LIFE CYCLE ASSESSMENT OF DIFFERENT TYPES OF CEMENT CONCRETE AND THEIR IMPACTS ON LEED CERTIFICATED BUILDINGS

by
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The ecosystems and biospheres of our planet are being destroyed due to the fossil fuel driven industrial development and excess production of goods. Fossil fuel combustion, land use change and overexploitation of resources have raised the global mean surface temperature.

Concrete production is a highly resource and emissions intensive process due to its cement content. Considering the carbon dioxide (CO_2) emissions associated with the calcination process and the combustion of fuels during clinker production, and the abiotic resource depletion of fossils and elements, a more eco-designed concrete should involve environment friendly clinker substitutes and supplementary cementitious materials (SCMs) in cement and in concrete as well as refuse derived fuels in fuel mix to create significant reduction in resource and emissions intensity. Moreover, the construction industry generates significant amount of waste that should be managed and integrated to value chain in the view of circular economy.

In this study, an integrated approach of application of waste to energy targets, utilizing clinker substitutes, SCMs and construction and demolition waste (CDW) in concrete mix will be interpreted with Life Cycle Assessment (LCA) for different selected scenarios. The results represent the environmental savings through the integrated approach in terms of their relatively reduced contribution to global warming, acidification, eutrophication, photochemical ozone creation, human toxicity and abiotic resource depletion of fossils and elements. In addition, the eco-designed concrete to be defined as a result of LCA study will be evaluated in terms of LEED green building certification system.

FARKLI TİP ÇİMENTO BETONLARIN YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ VE LEED SERTİFİKALI BİNALARA ETKİSİ

Gezegenimizin ekosistemi ve biyosferi fosil yakıt tüketimine ve aşırı üretime dayalı endüstriyel büyüme sebebiyle tahrip olmaktadır. Fosil yakıtların kullanılması, arazi kullanımlarındaki değişimler ve kaynakların aşırı kullanımı küresel ortalama yüzey sıcaklıklarını yükseltmiş durumdadır.

Çimento içeriği nedeniyle beton üretimi, kaynak kullanımı ve emisyon oluşumu açısından yüksek yoğunluklu bir prosestir. Fosil yakıt kullanılması ve hammaddelerin kalsinasyonu sonucu açığa çıkan karbondioksit (CO_2) emisyonları ile beton üretimi sırasında kullanılan fosil ve mineral kaynakların tükenmekte olduğu göz önünde bulundurulduğunda, kaynak ve emisyon yoğunluğunda önemli bir düşüş sağlayarak beton üretiminin çevresel performansını arttıracak katkı maddeleri, çimentomsu malzemeler ve alternatif yakıtların kullanılması şarttır. Dahası, inşaat sektörü yönetilmesi ve döngüsel ekonomi ışığında ekonomiye kazandırılması gereken önemli miktarda atık üretmektedir.

Bu çalışmada, atıktan türetilmiş yakıt (ATY), katkı maddeleri, çimentomsu malzemeler ve inşaat ve hafriyat atıklarının çimento ve beton üretim proseslerinin çevresel performansına etkisi Yaşam Döngüsü Değerlendirmesi (YDD) yöntemiyle değerlendirilecektir. Sonuçlar, entegre bir yaklaşımın, küresel ısınma, asidifikasyon, ötrofikasyon, fotokimyasal ozon oluşumu, insan toksisite ve abiyotik kaynakların tükenmesi potansiyelinde yaratacağı iyileştirmeyi ortaya koyacaktır. YDD çalışması sonucunda ortaya konulacak olan eko-tasarım beton ürünü, LEED yeşil bina sertifikasyon sisteminde değerlendirilecektir.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	**Explanation**	**Units**
ADP (elements)	Abiotic Depletion Potential Of Non-Fossil Resource	kg Sb eq.
ADP (fossil)	Abiotic Depletion Potential of Fossils	MJ
AP	Acidification Potential	kg SO_2 eq.
BAT	Best Available Techniques	-
BREF	Best Available Techniques Reference Document	-
C2S	Belite	-
C3A	Tricalciumaluminate	-
C3S	Alite	-
C4AF	Tetracalciumaluminaferrite	-
CCS	Carbon Capture and Storage	-
CDW	Construction and Demolition Waste	-
CEMBUREAU	The European Cement Association	-
CO	Carbon Monoxide	-
CO_2	Carbon Dioxide	-
CO_2e	Carbon Dioxide equivalent	-
CSI	Cement Sustainability Iniative	-
EBRD	European Bank for Reconstruction and Development	-
EC	European Commission	-
ECRA	The European Cement Research Academy	-
EIA	Energy Information Administration	-
ELV	Emission Limit Value	-
EP	Eutrophication Potential	kg PO_4 eq.
EPA	Environmental Protection Agency	-
EPD	Environmental Product Declaration	-
EU	European Union	-

FU	Functional Unit	-
GBC	Green Building Council	-
GHG	Greenhouse Gas	-
GW	Gigawatt	-
GWP	Global Warming Potential	kg CO_2- eq
HTP	Human Toxicity Potential	kg Ethane eq.
IEA	International Energy Agency	-
IPCC	Intergovernmental Panel on Climate Change	-
ISO	Organisation International Standards	-
LCA	Life Cycle Assessment	-
LCI	Life Cycle Inventory Analysis	-
LCIA	Life Cycle Impact Assessment	-
LEED	Leadership in Energy and Environmental Design	-
MW	Megawatts	-
MWh	Megawatt hour	-
NERI	National Environmental Research Institute	-
NOx	Nitrogen Oxides	-
NRMCA	National Ready Mixed Concrete Association	
OECD	Organization for Economic Cooperation and Development	-
PCB	Polychlorinated Biphenyl	-
PCR	Product Category Rules	-
PCR	Product Core Rules	-
POCP	Photochemical Ozone Creation Potential	kg 1.4-$C_6H_4C_{l2}$ eq.
RDF	Refuse derived fuel	-
SCM	Supplementary cementitious materials	
SETAC	Society of Environmental Toxicology and Chemistry	-
SNCR	Selective Non-Catalytic Reduction (DeNOx type)	-
TÇMB	Türkiye Çimento Müstahsilleri Birliği	-

VOC	Volatile Organic Compounds	-
WBCSD	World Business Council for Sustainable Development	-

1. INTRODUCTION

Recent decades have produced more material wealth, consumption and technological advances while destroying the ecosystems and biospheres of our planet due to the fossil fuel driven industrial development and excess production of goods. Fossil fuel combustion, land use change and overexploitation of resources have raised the global mean surface temperature by almost 0.9^{o}C since the end of the 19th century (IPCC, 2009). Rising sea levels, loss of arable lands, threatening food scarcity, biodiversity loss, and population displacement by extreme weather and mass extinctions are some important consequences of global warming that should be underlined. In order to prevent the risks to ecosystems and livelihood at tolerable level, the increase in global temperature should be held below 2°C compared to the temperature in pre-industrial times (IPCC, 2009). The emissions-mitigation report of the Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC) is framed to address this aim. Achieving this target is only possible with strict CO_2 emissions reductions. In order to meet such a level of CO_2 reductions, a comprehensive, integrated approach indicating the necessity of substantial decrease in consumption of: concrete for new structures, cement in concrete mixtures, and clinker and fossil fuels for cement production is required (Çelik, et al., 2014 and CEMBUREAU, 2013).

Every year, 10 billion tons of concrete are produced (Meyer, 2009). The massive production and consumption of concrete has considerable environmental impacts. Consuming large amounts of natural resources and carbon dioxide (CO_2) emissions associated with cement production are the major sustainability issues facing the concrete industry today. Concrete production consumes 42% of the aggregates annually produced (Marinkovic *et a.l*, 2010 and Boesch and Hellweg, 2010) and the production of 1 kg of cement requires 1.4 kg of raw materials in average (Boesch and Hellweg, 2009). Being highly resource and emissions intensive process, cement production accounts for 5-8% of the current worldwide CO_2 emissions (Boesch and Hellweg, 2010; CEMBUREAU, 2013; Gabel, 2004 and Marinkovic et al., 2010). Moreover, the industry produces nearly 50% of total waste. Thus, recycling construction and demolition waste (CDW) have become a consequential option for a more eco-designed concrete considering the large amounts of natural aggregates required in concrete mix.

Increasing demand and production capacity will lead to much more environmental impacts related to emissions release, resource depletion and waste generation that will force the construction industry to develop more durable and sustainable solutions. This thesis presents a study on the development of low-carbon cement concrete. Within this frame, several concrete production scenarios including different aggregate, binder and fuel combinations are evaluated by Life Cycle Assessment (LCA) Methodology in order to identify concrete production with maximum use of alternative materials. The results will demonstrate the environmental savings through the integrated approach with regards to RDF supplement in fuel mix, clinker substitution in cement, replacement of cement with fly ash and slag in concrete mix and utilizing CDW as aggregates.

2. LITERATURE REVIEW

2.1. Composition of Concrete

Concrete is defined as "Material formed by mixing cement, coarse and fine aggregate and water, with or without the incorporation of admixtures or addition, which develops its properties by the hardening of the cement paste (cement and water)". In accordance with the standard EN 206-1:2001, concrete is classified by compressive strength class. In addition, for any compressive strength class, concrete must be defined by environmental exposure class and optionally, slump class (PCR, 2013). EN 206-1 is a 'framework standard' with national provisions, detailed requirements and rules of application etc. provided by a complementary national standard which is TS EN 206-1 for Turkey. Table 2.1 shows compressive strength classes for normal and heavy concrete according to TS EN 206-1.

Table 2.1. Compressive strength classes for normal and heavy concrete (TS EN 206-1).

Compressive strength class	Lowest characteristic cylinder strength $f_{ck, cyl}$ N/mm^2	Lowest characteristic cube strength $f_{ck, cube}$ N/mm^2
C 8/10	8	10
C 12/15	12	15
C 16/20	16	20
C 20/25	20	25
C 25/30	25	30
C 30/37	30	37
C 35/45	35	45
C 40/50	40	50
C 45/55	45	55
C 50/60	50	60
C 55/67	55	67
C 60/75	60	75
C 70/85	70	85
C 80/95	80	95
C 90/105	90	105
C 100/115	100	115

Concrete typically consists of 8-15% cement, 2-5% water, about 80% aggregates (e.g. sand and gravel) and less than 0.1% chemical admixtures. The types of aggregate and cement selected depend on the service area of the concrete. Although aggregates have the biggest share in concrete composition, cement content and composition engender the environmental load of concrete (CSI/ECRA, 2009 and CEMBUREAU, 2013).

2.1.1. Cement

Cement is a hydraulic binder obtained by grinding clinker with several substitutes. Clinker is produced by heating up the raw materials to the required high temperature; about 1450^{o}C. Thus, the production of clinker is highly energy intensive process that provides the calcination of limestone ($CaCO_3$) to calcium oxide (CaO) and emits CO_2 (Yeğinobalı, 2003).

The main components of the cement's raw meal are limestone and clay which are the main source of calcium oxide (CaO) and silisium oxide (SiO_2). The followings are aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3). Aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) are generally obtained from clays or involved in addition. Other components like magnesium oxide (MgO) and other alkali oxides constitute a small fraction.

CaO reacts with other minerals in the clay to form the main clinker minerals; namely alite (C3S), belite (C2S), tricalciumaluminate (C3A) and tetracalciumaluminaferrite (C4AF) (EPA, 2010; Marinkovic et al., 2010 and Yeğinobalı, 2003). Clinker mixed with gypsum ($CaSO_4.2H_2O$) is referred as Portland cement. Controlling the early reaction of tricalciumaluminate (C3A), gypsum avoids flash setting of concrete and a rapid development of rigidity in freshly mixed Portland cement paste or concrete. The typical Portland cement consists of 60-67% CaO, 17-25% SiO_2, 3.0-8.0% Al_2O_3, 0.5-6.0% Fe_2O_3, 1.0-3.0% SO_3 and 0.2-1.3% alkalis (Yeğinobalı, 2003).

Several types of cement composition exist which varies depending on the different sources for calcium and different substitutes to regulate properties. The main constituents of the cement composition apart from the clinker are granulated slag (S), silica dust (D), natural and industrial pozzolans (P or Q), high silica and limestone fly ashes (V or W), burnt shales (T), and limestone (L or LL). According to European standards EN 197-1, cement composition is shown in Table 2.2.

Table 2.2. European standards EN 197-1 cement composition (Çelik et al., 2015).

