequester carbon dioxide emissions. Further, as already discussed, cement production is an energy intensive process that is heavily dependent on fossil fuels. Hence, a reduction in fossil fuel use is most likely to be seen first in the ecological footprint rather than the emergy. The reduction in the ecological footprint

compared to the BAU Scenario is as follows: Scenario 1 with the more efficient kiln approximately -8 %, Scenario 2 with the use of alternative fuels approximately -4 %, and Scenario 3 using both the more efficient kiln and alternative fuels approximately -10 %. As expected, the lowest Ecological Footprint, and thus the lowest environmental impact corresponds to Scenario 3. Note, however, that the reductions are not quite additive, i.e. a more efficient kiln plus alternative fuels does not give about a 12 % reduction in the ecological footprint. The complete explanation can be complex, but basically the more efficient kiln reduces the need for energy so there is opportunity to reduce the foot print with an alternative fuel.

5. Conclusion

In this study a combined Emergy and Ecological Footprint analysis along with an effort to reduce CO_2 emissions was investigated. The combination of these two environmental indicators is used, in order to explore improving of the sustainability of cement manufacturing processes. Reduction of CO_2 emissions was considered due to concerns over the exacerbation of climate change. To assess which manufacturing process is more sustainable at the lowest level of CO_2 emissions, the environmental impact of four different cement manufacturing scenarios was considered: business as usual BAU, Scenario 1 - energy efficient kiln process, Scenario 2 – 30 % of thermal energy produced by alternative fuel, and Scenario 3 - energy efficient kiln process together with 30 % of thermal energy produced by alternative fuel. Actual cement plant data were used to correctly study the environmental impact of these four processes. The input of Emergy did not vary significantly among the four scenarios, but it certainly did not increase. Hence, the criterion that Emergy input should not increase for sustainability was met. The Ecological Footprint did decrease from the BAU scenarios by 8 % for Scenario 1, 4 % for Scenario 2, and 10 % for Scenario 3. The emissions of CO_2 correspondingly decreased by 8 %, 4 %, and 10 % respectively. Note that due to the dominance of CO_2 emissions in the Ecological Footprint calculation, reductions in the Ecological Footprint mirror decreases in CO_2 emissions, but this should by no means be taken as anything other than incidental event and certainly not a general rule. Finally, it can be argued that all three alternative scenarios are more sustainable than the BAU case. However, it seems clear that Scenario 3, the combination of a more energy efficient kiln process together with the increased use of solid recovered fuel, is more sustainable, decreasing most significantly the impact that cement production has on the environment.

Another important point when assessing sustainability and changes in the sustainability of manufacturing processes is the need to use multiple and reasonably independent metrics rather than combining everything into a single quantity. There are two reasons for this: (1) different metrics have different sensitivity to specific changes on the process, and (2) not all changes map with equal fidelity into different metrics. In our case for cement manufacturing, the ecological footprint directly translates the changes in the manufacturing process into a land area, and the signal from this metric is clear. On the other hand, emergy is dominated by the emergy in the marl which came from the sun long ago. Hence we see little change with our modifications of the manufacturing process. This does not mean that emergy is unimportant, rather it means that it is insensitive to these specific set of changes. It also illustrates the principle that less sustainability with respect to any single metric usually implies that the process is less sustainable with respect to the other metrics, even though for some metrics the signal may not observable because it does not rise above the uncertainty.

Lastly, the sustainability improvements that were explored in the present work are based on accessible modifications to an existing cement plant. As mentioned, much more could be achieved with the consideration of novel or revolutionary technologies, albeit at substantially higher capital investment. It is important, however, that the methodology being present here for the quantitative assessment of sustainability improvements is applicable regardless of the technology being used. It is, therefore, a generic and scientifically based assessment method useful beyond the current specific case.

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Table captions

Table 1 Global cement production in 2012 (Oh et al., 2014).

Table 2 Emergy calculation for the BAU scenario.

Table 3 Emergy calculation for the three mitigation scenarios.

Table 4 Calculation of the fuel masses according to the thermal energy need for three mitigation scenario.

Table 5 CO_2 emissions and Ecological Footprint calculation.

Table 1
Global cement production in 2012 (Oh et al., 2014).