Cement Type	Designation	Notation	Clinker K	GGBS S	Silica Fume D	Pozzolana		Fly ashes		Burnt Shale T	Limestone		Minor Additi. constit.
						Nat. P	Indust. Q	Silic. V	Calcar W		L	LL	
I	Portland Cement	I	95-100	-	-	-	-	-	-	-	-	-	0-5
II	Portland Slag Cement	II/A-S	80-94	6-20	-	-	-	-	-	-	-	-	0-5
		II/B-S	65-79	21-35	-	-	-	-	-	-	-	-	0-5
	Portland Silica Fume Cement	II/A-D	90-94	-	6-10								0-5
	Portland Pozzolana Cement	II/A-P	80-94	-									0-5
		II/B-P	65-79	-									0-5
		II/A-Q	80-94	-									0-5
		II/B-Q	65-79	-									0-5
	Portland Fly Ash Cement	II/A-V	80-94	-									0-5
		II/B-V	65-79	-									0-5
		II/A-W	80-94	-									0-5
		II/B-W	65-79	-									0-5
	Portland Burnt Shale Cement	II/A-T	80-94	-	-	-	-	-	-	-	-	-	0-5
		II/B-T	65-79	-	-	-	-	-	-	-	-	-	0-5
	Portland Limestone Cement	II/A-L	80-94	-							6-20		0-5
		II/B-L	65-79	-							21-35		0-5
		II/A-LL	80-94	-								6-20	0-5
		II/B-LL	65-79	-								21-35	0-5
	Portland Composite Cement	II/A-M	80-94	←…………………………… 11-35 ……………………………→									
		II/B-M	65-79	←…………………………… 36-55 ……………………………→									
III	Blastfurnace Cement	III/A	35-64	35-65	-	-	-	-	-	-	-		0-5
		III/B	20-34	66-80	-	-	-	-	-	-	-		0-5
		III/C	5-19	81-95	-	-	-	-	-	-	-		0-5
IV	Pozzolonic Cement	IV/A	65-89	-	←……… 11-35 ………→				-	-	-		0-5
		IV/B	45-64	-	←……… 36-55 ………→				-	-	-		0-5
V	Composite Cement	V/A	40-64	18-30		←…… 18-30 ……→			-	-	-		0-5
		V/B	20-39	31-50		←…… 31-50 ……→			-	-	-		0-5

2.1.1.1. Blended Cements Portland cement consists of 95% clinker and 5% gypsum. Blended cements are Portland cements with clinker substitutes. Finely ground limestone (without being heated and transformed into lime) or natural pozzolans such as clays, shale and certain types of sedimentary rocks can be added to the clinker. Other alternatives can be listed as certain industrial by-products including fly ash, granulated blast furnace slag, silica fume and materials from ceramic industry with hydraulic binding or pozzolanic characteristics that react with calcium hydroxide ($Ca(OH)_2$) (Damtoft et al., 2008 and CEMBUREAU, 2013). Fly ash increases the long-term mechanical and durability properties of the concrete significantly due to the pozzolanic reaction between fly ash and calcium hydroxide. However, concerning the environmental impacts of the coal fired plants; the processes should be replaced by more environmentally sound processes such as de-carbonization or nitrogen oxides (NO_X) removing processes. Blast furnace slag utilization has its own difficulties. Predicting the future iron and steel production volumes is difficult (CSI/IEA, 2009). Thus, other clinker substitutes such as limestone powder should be focused to reduce the clinker content (Çelik et al., 2015 and Damtoft et al., 2008). Limestone powder (L) has been introduced into cement and concrete in small volumes for many years. The added limestone powder improves the workability and fills up the open pores and empty capillary spaces within the concrete depending on levels and replacement ratio. In the case of exceeding 5% level, it may lessen the amount of required sand in aggregates mix (Çelik et al., 2015). Pozzolanic cements and composite cements are suitable in the countries where cement production is high and substitution materials are abundant (CSI/IEA, 2009 and Kelly and Van Oss, 2007). Table 2.3 shows general information about clinker substitutes (CSI/IEA, 2009). The improvements in cement composition clearly exhibit the decline in the clinker content shown in Figure 2.1.

2.1.2. Aggregates

Aggregates are a mix of coarse and fine particles including sand, gravel and/or recycled concrete (Worrell et al., 2008 and CEMBUREAU, 2013). The chemical composition of the gravel consists of mainly SiO_2 with 97 wt% of the total and minor oxides such as Al_2O_3 and Fe_2O_3. The texture, water content and impurities in aggregates are important factors which effects water to cement ratio and thus, concrete quality as well.

Recently, using construction and demolition waste (CDW) as aggregates have become a considerable option for a more eco-designed concrete due to the large amounts of natural aggregates required in concrete mix. Although replacing natural aggregates with CDW is limited because using recycled aggregate generally results in a decrease in fresh concrete properties (mass density and workability), mechanical performance (compression and splitting tensile strength, modulus of elasticity) and durability performance (permeability, shrinkage, chloride and sulphate penetration resistance and carbonation resistance), combining fly ash or blast furnace slag with recycled aggregates can improve these properties to the desired levels. For instance, due to the higher porosity and lower density of recycled aggregates, utilization of recycled CDW as aggregates decreases compression

Table 2.3. General information about clinker substitutes (CSI/IEA, 2009 and Vefagom and Avellaneda, 2013).

Clinker substitutes	**Sources**	**Positive characteristics**	**Limited characteristics**	**Estimated annual production level**	**Availability**
Ground blast furnace slag	Iron or steel production	Higher long term strength	Lower early strength and higher electricity power demand for grinding	200 million tones (2006)	Future iron and steel production volumes are very difficult to predict
Fly ash	Flue gases from coal-fired furnace	Lower water demand, improved workability, higher long term strength, better durability (depending on the application)	Lower early strength availability may be reduced by change in fuel sources by the power sector	500 million tones (2006)	Future number and capacity for coal-fired power plants is very difficult to predict
Natural pozzolans (e.g., volcanic ash), rice husk ash, silica fume	Volcanos, some sedimentary rocks, other industries	Contributes to strength development, can demonstrate better workability, higher long term strength and improved chemical resistance	Most natural pozzolans lead to reduced early strength, cement properties may vary significantly	300 million tones available (2003) but only 50% used	Availability depends on local situation- many regions do not provide use of pozzolan for cement
Artificial pozzolans (e.g., calcined clay)	Specific manufacture	Similar to natural pozzolans	Calcination requires extra thermal energy and so reduces positive carbon abatement effect	Unknown	Very limited availability due to the economic constrains
Limestone	Quarries	Improved workability	Maintaining strength may require additional power for grinding clinker	Unknown	Readily available

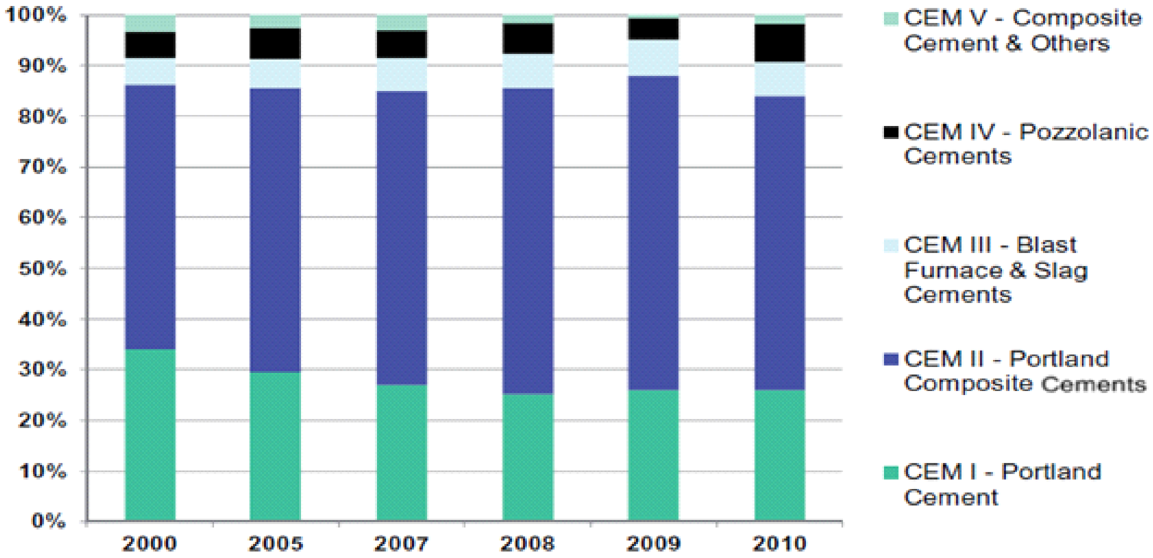


Figure 2.1. Domestic deliveries by cement type, CEMBUREAU 2000 - 2010 (CSI, 2011)

strength, splitting tensile strength, resistance to carbonation, chloride ion penetration and sulphate attack while increasing the shrinkage deformation, air and water permeability compared to those of natural aggregate concrete. But, fly ash increases the long-term mechanical and durability properties of the concrete significantly due to the puzzolanic reaction between fly ash and calcium hydroxide in the recycled aggregates concrete. It should be noted that the binding reaction between fly ash and aggregates occurs in longer times. Therefore, the higher content of fly ash increases required time (Anastasiou et al., 2014; Çakır, 2014; Kim et al., 2013; Kou and Poon, 2013; Lima et al., 2013; Limbachiya et al., 2012; Marie and Quiasrawi, 2012 and Soares et al., 2014). Combining fly ash with recycled aggregates leads to an increase in compactness and acts as a filling material by forming a secondary C-S-H between the aggregates and clinker minerals results in a decrease in the porosity of the concrete (Anastasiou et al., 2014; Behera et al., 2014 and Henrya et al., 2011). In addition, the use of good quality coarse aggregates recycled from precast elements that totally fit for the production of new concrete does not result in a loss of mechanical and durability performance (Soares et al., 2014). The observed general trend from the literature indicates that up to 30% coarse recycled CDW aggregates has no major negative effects on mechanical and durability properties (Çakır, 2014; Kim et al., 2013; Lima et al., 2013; Limbachiya et al., 2012 and Soares et al., 2014). In this study, CDW will be utilized by 20% weight replacement of natural aggregates to ensure the desired quality.

2.2. Concrete Production

Concrete production has two main lines which are cement production and aggregates processing. Figure 2.2 shows the general concrete production stages.

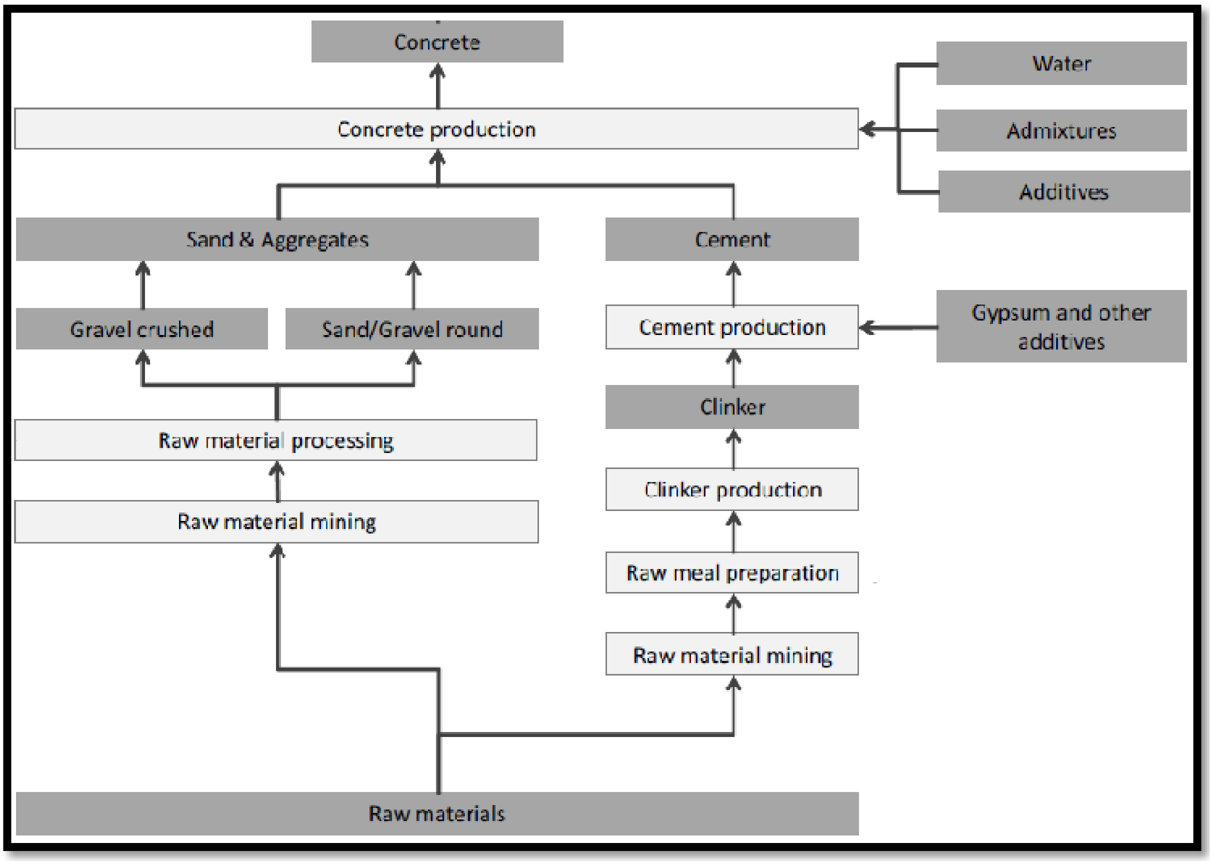


Figure 2.2. General stages of concrete production (Schepper et al., 2014)

2.2.1. Cement Production

Cement production has four main stages; raw material extraction from quarries, raw meal preparation, clinker processing in kilns and finish grinding. The cement production stages are shown in the Figure 2.3 and general flowchart of the cement production is shown in Figure 2.4)

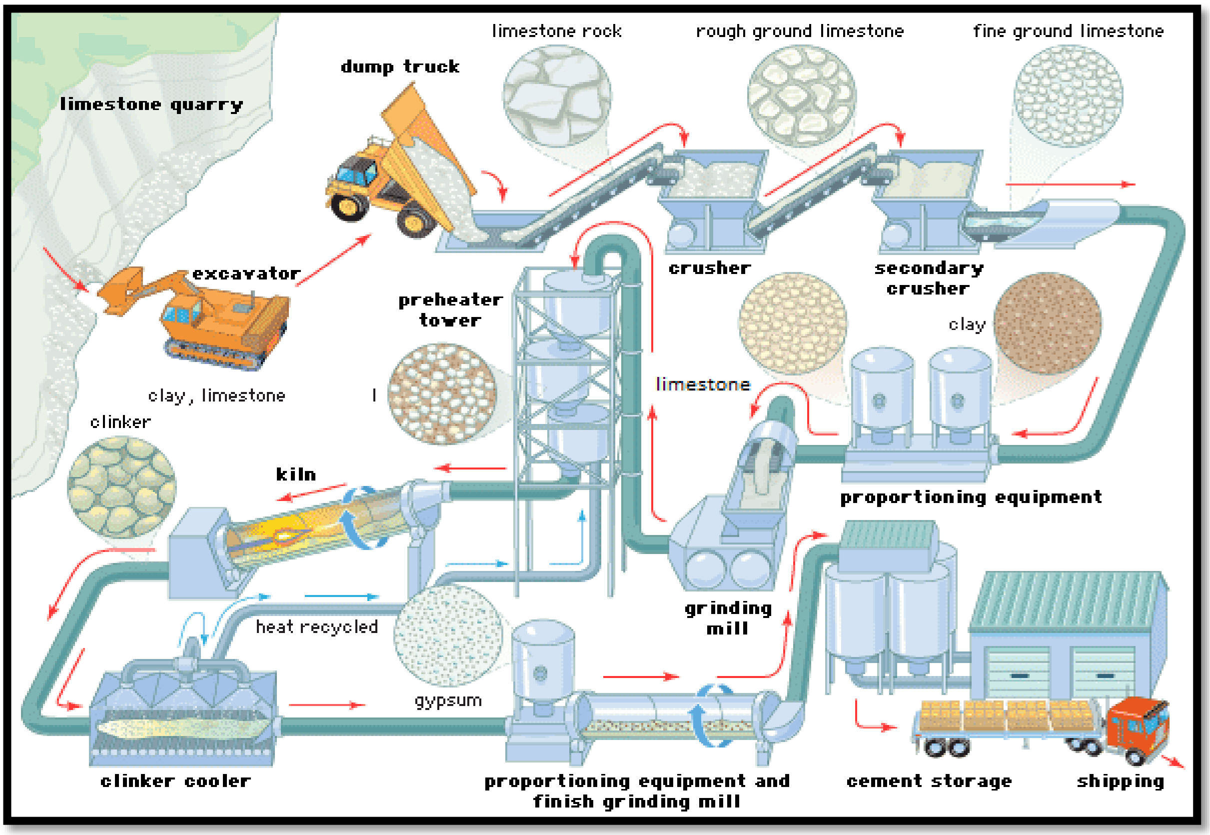


Figure 2.3. General production stages of cement production (Encyclopaedia Britannica, Inc., 2007)

<u>2.2.1.1. Raw Meal Preparation</u> In raw meal preparation stage, extracted raw materials such as limestone and clay are scaled to the required size by crushers. Crushed materials are transferred to homogenization unit to adjust the chemical composition of raw material.

<u>2.2.1.2. Clinker Processing</u> The most important stage of the cement production is the calcination of the raw materials to produce clinker which is the semi-product of cement. Calcination is separation of CO_2 from raw materials. Calcination reaction is shown below.

$$CaCO_3 \rightarrow CaO + CO_2 \quad (2.2)$$

Raw meal from the silo is fed into pre-heating tower before introducing to the kiln to save energy. Raw meal is partly calcined by heating between 60°C and 860°C in the pre-heating tower consisting of cyclones and calciner. The hot raw meal from the pre-heater is

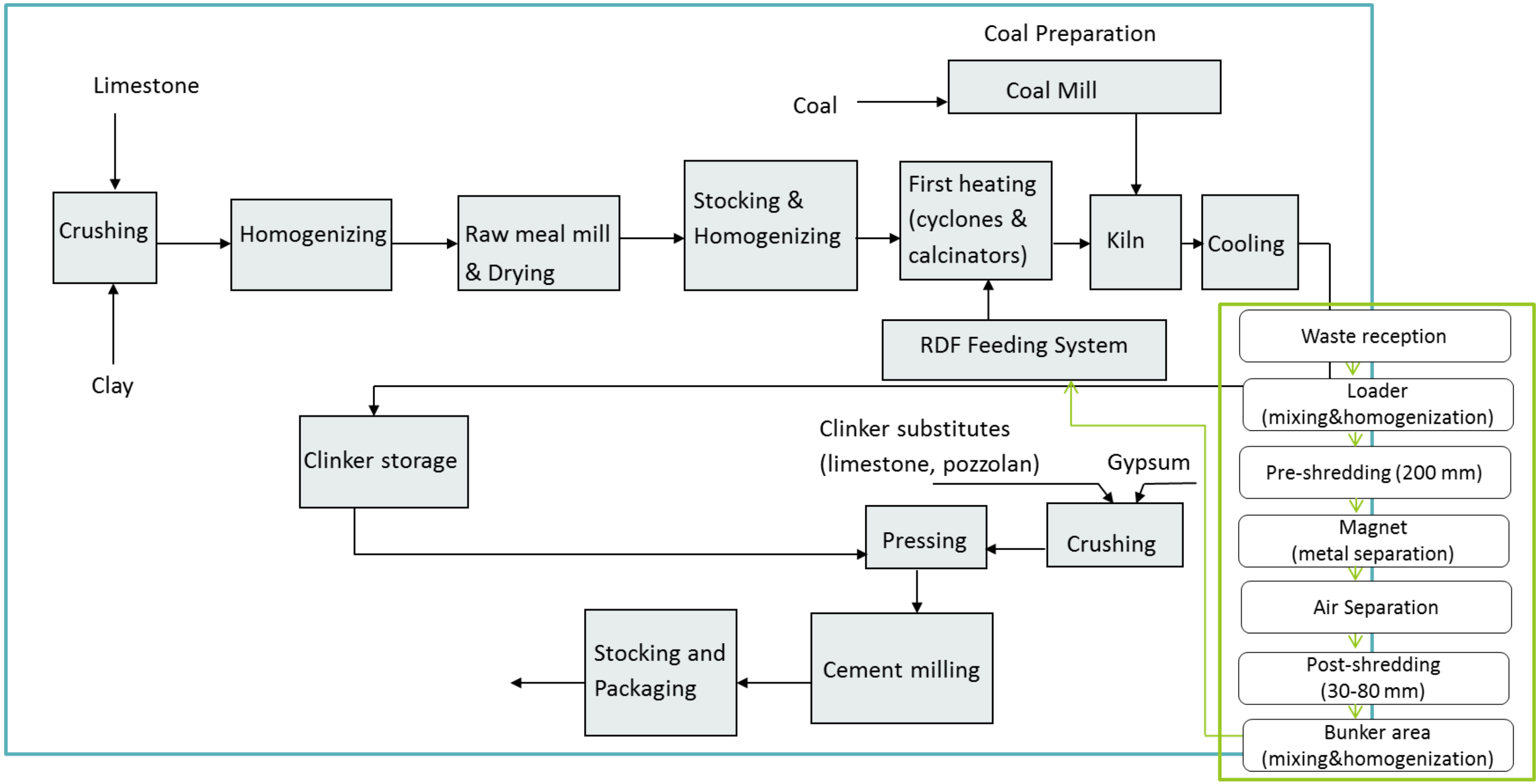


Figure 2.4. Cement production flowchart (Lamas et al., 2013

processed in the rotary kiln at 1450°C and granulated to produce clinker. The produced clinker is stored in the clinker silos (Yeğinobalı, 2003).

The required high temperature in the kilns is achieved by fuel mix including coal, petro coke, natural gas and RDF if used. Therefore, preparation of coal and RDF become another sub-process of the clinker processing stage. RDF preparation includes mixing and homogenization, pre-shredding, metal separation, air separation and post-shredding stages. Shredding system is required to arrange particle size. Magnets after the air separation enable metal separation. In air separation unit, waste is classified according to mass division and heavy fraction which may damage the system is picked out. The separated metals are sent to metal recovery facilities. Finally, RDF is mixed again to become homogenize before feeding to the system (Yeğinobalı, 2003 and Çelik et al., 2015).

Rotary kilns with the diameter of 3-7 meter and the length of 50-75 meter are accepted as the biggest process elements in industrial facilities. They are giant pipes made of steel sheet with 50 mm of thickness and covered by refractory brick. Approximately, the kilns are installed with the slope of 3-4% and rotate with 1,5-4 per minute. The materials from pre-heating tower move towards warmer regions till the flame at the lower end. The rest of CO_2 is separated during the movement of the materials among the kiln (Yeğinobalı, 2003).

While burning in the kilns, the lime, silica, iron and alumina transform into Free State at first, and then they create new compounds as the temperature increases. Free and crystal water in material evaporates while clay decomposes. CO_2 begins to separate from the limestone at the pre-heating and at the upper region of the kiln. When the calcination completes in lower and warmer regions, released CaO combines with SiO_2, Fe_2O_3 and Al_2O_3 separated from clay and creates calcium silicate and calcium aluminate (Yeğinobalı, 2003). Figure 2.5 shows the phase change in cement's raw materials during the transition from raw meal to clinker and main reaction in the kilns are summarized in Table 2.4.

The composition of clinker involves C3A ($3CaO.Al_2O_3$), C4AF ($4CaO.Al_2O_3.Fe_2O_3$), C2S and C3S. C3A gives a very rapid reaction with water and too much heat is released. As a result, cement paste becomes solid very quickly. Therefore, clinker is ground with gypsum. The binding property of C3A is low. It also decreases the strength of cement against sulphate attacks. The binding property of C4AF is low and its reaction with water is less.

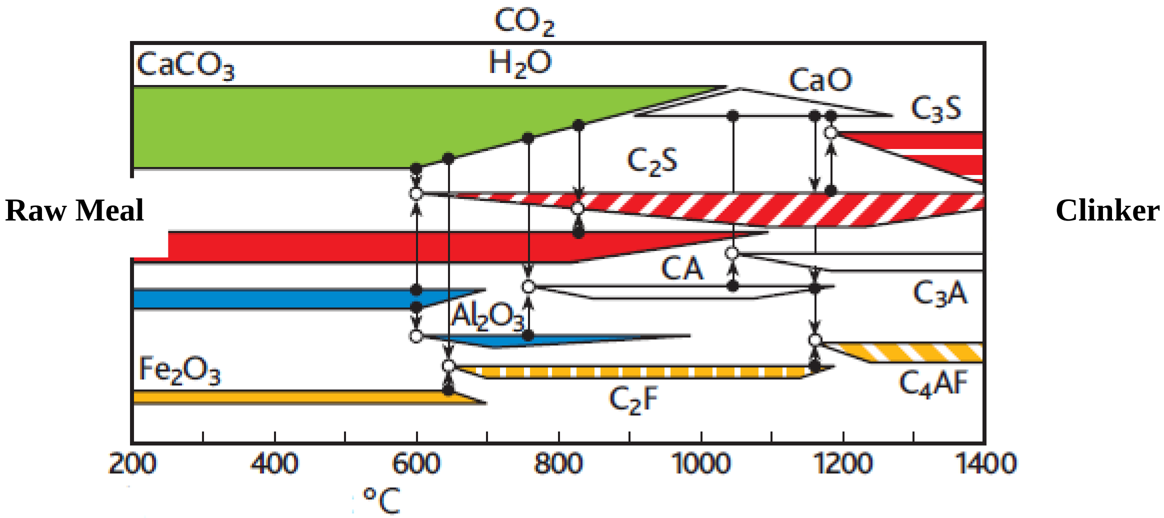


Figure 2.5. Mineral phase change (Yeğinobalı, 2003)

Table 2.4. Chemical reactions of clinker production (Yeğinobalı, 2003).

650-1050°C

I. Al_2O_3 2 SiO_2 2 H_2O+5 $CaCO_3$ $\rightarrow$ CA+2 C2S+2 H_2O+5 CO_2 (2.3)

II. Fe_2O_3 + 2 $CaCO_3$ $\rightarrow$ C2F + 2 CO_2 (2.4)

III. C + O_2 $\rightarrow$ CO_2 (2.5)

IV. SiO_2 + 2 $CaCO_3$ $\rightarrow$ C2S + 2 CO_2 (2.6)

V. $CaCO_3$ $\rightarrow$ C + CO_2 (2.7)

1250-1450°C

VI. C2F + Ca + C $\rightarrow$ C4AF (2.8)

VII. CA + 2C $\rightarrow$ C3A (2.9)

VIII. C2F + Ca + C $\rightarrow$ C4AF (2.10)

IX. C2S + C $\rightarrow$ C3S (2.11)

The reaction between C2S and water is slow and released heat is low. The high binding property of C2S shows itself in years. The reaction rate of C3S with water and released heat is medium. High binding property is effective from the first years.