Country	Production (million metric tonnes)	Share in the world production
China	2150	58.1%
India	250	6.7%
United States	74	2.0%
Brazil	70	1.9%
Iran	65	1.8%
Vietnam	65	1.8%
Turkey	60	1.6%
Russian Federation	60	1.6%
Japan	52	1.4%
South Korea	49	1.3%
Egypt	44	1.2%
Saudi Arabia	43	1.2%
Mexico	36	1.0%
Germany	34	0.9%
Thailand	33	0.9%
Pakistan	32	0.9%
Italy	32	0.9%
Indonesia	31	0.8%
Spain	20	0.5%
Other (rounded)	500	13.5%
World total (rounded)	3700	-

Table 2
Emergy calculation for the BAU scenario.*

Cement plant technical data for BAU scenario						
	Quantity	**Unit**	**Unit Emergy Values**	**Units & Details**	**Emergy Calculation**	**Units & Details**
MAIN DATA						
Clinker Production	3.15E+05	t	1.28E+13	seJ/kg (Switzerland)	4.02E+21	seJ
Specific Thermal Energy Consumption	3.67E+03	MJ/t clinker				
Cement Production	3.91E+05	t	1.07E+13	seJ/kg (Switzerland)	**4.17E+21**	**seJ (Cement produced)**
Specific Electrical Energy Consumption	9.03E+01	kWh/t cement				
Total Electrical Energy Consumption	3.82E+07	kWh	8.43E+11	seJ/kWh (Austria mix)	3.22E+19	seJ
Electrical Energy per Ton of Clinker	121	kWh/t clinker				
INPUT						
Raw Materials for clinker production						
High grade marl	1.90E+05	t	7.61E+12	seJ/kg (Switzerland)	1.45E+21	seJ
Low grade marl	3.18E+05	t	7.61E+12	seJ/kg (Switzerland)	2.42E+21	seJ
Quartz sand	1.89E+03	t	1.13E+14	seJ/kg (subsoil)	2.14E+20	seJ
Iron oxide	1.78E+03	t	1.06E+13	seJ/kg (Iron, element mass ratio in Taconite minerals; {Fe2O3, Fe3+2Fe2+O4, and Fe2+CO3}; 0.1 g/g in ground)	1.88E+19	seJ
Fuels for clinker production						
Coal	2.16E+04	t	3.74E+12	seJ/kg (Austria Hard Supply Mix)	8.06E+19	seJ
Petrol Coke	1.36E+04	t	6.57E+12	seJ/kg (Europe petroleum coke at refinery)	8.92E+19	seJ
Heavy fuel oil	369	t	5.76E+12	seJ/kg (Europe regional storage)	2.13E+18	seJ
Tyres	2.59E+03	t	3.39E+12	seJ/kg (Switzerland rubber municipal incineration)	8.79E+18	seJ
Waste Oil	1.29E+03	t	9.07E+12	seJ/kg (Europe lubricating oil at plant)	1.18E+19	seJ
SRF	4.18E+03	t	9.45E+11	seJ/kg (Europe 60% paper @ 3.11E5 SEJ/kg + Switzerland 40% mixed platics @ 1/2[2.46E5+1.69E6])	3.95E+18	seJ
Mineral components for cement production						

Chemical Gypsum	1.33E+04	t	1.65E+14	seJ/kg (Switzerland, mineral at mine)	2.19E+21	seJ
Blast Furnace Slag	2.34E+04	t	5.98E+12	seJ/kg (Switzerland, blast funance cement plant)	1.40E+20	seJ
Limestone	2.51E+04	t	9.09E+12	seJ/kg (Switzerland milled loose at plant)	2.29E+20	seJ
Fly ash	4.87E+04	t	4.66E+11	seJ/kg (Austria disposal of hard coal ash to landfill)	2.27E+19	seJ
Fuel for drying in cement production						
Light oil	459	t	5.88E+12	seJ/kg (Europe light fuel oil at regional storage)	2.70E+18	seJ
Air mass						
Air for burning	5.27E+05	t	2.58E+07	seJ/kg	1.36E+16	seJ
Air excess at preheater outles	6.41E+05	t	2.58E+07	seJ/kg	1.65E+16	seJ
Water mass						
Water for cooling of hot gases before main filter	4.42E+04	t	1.22E+09	seJ/kg (Europe completely softened at plant)	5.40E+16	seJ
Water for equipment cooling	2.50E+03	t	1.22E+09	seJ/kg (Europe completely softened at plant)	3.05E+15	seJ
					6.85E+21	**seJ (Sum of input)**
OUTPUT						
Air mass						
Air at chimney	1.12E+06	t	1.29E+09	seJ/kg	1.44E+18	seJ
Absolute Gross CO_2 Emissions	2.78E+05	t	6.26E+07	seJ/kg	1.74E+16	seJ
Thermal loses						
Radiation loses	173	MJ/t clinker	9.90E+11	seJ/kg clinker	3.12E+20	seJ
					3.14E+20	**seJ (Sum of output)**