Arranging the proportions of these four main components of clinker while preparing the raw meal provides cement to have desired properties for different services. For instance, to produce cement which high early strength, increasing C3S amount; to produce sulphate resistance cement, decreasing C3A; and to produce low heat cement, decreasing both C3A and C3S amount is required. Moreover, the amounts of free CaO, MgO and other alkali oxides and SO_3 are limited because the presences of them may results in volume expansion and cracks in next years.

In the low end of the kiln, the temperature reaches to 1870°C (one third of the surface temperature of the sun) due to the flame of the fuel mix including coal, natural gas, fuel oil, etc. In this hottest region, the temperature of the calcined material reaches to 1480°C. The calcined materials partly melt in this temperature and the thin particulates sticks together to produce clinker. The semi-product clinker leaves the kiln at 1300°C. Thus, the operations of cooling of the clinker and recycled of the waste heat are activated. Clinker is cooled to 100^{o}C by treating with air. The cooling operation influence inner structure of the clinker, so it should be under control. The recycled waste heat which is approximately one third of required heat energy is used for heating the kilns and pre-calcination. The waste heat can be used for drying of raw material, hot water supply and heating the buildings (Yeğinobalı, 2003).

2.2.1.3. Cement Grinding In finish grinding stage, the clinker from the silo is first pressed and then ground in the cement mill with calcium sulphate including materials such as gypsum in order to control the chemical reactions and solidification process when the cement is mixed with water. Some chemicals for easy grinding facilitation and/or some mineral substitutes to decrease clinker/cement ration can be added during this stage. Clinker particles with diameter of about 2 centimeters should be ground until they reach to diameter of 15-20 microns. Clinker substitutes are transferred to cement mill for finish grinding after reaching the required size by another crusher. The produced cement is stored in cement silos. The typical Portland cement consists of 60-67% CaO, 17-25% SiO2, 3.0-8.0% Al_2O_3, 0.5-6.0% Fe_2O_3, 1.0-3.0% SO_3 and 0.2-1.3% alkalis (Yeğinobalı, 2003).

2.2.2. Concrete Mixing

Concrete consisting of cement, aggregates, water and slight amount of chemical admixture (super plasticizers, air entrainers, retarders and accelerators) that helps concrete to adjust the required performance criteria for the selected application, simply produced by a mixing process. Materials processed in the crushers are filled to separate compartments in aggregates silo via loaders. The certain amounts of aggregates from the compartments, the cement from the cement silo, water and chemical admixtures are fed into central plant mixer to form concrete mix. All components of a ready-mix concrete are mixed for specified period of time according to the concrete receipt in compliance with EN 206-1. The higher concrete class takes the longer period of times. When the ready mix concrete meets the standard, it is loaded to truck mixers for transportation to the destination.

2.3. Current Situation and the Future of Cement Industry

Global cement production increased significantly in the 20th century due to the evolution of the industry and increase in urbanization as well as geographically available raw materials. It has continued to increase in 21th century - for instance, it has increased by 54% between 2000 and 2006 and reached 2.55 billion tones and it is predicted to reach 3.69-4.40bn in 2050 by rising 43-72% from the year 2006 (CSI/IEA, 2009 and Kelly and Van Oss, 2007). Figure 2.6 shows the total production volumes of cement between 2006 and 2014 (USGC, 2015). As modernization and growth continues, demand for cement production is estimated to grow, especially in developing countries such as India, Africa and the Middle East. Moreover, in some European countries such as Greece, Portugal, Spain and also Turkey, cement production is predicted to increase due to the considerable economic growth in the last decade (CSI, 2011). World cement production by region and main countries can be seen in Figure 2.7 (USGS, 2015).

The production capacity of Turkish cement industry has increased from 20.000t/yr to over 66.000.000 t/yr in 100 years and has reached a usable production capacity over 80 million tons. Cement industry has posed an important role for a national economy by 2010 with turnover of about US$4.5bn and direct employment of 15.000 people (Becan, 2011). Turkey ranks first in Europe and 4th in the world after China, India and USA (Olivier, et al., 2014). With respect to cement exports, Turkish cement industry has a global share of 12%, leaving China and many countries of South Eastern Asia behind and exports have a value of US$1bn.

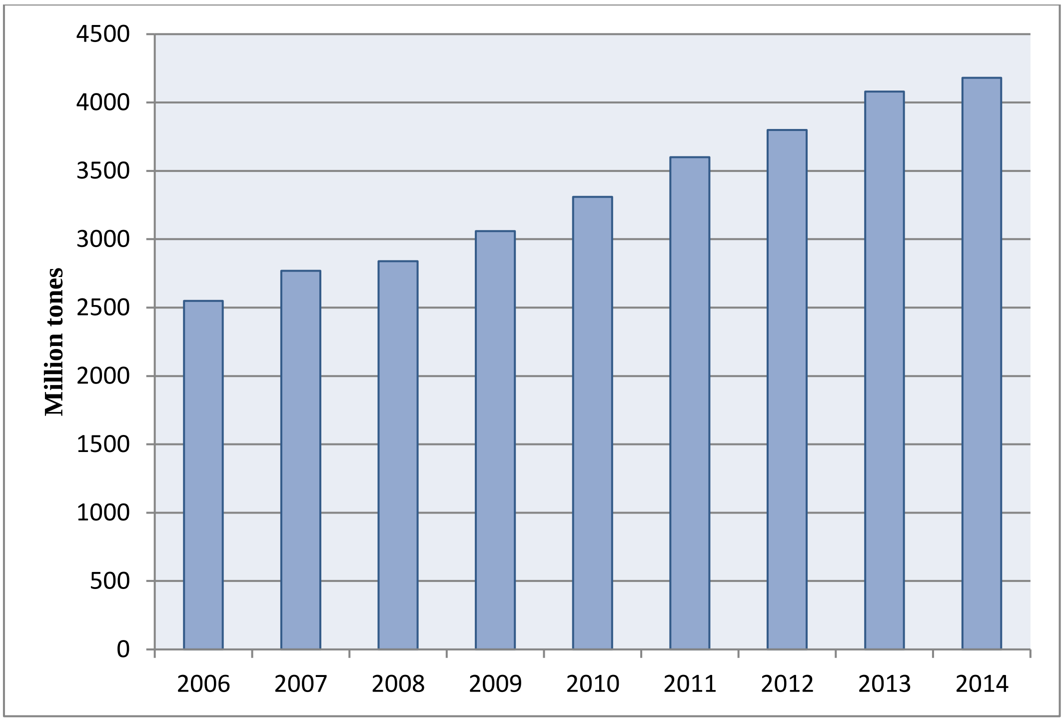


Figure 2.6. The global cement production, 2006 - 2014 (USGC, 2015)

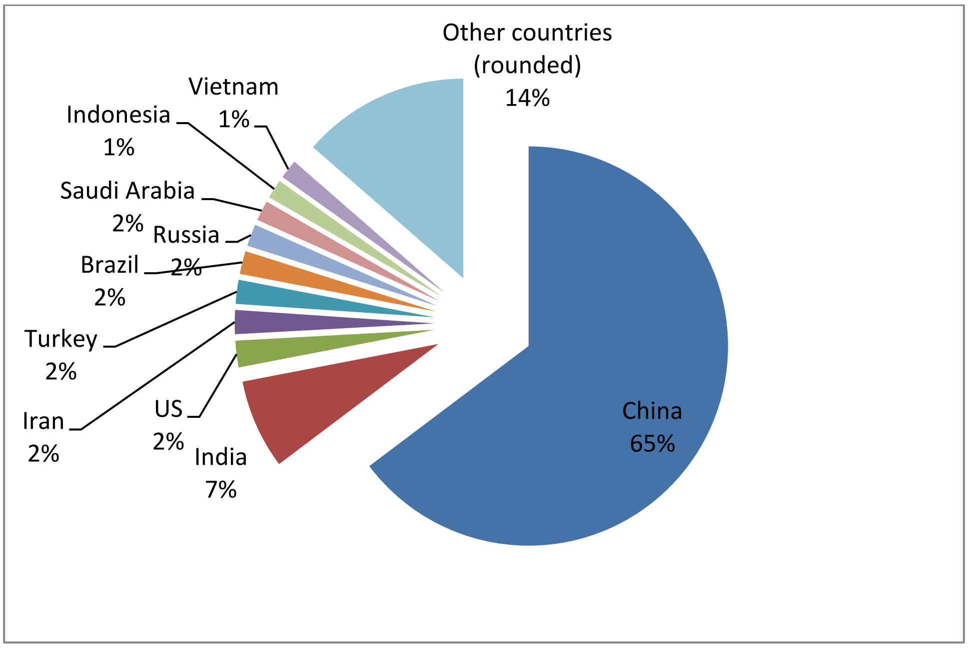


Figure 2.7. World cement production 2014, by main countries (USGS, 2015)

By 2020, it is estimated that the production capacity of cement will reach to 100.000.000 t/yr. Projected cement production and export volume for Turkey between 2012 and 2020 are shown in Table 2.5 (Becan, 2011).

Table 2.5. Projected cement production and export volume for Turkey 2012 - 2020 (Becan, 2011).

Year	Cement Production (Mt/yr)	Potential Volume for Export (mt)
2014	75	16
2015	78	17
2020	90	20

2.4. Environmental Impacts of Cement Production

The environmental impacts of cement manufacturing can be local, regional, or global in scale. During inventory analysis (LCI), large quantities of natural resources are consumed and the emissions produced in various stages of the complete life cycle of concrete production. The production of 0.91 ton of clinker or 1.0 ton of finished ordinary Portland cement commonly results in CO_2 emissions exceeding 0.8 tons CO_2. Each ton of cement requires 1.4 ton of raw materials, 3 GJ of fuel energy and almost 120 kWh of electrical energy (Heede and Belie, 2012, Benhelal et al., 2013 and Lamas et al., 2013). This study focuses on global environmental impacts, particularly global warming, abiotic depletion of elements and fossils, and how alternative cement and concrete mixes impact the overall global warming and abiotic depletion potential of cement and concrete production.

2.4.1. Global scale

Cement production is highly energy and emissions intensive process. It consumes about 12–15% of industrial energy, 7% of industrial fuel and contributes approximately 9.5% of the current total worldwide CO_2 emissions (Gabel et al., 2004; CEMBUREAU, 2009; CSI/IEA, 2009; Boesch and Hellweg, 2010; Marinkovic et al., 2010, Ekincioğlu, 2014 and Olivier et al., 2014). Direct CO_2 emissions originating from combustion of fossil fuels and the calcination process of limestone in kilns and indirect CO_2 emissions originating from electricity consumption and transport contribute to global climate change.

Regarding the environmental performance, clinker manufacturing is responsible for 90% of cement environmental impact due to the calcination of limestone and fuel combustion during clinker production (CSI, 2011, Heede and Belie, 2012, Benhelal et al., 2013, Lamas et al., 2013 and Ekincioglu 2014). The largest non-combustion source of CO_2 from industrial manufacturing is calcination process related to clinker production which is approximately responsible for 4.8% of the total global emissions in 2013 (Olivier et al., 2014).

In recent years, the increasing global cement production has resulted in an increase of absolute CO_2 emissions by an estimated 42% (560 Mt) reaching 1.88 Gt only from direct energy and process emissions in 2006 (CSI/IEA, 2009). Assuming an average 860 kg of CO_2 generation per ton of cement, about 50% of CO_2 are being generated due to the calcination of limestone while nearly 40% of CO_2 originated from the combustion of fuel required to meet the heat required for the clinker burning process. Electricity and transportation constituted a small fraction; 10%, of the total CO_2 emissions from a cement plant. Low-carbon cement is one of attractive opportunity for the construction materials sector that can achieve annual savings of 1 billion tons of CO_2 if 50% of Portland cement were replaced by a low-carbon alternative (Benhelal et al., 2013, CEMBUREAU, 2013 and Çelik et al., 2015).

In Turkey, with 63 Mt clinker production capacity annually, sector emissions remains at around 37 $MtCO_2$ that accounts for 45% of industrial emissions. Estimated emissions between 2008 and 2030 are shown in Figure 2.8. “Static” emissions refer to the emissions density which current emissions and related technologies are similar to each coming years.

EU-wide emission limit values do not exist for cement industry. However, as a member of CEMBUREAU (the European Cement Association), companies must consider the requirements of an official Best Available Techniques (BAT) reference document for cement and lime industries. The database contains detailed tables of emission limit values referring to particles, NO_X and SO_2 and several other pollutants for the member of CEMBUREAU; the national cement industry associations and cement companies of the European Union (with the exception of Cyprus, Malta and Slovakia) plus Norway, Switzerland and Turkey (NERI, 2004; CEMBUREAU, 2013). The revised cement, lime,

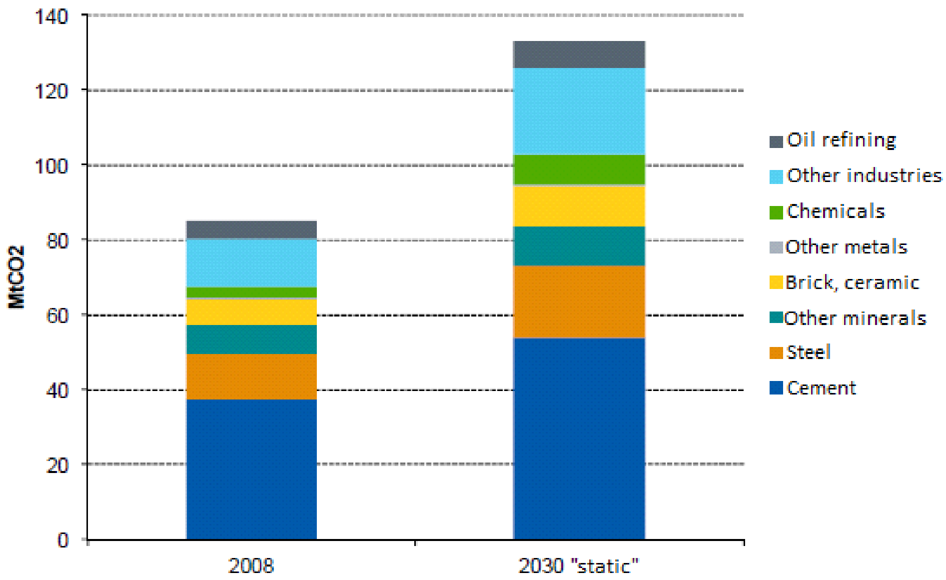


Figure 2.8. Emissions in 2008 and 2030, "static" emission estimation (EBRD, 2011)

and magnesium oxide Best Available Techniques Reference Document (BREF) was adopted at the IPPC Information Exchange Forum meeting in April 2009. Current version is the recast one which was adopted by the European Parliament and the Council of 24 November 2010 under the provisions of the Industrial Emissions Directive 2010/75/EU (IPPC).

Available key reduction levers to the cement industry for CO_2 emissions abatement is indicated as thermal and electric efficiency, alternative fuel use, clinker substitution and carbon capture and storage (CCS). By the year 2020, decrease in energy intensity, clinker to cement ratio and increase in alternative fuel use are projected to be 8%, 3% and %7 respectively (CSI/IEA, 2009). By the year 2030, 30% reduction from current levels in fossil fuel energy intensity and 5% in non-renewable, primary raw material intensity is expected to be achieved (European Commission, 2013).

These opportunities for CO_2 emissions reductions; energy efficiency, alternative fuel use and clinker substitution are estimated to contribute 10%, 24% and 10% respectively by the year 2050. In addition, CCS technologies are expected to have the largest improvement in CO_2 emissions reductions by 56%. But these technologies should become cost effective before applying in a large scale.

In light of these developments, emission values are expected to attain 18% reduction target by the year 2050 according to CSI/IEA, 2009 of World Business Council for Sustainable Development (WBCSD) Cement Sustainability Initiative (CSI) and International Energy Agency (IEA). Further targets (2010-2050) for decrease in energy intensity, clinker to cement ratio and increase in alternative fuel are shown in Figures 2.9 and 2.10.

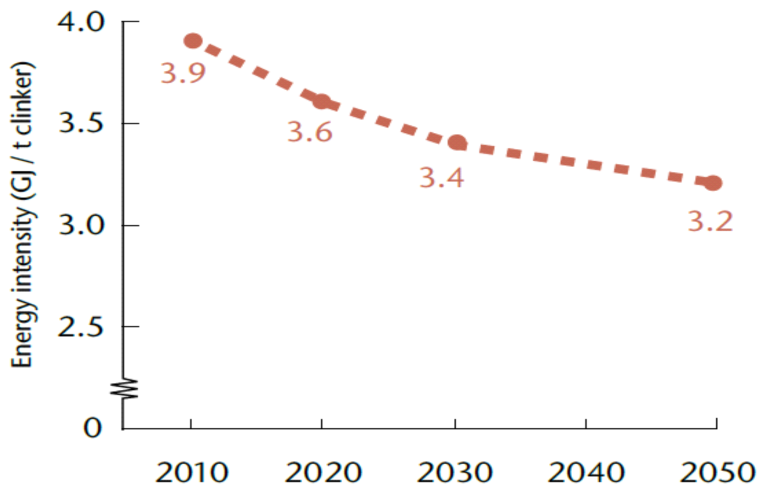


Figure 2.9. Targets for decrease in energy intensity, 2010-2050 (CSI/IEA, 2009).

Over the last two decades considerable gains in energy efficiency during cement production have been realized (CEMBUREAU, 2013 and Çelik et al., 2015).

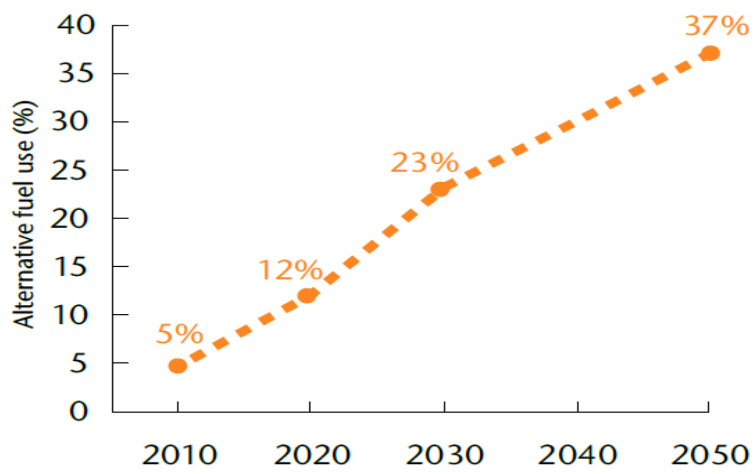


Figure 2.10. Targets for alternative fuel use, 2010-2050 (CSI/IEA, 2009).

Since fuel combustion accounts for 40%, using alternative fuels significantly reduce CO_2 intensity. Replacing fossil fuels by alternative ones such as pre-treated industrial waste including discarded tyres, waste oil and solvents, plastics, textiles and paper residues; municipal solid wastes (domestic waste), and biomass (animal meal, logs, wood chips and residues, recycled wood and paper, agricultural residues like rice husk, sawdust, sewage sludge and biomass crops) which are otherwise incinerated or landfilled, prevents both the CO_2 emissions generated by fossils use in cement kilns and additional fossil requirement for incineration process of waste treatment. In addition, unnecessary land-filling which will lead to landscape management problems is avoided as well (CSI/IEA, 2009). However, sludge like biological waste with low calorific value will result a decrease in energy efficiency and hazardous waste will cause undesired emissions at intolerable levels. Thus, selection of types of alternative fuel becomes very important (CEMBUREAU, 2009, Benhelal et al., 2013 and Lamas et al., 2013 and Martos and Schoenberg, 2014).

When these alternatives are used as fuel supplement, the inorganic components e.g., ashes, are utilized in the clinker product (CEMBUREAU, 2011). Relative amounts of alternative fuels used for clinker production in Europe are shown in Figure 2.11.

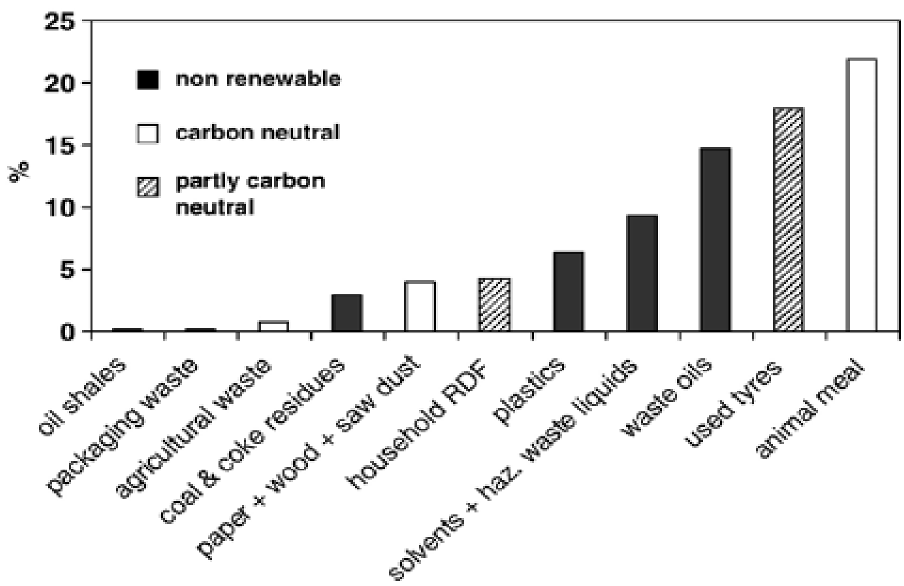


Figure 2.11. Relative amounts of alternative fuels used for clinker production in Europe (CEMBUREAU, 2011).

Although shifting fossils fuel to alternative fuels up to 100% is available technically, there are some practical, political and legal barriers. Pre-treatment is often required because of low calorific value, high moisture content, or high concentration of chlorine or other trace substances like volatile metals (e.g., mercury, cadmium, thallium). Using higher amount of alternative fuels is only possible if the legislations restrict land-filling or dedicated incineration. Potential impacts of using alternative fuel are shown in Figure 2.12 (CSI/IEA, 2009).

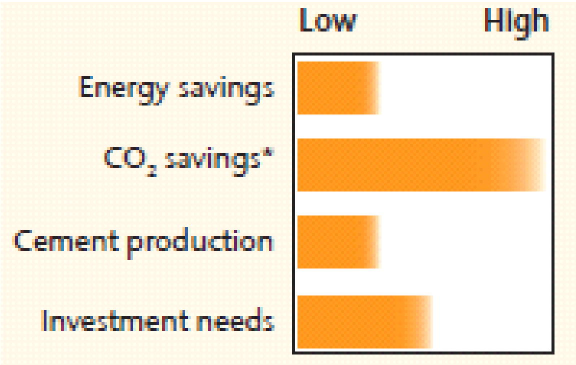


Figure 2.12. Potential impacts of using alternative fuel (CSI/IEA, 2009)

The increased use of clinker substitutes offers a possible solution in reducing global CO_2 emissions. Substitution of clinker by mineral components reduces the amount of energy-intensive clinker required for each ton of cement. This provides reduction in emissions stem from both fuel or power consumption and calcination reaction and the energy and carbon intensity of the cement produced. Therefore, blended cements have lower CO_2 emissions than ordinary Portland cement. Energy substitution by RDF does not affect emissions from calcination reaction of limestone in kilns which is the main contributor to CO_2 emissions. Decreasing clinker to cement ratio has a significant role in low-carbon cement (CSI, 2011). Further targets (2010-2050) for decrease in clinker ratio in cement are shown in Figure 2.13.

Blended cements perform not only sustainability by utilizing waste materials in valuable applications, contributing to resource preservation and reducing the energy and carbon intensity, but also technical improvement such as higher long-term strength and higher resistance to acids and sulphates. Early strength (measured after less than 7 days) may be lower; however, if it is necessary, it can be handled by keeping substitutes content less than 30% (Worrell et al., 2008). Potential impacts of using clinker substitutes are shown in Figure 2.14 (CSI/IEA, 2009).

Regional constraints, transportation distance, compatibility issues between properties of substitution materials, intended application and national standards for cements may limit the implementation of clinker substitutes. The key is to developing appropriate policies at national level to promote the general recommendations (CSI/IEA, 2009).

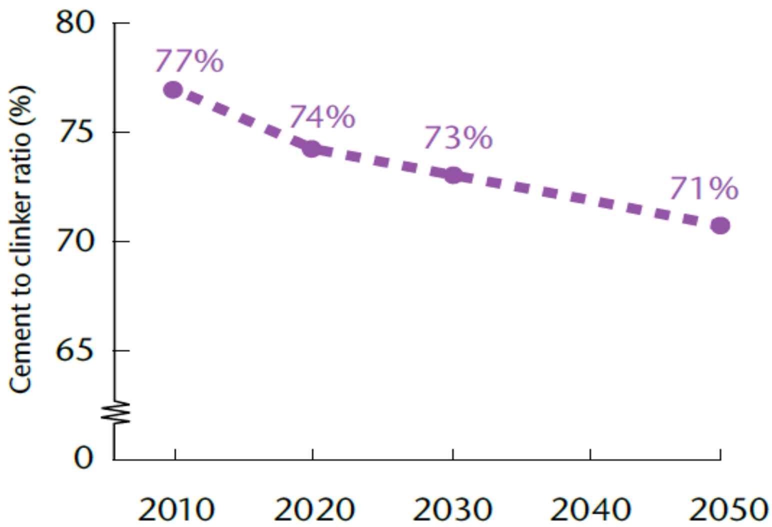


Figure 2.13. Targets for decrease in cement to clinker ratio, 2010-2050 (CSI/IEA, 2009).

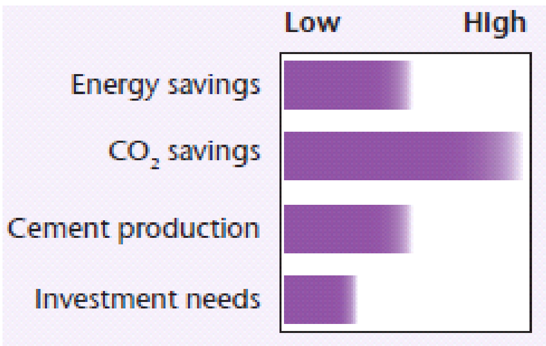


Figure 2.14. Potential impacts of clinker substitutes (CSI/IEA, 2009)

2.4.2. Regional Scale

Nitrogen oxides (NO_X), sulphur dioxide (SO_2) and carbon monoxide (CO) emissions emitted as a result of fuel consumption in the kiln to produce required energy induce acidification, photochemical ozone creation, eutrophication and human toxicity potential on a regional scale (Heede and Belie, 2012, Benhelal et al., 2013 and Lamas et al., 2013)

Almost all SO_2 emissions have been absorbed by CaO content. Thus, the majority of the SO_2 fixes in the clinker due to the high alkalinity of nker. For NO_X abatement, SCNR (selected non-catalytic reduction) installations are widely applied in recent years (Shi and Zheng, 2007 and Ekincioğlu 2014). Improvement in clinker quality and use of clinker substitutes in cement also contributes to reducing energy consumption and emissions to air (European Commission, 2013).