* To simplify the formatting of tables, in Tables 2-5 the E is used as a replacement for 10, meaning that if as an example a value of 2.58E+07 is given in the table, the actual value is $2.58 \cdot 10^{7}$.

Table 3
Emergy calculation for the three mitigation scenarios.

	Scenario 1	Scenario 2	Scenario 3		Scenario 1	Scenario 2	Scenario 3
	Quantity			Unit	Emergy Calculation (seJ)		
MAIN DATA							
Clinker Production	3.15E+05			t	4.02E+21		
Specific Thermal Energy Consumption	3.00E+03	3.67E+03	3.00E+03	MJ/t clinker			
Cement Production	3.91E+05			t	**4.18E+21 (Cement produced)**		
Specific Electrical Energy Consumption	90.3			kWh/t cement			
Total Electrical Energy Consumption	3.82E+07			kWh	3.22E+19		
Electrical Energy per Ton of Clinker	121			kWh/t clinker			
INPUT							
Raw Materials for clinker production							
High grade marl	1.90E+05			t	1.45E+21		
Low grade marl	3.18E+05			t	2.42E+21		
Quartz sand	1.89E+03			t	2.14E+20		
Iron oxide	1.78 E+03			t	1.88E+19		
Fuels for clinker production							
Coal	1.68E+04	1.79E+04	1.46 E+04	t	6.27E+19	6.69E+19	5.45E+19
Petrol Coke	1.06E+04	1.13E+04	9.19E+03	t	6.94E+19	7.41E+19	6.04E+19
Heavy fuel oil	369			t	2.13E+18		
Tyres	2.59E+03			t	8.79E+18		
Waste Oil	1.29E+03			t	1.18E+19		
SRF	4.18E+03	1.37E+04	9.90E+03	t	3.95E+18	1.30E+19	9.36E+18
Mineral components for cement production							
Chemical Gypsum	1.33E+04			t	2.19E+21		
Blast Furnace Slag	2.34E+04			t	1.40E+20		

Limestone	2.51E+04			t	2.29E+20		
Fly ash	4.87E+04			t	2.27E+19		
Fuel for drying in cement production							
Light oil	459			t	2.70E+18		
Air mass							
Air for burning	5.27E+05			t	1.36E+16		
Air excess at preheater outles	6.41E+05			t	1.65E+16		
Water mass							
Water for cooling of hot gases before main filter	4.42E+04			t	5.40E+16		
Water for equipment cooling	2.50E+03			t	3.05E+15		
					6.82E+21 (Sum of input)	**6.82E+21 (Sum of input)**	**6.80E+21 (Sum of input)**
OUTPUT							
Air mass							
Air at chimney	1.12E+06			t	1.44E+18		
Absolute Gross CO_2 Emissions	2.56E+05	2.67E+05	2.42E+05	t	1.60E+16	1.67E+16	1.52E+16
Thermal loses							
Radiation loses	173			MJ/t clinker	3.12E+20		
					3.14E+20 (Sum of output)		

Table 4
Calculation of the fuel masses according to the thermal energy need for three mitigation scenario.