2.4.3. Local Scale

Local effects include dust, noise, air quality, and natural disturbance such as the impacts of change in landscape to local ecosystem during mining of raw materials such as limestone, iron ore, and clay (Heede and Belie, 2012).

The main contributor to the local impact is dust emissions for cement plants. Dust emission reductions have been achieved to be reduced to a certain extent by approximately 80% with shifting electro filter to bag filter.

NO_X, SO_2, dust and other emissions to air are reported from European cement kilns are shown in Table 2.6.

2.4.4. Resource Conservation

Resource efficiency engaged with the efficient use of economic resources and minimization of the potential environmental impacts of resource use. The concept of the resource efficiency can be summarized as producing more well-being to meet human needs with less resource consumption including materials, energy, water, land, and emissions associated with the consumption and production of goods and services over their entire life cycles (UNEP, 2011).

Table 2.6. Emissions averages and ranges from European cement kilns (BREF, 2010).

Reported emissions from European cement kilns			
Pollutant	Average concentration (mg/Nm^3)	Concentration range from/to (mg/Nm^3)	Average specific emission
Dust	20.3	0.3/227	46.7
NO_x as NO_2	785	145/2040	1.805
SO_2	219	Up to 4837	0.504
CO		Up to 2000	
VOC/THC as C	22.8	1/60	52.4
HCl	4.0.33	0.02/20	9.8
HF	0.016	0.01/1.0	0.7
PCDD/F as ITEQ		0.000012/0.27	0.037
Metals			
Hg	0.02	0.0/0.03	0.046
∑ (Cd, Tl)	0.02	0.0/0.68	0.046
∑ (As, Sb, Pb, Cr, Co, Cu, Mn, Ni, V)	0.14	0.0/4.0	0.322
• Concentrations are reference concentrations, i.e. 273 ^{0}K, 101,3 kPa, 10% 02 and dry gases • Specific emissions are based on kiln exhaust volumes of 2300 m^3/ton clinker			

resource and energy consumption.

Depending on available resources, supplementary cementitious materials (SCM) can be used as partial replacement for Portland cement, while alternative materials can be used to substitute natural aggregates, producing a more eco-designed concrete in terms of

The construction sector uses 50% of the Earth's raw materials. 1.4 ton of raw materials, 3 GJ of fuel energy and almost 120 kWh of electrical energy are consumed for producing 1 ton of cement (Heede and Belie, 2012, Benhelal et al., 2013 and Lamas et al., 2013) and approximately 2 tons of aggregate during concrete mixing. Thus, using CDW as a part of aggregate mix instead of natural aggregates becomes an attractive option in terms of resource conservation. On the other hand, the construction industry in Europe consumes 40% of the total energy and generates 31% of the total waste which means 850 million tons of waste annually corresponding to more than 480 kg per person per year. The 40%–67% of the CDW belongs to concrete fraction and about 75% of CDW is sent to landfilling. This approach supports not only resource conservation but also waste management by preventing these materials which would otherwise be landfilled (Fischer and Werge, 2009 and Marinkovic et al., 2010).

Since resource management is promoted throughout European cement industry, in addition to recycling CDW, materials from ceramic industry with hydraulic binding or puzzolanic characteristics, granulated blast furnace slag, fly ash and silica fume are used in blended cements. Furthermore, fly ash, granulated blast furnace slag and silica fume are also utilized in concrete mix as SCMs to produce concrete in an environmental friendly manner due to the decrease in required cement and/or aggregate content (Marie and Quiasrawi, 2012).

The use of recycled aggregate generally worsens concrete properties and performance including workability, strength and durability while using recycled CDW as aggregates for concrete. However, incorporating fly ash in concrete mix can meet the performance requirements while contributing additional value. The use of fly ash in concrete as a supplementary binder material has proven to improve workability and long term strength, minimize risk of alkali silica reaction, lower hydration heat in mass concrete, reduce permeability and shrinkage deformations of concrete prepared with recycled aggregate (Anastasiou et al., 2014; Kim et al., 2013; Lima et al., 2013; Kou and Poon, 2013 and Limbachiya et al., 2012).

2.5. Green Building Classification Systems

The energy consumption during the use phase of the buildings reaches over 85% of the total environmental impacts. The environmental impact assessment conducted throughout LCA studies of a building showed that the environmental impact of the building is not restricted to the energy use of the building. The second highest environmental impact occurs in construction stage due to the material used (European Commission, 2013 and Cabeza et al., 2014). Building materials are responsible for about 10-30 % of the environmental load of a building. The influence of building materials will increase as the building structure develops towards low energy, passive and zero energy standards (Cabeza et al., 2014)

ISO 14025:2006 was published to provide core product category rules (PCR) for Type III environmental declarations. PCR defines the environmental impact indicators, the stages of the product’s life cycle, and the rules for the condition of additional information about the product and for the system boundary, cut-offs and allocation.

Environmental Product Declarations (EPD) is an example of a Type III Environmental Label which is defined in ISO Standard ISO 14020:2001, Environmental Labels and Declarations – General principles. EPD is based on Life Cycle Assessment (LCA), and are governed by a number of International and European standards. ISO 21930:2007 was published for EPD for construction products and EN 15804, a European standard, was published in 2012 for sustainability in construction work to provide core rules for Construction Products and to create EPD. The standard will fix essential information that can be transferred from scheme to scheme across Europe, minimizing barriers to trade by using the same environmental indicators (BREF, 2010 and NERI, 2014). Credits are given for building materials with low environmental impacts (PCR, 2013).

DGNB – German Sustainable Building Certification Scheme, BREEAM – UK Environmental Building Certification Scheme and LEED – US Environmental Building Certification Scheme give extra credits to EPD for building materials. According to DGNB, a building level LCA must be carried out and IBU (Institut Bauen und Umwelt e.V.) EPD is included in various calculation tools while BREEAM uses LCA approach to evaluate the carbon footprint of a building. Among a large number of green rating systems that have been introduced by different organizations, LEED and BREEAM are internationally accepted. Most of the others are limited to a specific country. For this study, LEED system is selected because it includes LCA points, the application of the system is more flexible and it provides more global perspective (Alshamrani et al., 2014).

2.5.1. LEED – US Environmental Building Certification Scheme

LEED system defines a set of goal to improve the environmental performance of the buildings. LEED v4 covers six main credit categories including location & transportation, sustainable sites, water efficiency, energy & atmosphere, materials & resources and indoor environmental quality and additional credits including integrative process, innovation and regional priority. Each credit category involves in credits which are broken down into individual points.

LEED v4 provides different rating systems including LEED v4 for Building Design and Construction, LEED v4 for Interior Design and Construction, LEED v4 for Building Operations and Maintenance, LEED v4 for Neighbourhood Development and LEED v4 for Building Design and Construction: Homes and Midrise. LEED v4 rating systems have similar credits available but may vary slightly in the points available for each credit. Table 2.7 illustrates LEED v4 credit categories and available points for LEED BD+C: New Construction and Major Renovations.

A product could perform well in one category while it fails in another. Therefore, a holistic approach is required in order to clarify the materials' impacts. LCA is the most comprehensive approach for determining environmental impacts of a building. Thus, LEED v4 credits identify a specific action that attempt to enable embodied impact reduction by adapting LCA (USGBC, 2013, Alshamrani et al., 2014, and Lemay and Peng, 2014)

2.5.2. Concrete's Contribution to LEED v4

Using concrete can contribute to as many as 74 of the 110 points available in credit categories. Table 2.8 illustrates LEED v4 credits influenced by concrete. Although using concrete does not directly achieve credits, concrete's environmental attributes enables achieving LEED certification (ECP, 2007 and Lemay and Peng, 2014). In this study, special emphasize will be given to LEED material and resource and innovation categories to reveal the impact of eco-designed concrete.

LEED material and resource category focuses on improving environmental performance and resource efficiency through the regional materials and rapidly renewable materials, the reusing and recycling of major structural components and the disposal of construction waste in order to minimize the embodied energy and other impacts associated with the extraction, processing, transport, maintenance, and disposal of building materials.

Material and Resources category requires applying prerequisite point ratings such as storage and collection of recyclables and construction and demolition waste management planning. This category is assigned 13 LEED scores and contains building life cycle reduction, building product disclosure and optimization and construction and demolition waste management (USGBC, 2013).

Table 2.7. LEED BD+C: New construction and major renovations.

Credit 1	Integrative Process		1
Location and Transportation		Possible Points:	16
Credit 1	LEED for Neighbourhood Development Location		16, or
Credit 2	Sensitive Land Protection		1
Credit 3	High Priority Site		2
Credit 4	Surrounding Density and Diverse Uses		5
Credit 5	Access to Quality Transit		5
Credit 6	Bicycle Facilities		1
Credit 7	Reduced Parking Footprint		1
Credit 8	Green Vehicles		1
Sustainable Sites		Possible Points:	10
Prereq 1	Construction Activity Pollution Prevention		Required
Credit 1	Site Assessment		1
Credit 2	Site Development--Protect or Restore Habitat		2
Credit 3	Open Space		1
Credit 4	Rainwater Management		3
Credit 5	Heat Island Reduction		2
Credit 6	Light Pollution Reduction		1
Water Efficiency		Possible Points:	11
Prereq 1	Outdoor Water Use Reduction		Required
Prereq 2	Indoor Water Use Reduction		Required
Prereq 3	Building-Level Water Metering		Required
Credit 1	Outdoor Water Use Reduction		2
Credit 2	Indoor Water Use Reduction		6
Credit 3	Cooling Tower Water Use		2

Credit 4	Water Metering	1
Energy and Atmosphere	Possible Points:	33
Prereq 1	Fundamental Commissioning and Verification	Required
Prereq 2	Minimum Energy Performance	Required
Prereq 3	Building-Level Energy Metering	Required
Prereq 4	Fundamental Refrigerant Management	Required
Credit 1	Enhanced Commissioning	6
Credit 2	Optimize Energy Performance	18
Credit 3	Advanced Energy Metering	1
Credit 4	Demand Response	2
Credit 5	Renewable Energy Production	3
Credit 6	Enhanced Refrigerant Management	1
Credit 7	Green Power and Carbon Offsets	2
Materials and Resources	Possible Points:	13
Prereq 1	Storage and Collection of Recyclables	Required
Prereq 2	Construction and Demolition Waste Management Planning	Required
Credit 1	Building Life-Cycle Impact Reduction	5
Credit 2	Building Product Disclosure and Optimization - Environmental Product Declarations	2
Credit 3	Building Product Disclosure and Optimization - Sourcing of Raw Materials	2
Credit 4	Building Product Disclosure and Optimization - Material Ingredients	2
Credit 5	Construction and Demolition Waste Management	2
Indoor Environmental Quality	Possible Points:	16
Prereq 1	Minimum Indoor Air Quality Performance	Required
Prereq 2	Environmental Tobacco Smoke Control	Required
Credit 1	Enhanced Indoor Air Quality Strategies	2
Credit 2	Low-Emitting Materials	3

Credit 3	Construction Indoor Air Quality Management Plan			1
Credit 4	Indoor Air Quality Assessment			2
Credit 5	Thermal Comfort			1
Credit 6	Interior Lighting			2
Credit 7	Daylight			3
Credit 8	Quality Views			1
Credit 9	Acoustic Performance			1
Innovation			Possible Points:	6
Credit 1	Innovation			5
Credit 2	LEED Accredited Professional			1
Regional Priority			Possible Points:	4
Credit 1	Regional Priority: Specific Credit			1
Credit 2	Regional Priority: Specific Credit			1
Credit 3	Regional Priority: Specific Credit			1
Credit 4	Regional Priority: Specific Credit			1
Total			Possible Points:	110
Certified 40 to 49 points	**Silver 50 to 59 points**	**Gold 60 to 79 points**	**Platinum 80 to 110**	

Innovation category provides up to 5 points for innovative green design strategies which are not covered by the six major credit categories or provides contribution significantly beyond the requirement to the other existing credit categories (USGBC, 2013 and Lemay and Peng, 2014).

Table 2.8. LEED v4 credits influenced by concrete (Lemay and Peng, 2014).

CREDIT CATEGORIES	POSSIBLE POINTS
Integrative Process	1
Location & Transportation (16 Points Available)	
Neighbourhood Development Location	16, or
High Priority Sites	2
Surrounding Density and Diverse Uses	3
Access to Quality Transit	5
Sustainable Sites (10 Points Available)	
Site Development ─ Protect or Restore Habitat	2
Open Space	1
Rainwater Management	3
Heat Island Reduction	2
Water Efficiency (11 Points Available)	
Outdoor Water Use Reduction	2
Indoor Water Use Reduction	6
Energy & Atmosphere (33 Points Available)	
Minimum Energy Performance	Required
Optimize Energy Performance	18
Material and Resources (13 Points Available)	
Construction and Demolition Waste Management Planning	Required
Building Life-Cycle Impact Reduction	3
Building Product Disclosure and Optimization – Environmental Product Declarations	2
Building Product Disclosure and Optimization – Sourcing of Raw Materials	2
Building Product Disclosure and Optimization – Material Ingredients	2
Construction and Demolition Waste Management	2
Indoor Environmental Quality (16 Points Available)	
Low-Emitting Materials	3
Daylight	3
Quality Views	1
Acoustic Performance	1
Innovation (6 Points Available)	
Innovation	5
LEED AP +	1
Regional Priority (4 Points Available)	4
TOTAL	74

2.6. Life Cycle Assessment

Life Cycle Assessment (LCA) is defined as "the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO, 2006a). Around the world, LCA has become a well-known instrument for studying environmental effects. LCA is a an evaluation tool of environmental performance throughout the activities in creating a product or performing a service by identifying and quantifying extraction and consumption of resources and releases to air, water, and soil. It enables to assess those energy and material uses and releases on the environment, implement opportunities to effect environmental improvements and describe how the environmental exchanges of the system can be expected to change as a result of actions taken in the system as well. The potential contribution of the activities in creating a product or performing a service is assessed by environmental impact categories including climate change, resource depletion, human toxicity, photochemical ozone depletion, acidification and eutrophication (UNEP, 2011).

2.6.1. Structure of Life Cycle Assessment

According to the ISO 14040 series, LCA is structured in four phases; goal and scope definition, inventory analysis, impact assessment and interpretation which are indicated in the Figure 2.15 (UNEP, 2011).

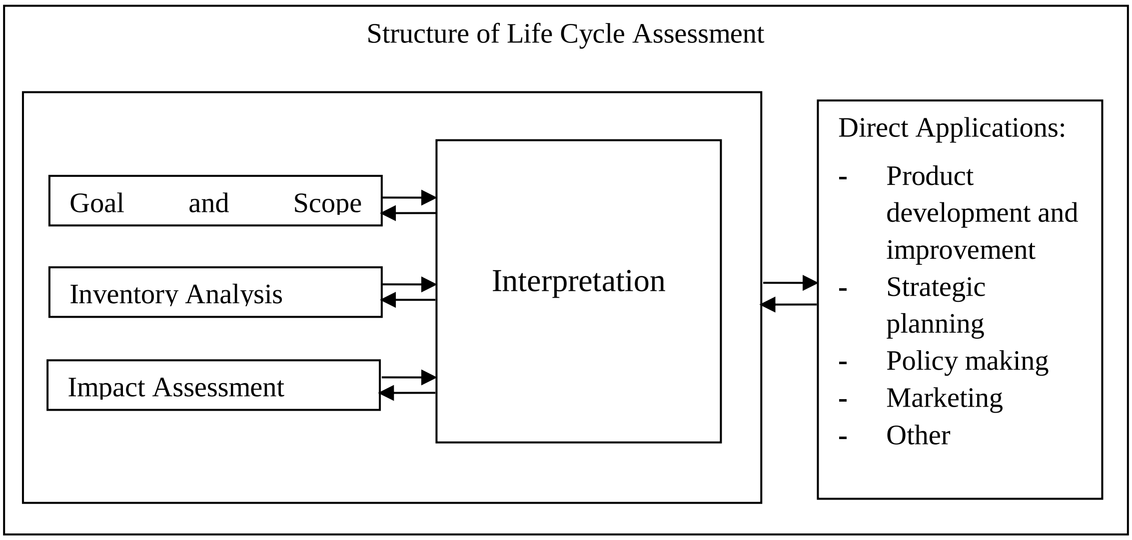


Figure 2.15. Structure of life cycle assessment (ISO, 2006b.)

The UNEP/SETAC Life Cycle Initiative has grouped environmental impacts into the UNEP/SETAC Life Cycle Impact Assessment Midpoint-Damage Framework (Figure 2.16). Resource consumption and emissions in the life cycle inventory (LCI) analysis are linked to midpoint impact categories such as climate change, resource depletion, human toxicity, photochemical ozone depletion, acidification and eutrophication and final damage categories which are human health, ecosystem quality, and resource depletion within this framework.

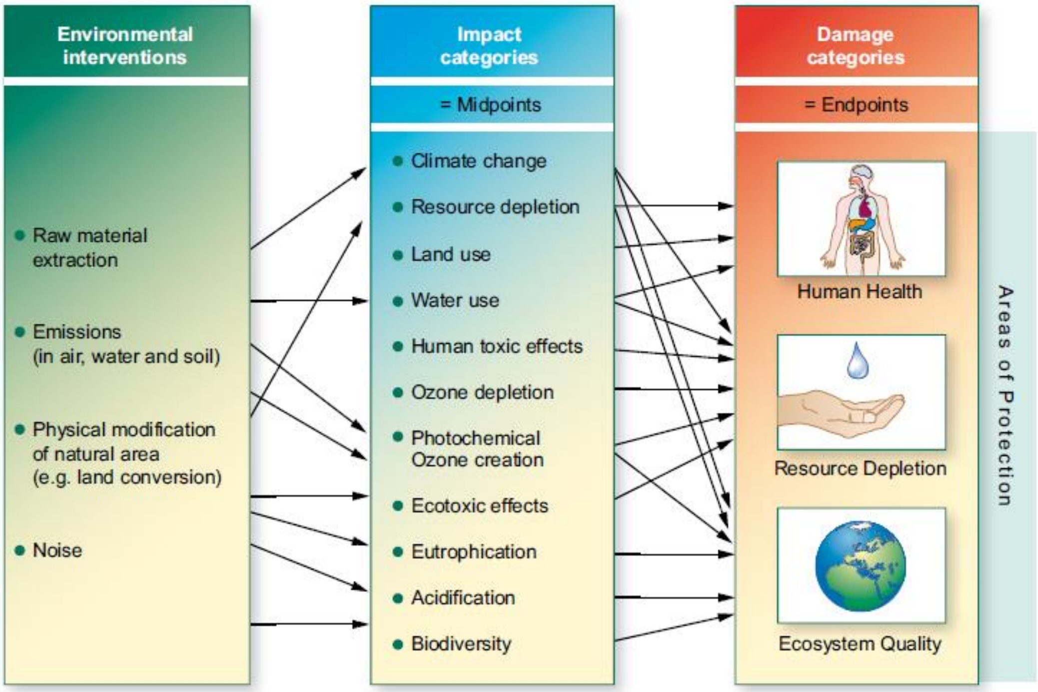


Figure 2.16. UNEP/SETAC Life cycle impact assessment midpoint-damage framework

3. MATERIALS AND METHODS

The LCA methodology according to ISO 14040–44 (ISO 14040, 2006; ISO 14044, 2006) was used to draw a comprehensive environmental picture of the defined integrated approach to assess and compare the environmental impacts of the cement and concrete production scenarios. Besides, eco-designed concrete which will be defined at the end of the LCA study will be evaluated in terms of LEED v4 Building Design and Construction (BD+C): New Construction (NC).

3.1. Goal and Scope Definition

Goal and scope phase defines the overall frame of the study by pointing out the purpose of the study, functional unit, system boundary, data sources, assumptions and limitations of the study such as time, place and life cycle stages, quality of necessary data, the required level of detail and determines the demands on the further phases.

The goal of this study is to interpret integrated approach involving application of waste to energy targets, reducing clinker to cement ratio by using clinker substitutes and; utilizing CDW as aggregates and SCMs as to decrease the amount of required aggregates and cement in concrete mix with the frame of the Life Cycle Assessment in order to achieve a more eco-designed concrete.

While several life-cycle assessment studies have been conducted to examine the environmental performance of different concrete products, the variety of the distance to construction plant and the applications (volume requirements, steel reinforcement requirements), comparative LCA between different concrete products is limited. In addition, environmental impacts originated from the service of the building have relatively equal impacts for the concrete mixtures that are designed to achieve maximum use of alternative materials (Medina et al., 2013). Therefore, this study presents a cradle-to-gate life-cycle assessment of several concrete mixtures to reduce the uncertainty generated from the wide-range applications and transportation distance. Since cement manufacturing is the most energy and emission intensive process and large amounts of minerals depletion can be realized in the production of concrete such a reduced scope is reasonable. (Heede and Belie, 2012). Thus, the scope of this study covers the concrete manufacturing stages beginning with raw material extraction to the finished product of ready-mix concrete with the main focus of Global Warming Potential and Abiotic Depletion. Moreover, the transportation of solid fuels is excluded because their impacts dominate the scenarios and the environmental savings gained through the resource efficiency could not be revealed.

Life Cycle Assessment (LCA) methodology will be applied to evaluate the environmental impact of raw material selection and RDF supplement in fuel mix on relevant concrete manufacturing processes for different selected scenarios. Selected scenarios are shown in Table 3.1.

Table 3.1. Selected scenarios for concrete production.

Scenario 1	Ready-mix concrete from ordinary Portland cement (CEM I) and natural aggregates
Scenario 2	Ready-mix concrete from ordinary Portland cement produced by RDF supplement in fuel mix and natural aggregates
Scenario 3	Ready-mix concrete from blended cement (CEM II) produced by RDF supplement in fuel mix and natural aggregates
Scenario 4	Ready-mix concrete from ordinary Portland cement (CEM I) and utilizing fly ash for cement replacement and natural aggregates
Scenario 5	Ready-mix concrete from blended cement (CEM II) produced by RDF supplement and utilizing blast furnace slag for cement replacement and natural aggregates
Scenario 6	Ready-mix concrete from ordinary Portland cement (CEM I), utilizing CDW as aggregates substitutes, fly ash for cement replacement and natural aggregates
Scenario 7	Ready-mix concrete from ordinary Portland cement (CEM I) produced by RDF supplement, utilizing CDW as aggregates substitutes, fly ash for cement replacement and natural aggregates
Scenario 8	Ready-mix concrete from blended cement (CEM II) produced by RDF supplement, utilizing CDW as aggregates substitutes, blast furnace slag for cement replacement and natural aggregates

The overall goal of this study is to interpret the human health, material welfare and ecosystem quality through the life cycle perspective for defined scenarios. These scenarios will be investigated by the application of Gabi 6 software. Besides, CEM I and CEM II will be compared in terms of potential environmental impacts on a mass by mass basis to expand on the impact of clinker substitutes.

Since the environmental impact assessment conducted throughout LCA studies of a building showed that once energy consumption is optimized; material and energy related impacts are equally important, extra gains expected through optimal recycling of building components and selection of building materials. In this study, the impact of eco-designed concrete on green building certification system is evaluated through two categories of the LEED rating system: materials and resources, and innovation through adapting LCA methodology. LEED v4 for New Construction and Major Renovations system is selected for rating system considering the available credits for impact reduction. The fact that the impacts of the defined eco-designed concrete which is considered to be used in a green building construction will be evaluated in terms of LEED v4 for New Construction and Major Renovations system, will bring an additional value to the study.

3.1.1. System Boundaries

System boundary points out the burdens of the surveyed system and interface of the environment. It also defines which unit processes are included in or excluded from the survey (ISO 2006a).

The system boundaries of the concrete production consist of two main sub-systems which are “cement production” and “concrete mixing”. System boundaries are created based on the PCRs EPD Type-III demands and shown in Figure 3.1.

Cement production consists of four main stages; raw material extraction from quarries, raw meal preparation, clinker burning in kilns and finish grinding. Raw meal preparation stage includes crushing, homogenization and grinding of the extracted raw materials such as limestone and clay. Prepared raw meal is fed into pre-heater and rotary kiln respectively to produce clinker; the semi-product of cement. The calcination of the raw materials in kilns to produce clinker is the main process of cement manufacturing. The required high temperature in the kilns is adjusted by fuel mix including coal, petro coke, natural gas and

RDF if used. Therefore, preparation of coal and RDF if used is another sub-process of the clinker burning stage. The last stage of the cement production is the finish grinding stage

that includes pressing the clinker and grinding it with other substitutes such as gypsum, trass and other puzzolanic materials in the cement mill. Clinker substitutes are transferred to cement mill for finish grinding after reaching the required size by another crusher. The produced cement is stored in cement silos.