	BAU Scenario	Scenario 1	Scenario 2	Scenario 3
Clinker production (t/y)	3.15E+05			
Specific Thermal Energy Consumption (GJ/t)	3.67	3.00	3.67	3.00
Thermal energy needed (GJ/y)	1.16E+06	9.46E+05	1.16E+06	9.46E+05
Petrol coke - NCV (GJ/t)	31.8			
Petrol coke - used (t/y)	1.36E+04	1.056E+04	1.13E+04	9.18E+03
Thermal energy produced from Petrol coke (GJ/y)	4.32E+05	3.36E+05	3.58E+05	2.92E+05
Coal - NCV (GJ/t)	24.3			
Coal - used (t/y)	2.16E+04	1.68E+04	1.79E+04	1.46E+04
Thermal energy produced from Coal (GJ/y)	5.25E+05	4.08E+05	4.36E+05	3.55E+05
Heavy fuel oil - NCV (GJ/t)	40.8			
Heavy fuel oil - used (t/y)	369			
Thermal energy produced from Heavy fuel oil (GJ/y)	1.51E+04			
Tyres - NCV (GJ/t)	26.4			
Tyres - used (t/y)	2.59E+03			
Thermal energy produced from Tyres (GJ/y)	6.84E+04			
Waste Oil - NCV (GJ/t)	35.9			
Waste Oil - used (t/y)	1.29E+03			
Thermal energy produced from Waste oil (GJ/y)	4.66E+04			
SRF - NCV (GJ/t)	16.9			
SRF - used (t/y)	4.18E+03		1.37E+04	9.90E+03
Thermal energy produced from SRF (GJ/y)	7.11E+04		2.33E+05	1.68E+05

Table 5
CO_2 emissions and Ecological Footprint calculation.

	BAU Scenario	Scenario 1	Scenario 2	Scenario 3
Petrol coke - used (t/y)	1.36E+04	1.06E+04	1.13E+04	9.19E+03
Petrol coke - NCV (GJ/t)	33.5			
Emission factor ($kgCO_2/GJ$)	94.0			
Oxidation factor	1.00			
CO_2 Emissions Petrol coke - calculated (kg/y)	4.27E+07	3.33E+07	3.55E+07	2.89E+07
Coal - used (t/y)	2.15E+04	1.68E+04	1.79E+04	1.46E+04
Coal - NCV (GJ/t)	24.3			
Emission factor ($kgCO_2/GJ$)	9..3			
Oxidation factor	1.00			
CO_2 Emissions Coal - calculated (kg/y)	5.16E+07	4.01E+07	4.28E+07	3.49E+07
Heavy fuel oil - used (t/y)	369			
Heavy fuel oil - NCV (GJ/t)	40.8			
Emission factor ($kgCO_2/GJ$)	77.4			
Oxidation factor	1.00			
CO_2 Emissions Heavy fuel oil - calculated (kg/y)	1.17E+06			
Tyres - used (t/y)	2.59E+03			
Tyres - NCV (GJ/t)	35.9			
Emission factor ($kgCO_2/GJ$)	85.0			
Oxidation factor	1.00			
CO_2 Emissions Tyres - calculated (kg/y)	7.92E+06			
Waste Oil - used (t/y)	1.29E+03			
Waste Oil - NCV (GJ/t)	35.9			
Emission factor ($kgCO_2/GJ$)	80.0			
Oxidation factor	1.00			
CO_2 Emissions Waste Oil - calculated (kg/y)	3.73E+06			

SRF - used (t/y)	4.18E+03	4.18E+03	1.37E+04	9.90E+03
SRF - NCV (GJ/t)	16.9			
Emission factor ($kgCO_2/GJ$)	95.7			
Biogenic fraction (%)	60.0			
Oxidation factor	1.00			
Fossil Fraction Emission factor ($kgCO_2/GJ$)	37.4			
CO_2 Emissions SRF - calculated (kg/y)	2.66E+06	2.66E+06	8.71E+06	6.29E+06
Total Fuel CO_2 Emissions - calculated (kg/y)	1.10E+08	8.89E+07	9.99E+07	8.29E+07
Process Plant CO_2 Emissions - given from plant (kg/y)	1.67E+08			
Annual Plant CO_2 Emissions (kg) [P_C]	2.78E+08	2.56E+08	2.67E+08	2.50E+08
Fraction of CO_2 sequestered by the ocean [S_{Ocean}]	0.28			
Average global yield (kg/gHa) [Y_C]	3.59			
Equivalence factor [EQF]	1.26			
Ecological Footprint (gHa) [EF_C]	7.01E+04	6.47E+04	6.75E+04	6.32E+04