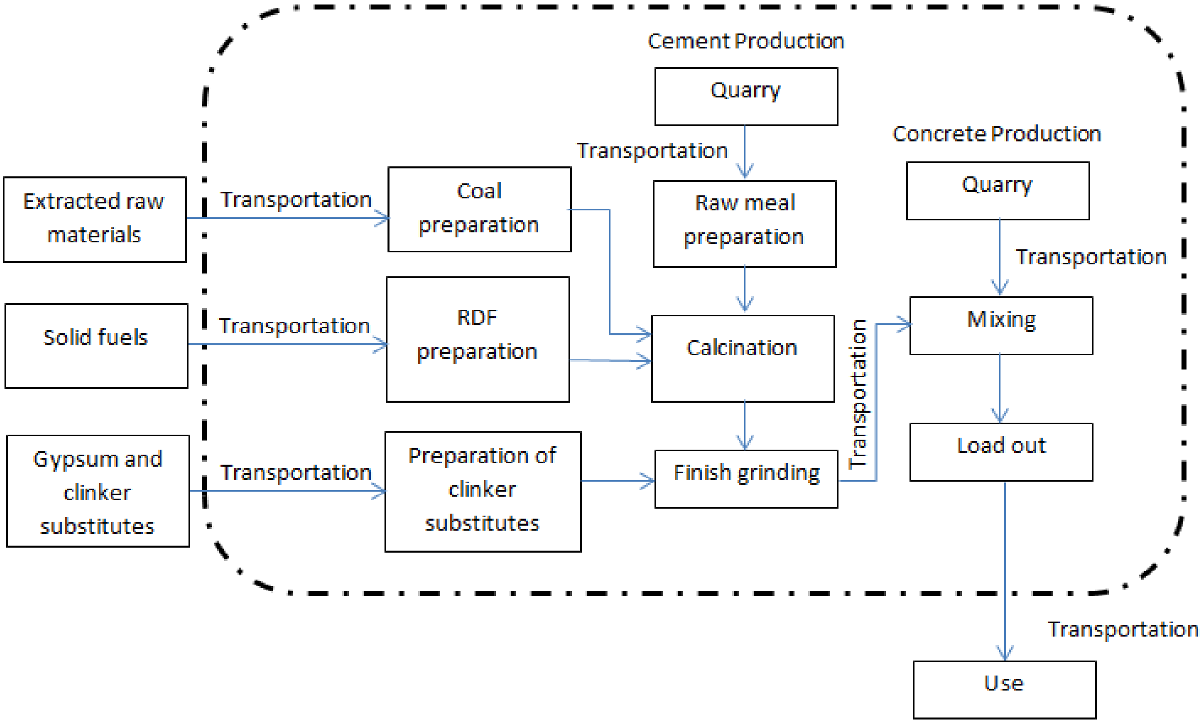


Figure 3.1. The concrete production system boundary developed for this study.

Concrete production consists of different unit operations. The certain amounts of extracted aggregates; sand and gravel from the quarries, the cement from the cement silo, water and chemical admixtures are fed into central plant mixer to form concrete mix. The ready mix concrete is loaded to truck mixers for transportation to the destination.

3.1.2. Functional Unit

Functional unit serves as a reference unit for all input and output streams and the potential environmental effects. It must be clearly defined and must be measurable. A common functional unit needs to be defined that will successfully represent the environmental performance as well as the mechanical and durability performance for the certain constituent of the concrete product (Forés et al., 2013). In addition, the scope is developed with the cradle-to-gate LCA approach. Considering all these factors, the functional unit of this study is selected one cubic meter of concrete, produced from different aggregate, binder and fuel combinations. Only when the different production scenarios of cement are compared, functional unit is selected as 1 ton of cement.

3.2.Life Cycle Inventory Analysis

Life Cycle Inventory (LCI) is the list of resources, outputs and emissions to air, water and land associated with the product. Therefore, LCI phase involves data collection and calculation procedures to quantify relevant inputs and outputs. The stage includes development of a flow diagram of the processes being evaluated, data collection and evaluation and reporting of results (ISO 2006a).

3.2.1. Data collection for Life Cycle Inventory (LCI)

Detailed information on cement and concrete production is collected from the selected cement and concrete plant. The collected data set is on energy consumption; raw materials and additives used, and generated emissions at the facility for each stage of cement and concrete production.

3.2.2. Life Cycle Inventory (LCI) Analysis and the Key Assumptions

During inventory analysis (LCI), large quantities of natural resources consumed and the emissions produced in various stages of the complete life cycle of concrete production. The electrical energy consuming stages are crushing, grinding, pressing, coal and RDF preparation, clinker burning, concrete mixing, compressors and lightening. The thermal energy is used in kiln for calcination of the raw materials. The main streams of CO_2 emissions are calcination of raw materials and fuel consumption in kilns during clinker production. Other significant emissions generated in kilns are NO and NO_2. Besides, trace amount of VOC/THC as C, heavy metals, HCl, HF and PCDD/F are generated from the kilns. Particulate matter, consisting primarily of cement and pozzolan dust, but including some aggregate and sand dust emissions are generated from quarrying, material loading/unloading, material transportation, crushing, grinding, pressing, clinker processing and storage facilities. In addition, there are emissions of metals that are associated with this particulate matter.

Regarding the waste co-incineration in the kiln, 21% of the required thermal energy is obtained from waste-derived fuels. The used amount of refuse derived fuel replaces about 31 kg of coal and 33 kg of total fossils per ton of clinker produced. The main component of waste-derived fuel composition is RDF by 81%. End-of-life tire has the second significant share by 17% and the rest is waste oil and waste solvent. In this study, all waste originated fuels including end-of-life tire, refuse derive fuel, waste oil and waste solvent are assigned as RDF.

The total share of clinker substitutes is 23%. The total share of clinker substitutes including limestone and the industrial wastes is 10% of the cement mix. The rest includes gypsum, trass and other industrial wastes. Trass is excluded because appropriate flow for trass could not be found on the used databases. The share of industrial wastes utilized as clinker substitutes have been calculated as 15% of the total clinker substitutes and 4% of the total raw material consumption. The total amount of different types of industrial waste as clinker substitutes is 34270 tones, annually. Moreover, fly ash and blast furnace slag were used as 12% and 30%, respectively, by weight replacements of cement. Recycled aggregate was utilized as 20% by weight replacements of the natural coarse aggregate. Since chemical admixtures are less than 1% of the total mass related to concrete manufacturing process and they do not have a significant contribution to emissions or energy consumption, they are not included to LCI in accordance with the SETAC guidelines. The scope of this study excludes the laboratory analysis for determination of the concrete's strength class. However, all the produced 1 m^3 of concrete samples through each scenario were considered to have the same compressive strength classes. Required laboratory analysis is made regularly on site. Table 3.3 illustrates the key assumptions for the concrete mix production for LCA calculations.

The energy and emission inventory elements for the different cement and concrete manufacturing scenarios generated for LCA through input and output balances are shown in Tables 3.3-3.10 and Figures 3.2-3.10.

Table 3.2. Key assumptions for the concrete production.

Input Data:		
Type of cement	Ordinary Portland Cement (CEM I) Blended Cement (CEM II)	
Type of clinker substitutes and SCMs	Limestone, fly ash, blast furnace slag	
Type of concrete	C25/30 C25/30 blended	
Electricity grid mix	EU 25+3 Technology grid mix	
Transportation details:	**Mode**	**Distance (km)**
Cement raw materials to cement plant	Diesel driven, Euro 3, cargo	4.5
Gypsum to cement plant	Diesel driven, Euro 3, cargo	100
Limestone-like industrial waste to cement plant	Diesel driven, Euro 3, cargo	20
Gypsum-like industrial waste to cement plant	Diesel driven, Euro 3, cargo	20
Cement to concrete plant	Diesel driven, Euro 3, cargo	0.5
Fine aggregates to concrete plant	Diesel driven, Euro 3, cargo	30
Coarse aggregates to concrete plant	Diesel driven, Euro 3, cargo	30
Fly ash to concrete plant	Diesel driven, Euro 3, cargo	120
Blast furnace slag to concrete plant	Diesel driven, Euro 3, cargo	190
The distance from a CDW sorting plant to a cement plant	Diesel driven, Euro 3, cargo	90
Technology options:	**Type of technology selected**	
Cement raw materials pre-homogenization	Dry, raw storing, pre-blending	
Cement raw materials grinding	Dry, raw grinding, vertical mill	
Cement raw meal blending/homogenization	Dry, raw meal blending, storage	
Clinker processing	Pre-heater/Pre-calciner kiln	
Clinker pressing	Roller press	
Cement finish milling/grinding/blending	Ball mill	
Concrete batching plant loading/ mixing	Mixer loading (central mix)	
Concrete batching plant PM control	Fabric filter	

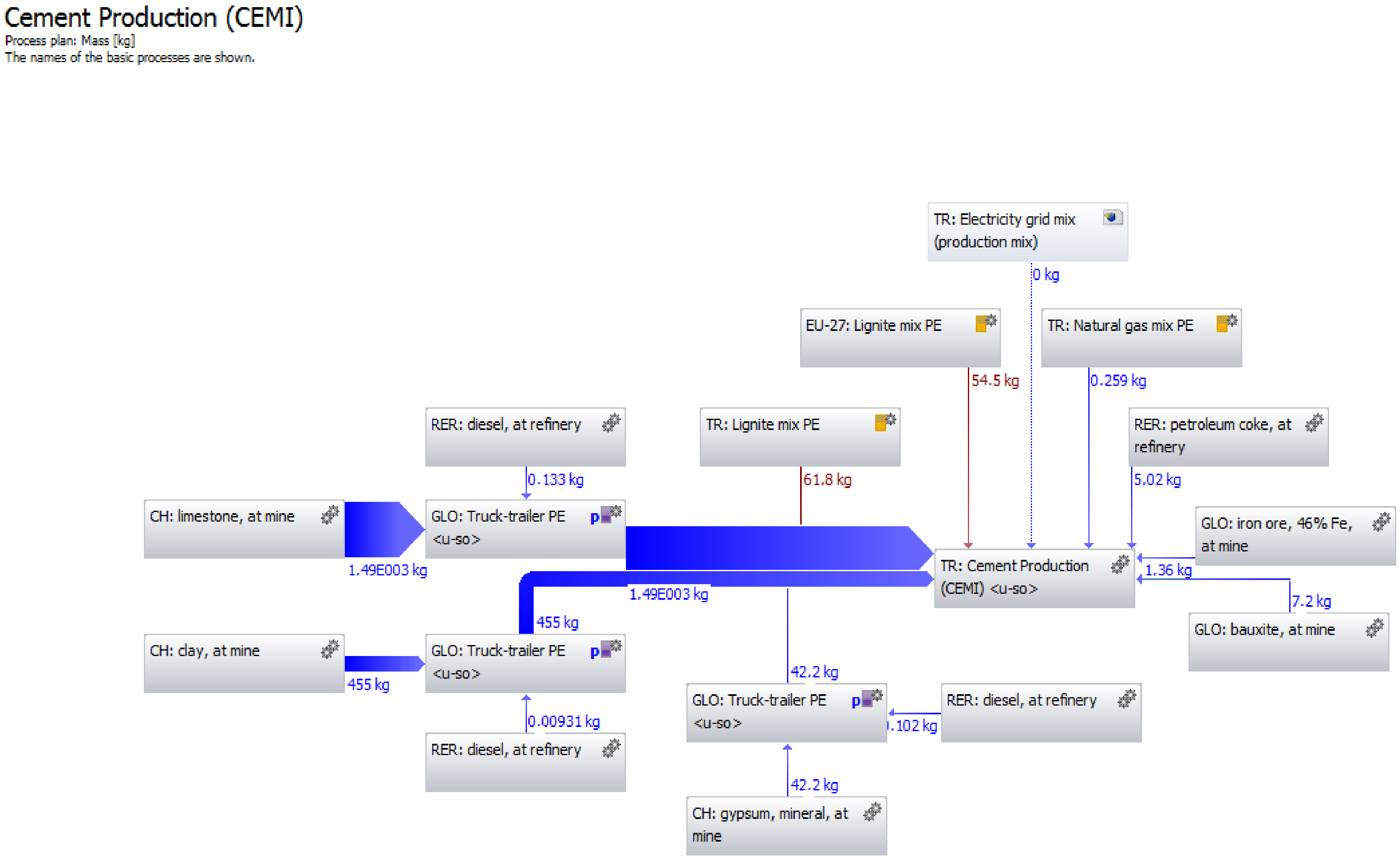


Figure 3.2. Production flow for 1 ton of Portland cement.

Table 3.3. Inputs for production of 1 ton of Portland cement.

Flow	Quantity	Amount	Unit
Bauxite [Non-renewable resources]	Mass	7.2	kg
Clay [Non-renewable resources]	Mass	455	kg
Electricity [Electric power]	Energy (net calorific value)	402.984	MJ
Gypsum (natural gypsum) [Non-renewable resources]	Mass	42.2	kg
Iron ore (56.86%) [Non-renewable resources]	Mass	1.36	kg
Lignite ecoinvent [Lignite (resource)]	Mass	54.5	kg
Lignite Turkey [Lignite (resource)]	Mass	61.8	kg
Limestone (calcium carbonate) [Non-renewable resources]	Mass	1492.93	kg
Natural gas Turkey [Natural gas (resource)]	Mass	0.259	kg
Petrol coke [Refinery products]	Mass	5.02	kg

Table 3.4. Outputs for production of 1 ton of Portland cement.

Flow	Quantity	Amount	Unit
Cement (CEM I 42.5) [Minerals]	Mass	1000	kg
Carbon dioxide [Inorganic emissions to air]	Mass	822.86	kg
Carbon monoxide [Inorganic emissions to air]	Mass	0.4597	kg
Dust (unspecified) [Particles to air]	Mass	1.177	kg
Heavy metals to air (unspecified) [Heavy metals to air]	Mass	1.456E-5	kg
Nitrogen dioxide [Inorganic emissions to air]	Mass	1.0758	kg
Nitrogen oxides [Inorganic emissions to air]	Mass	0.6663	kg
VOC (unspecified) [Organic emissions to air (group VOC)]	Mass	0.297	kg
HCl [Inorganic emissions to air]	Mass	0.00047	kg
HF [Inorganic emissions to air]	Mass	0.00048	kg
Dioxin/Furan [Organic emissions to air (group Halogenated organic emissions to air)]	Mass	3.19E-12	kg

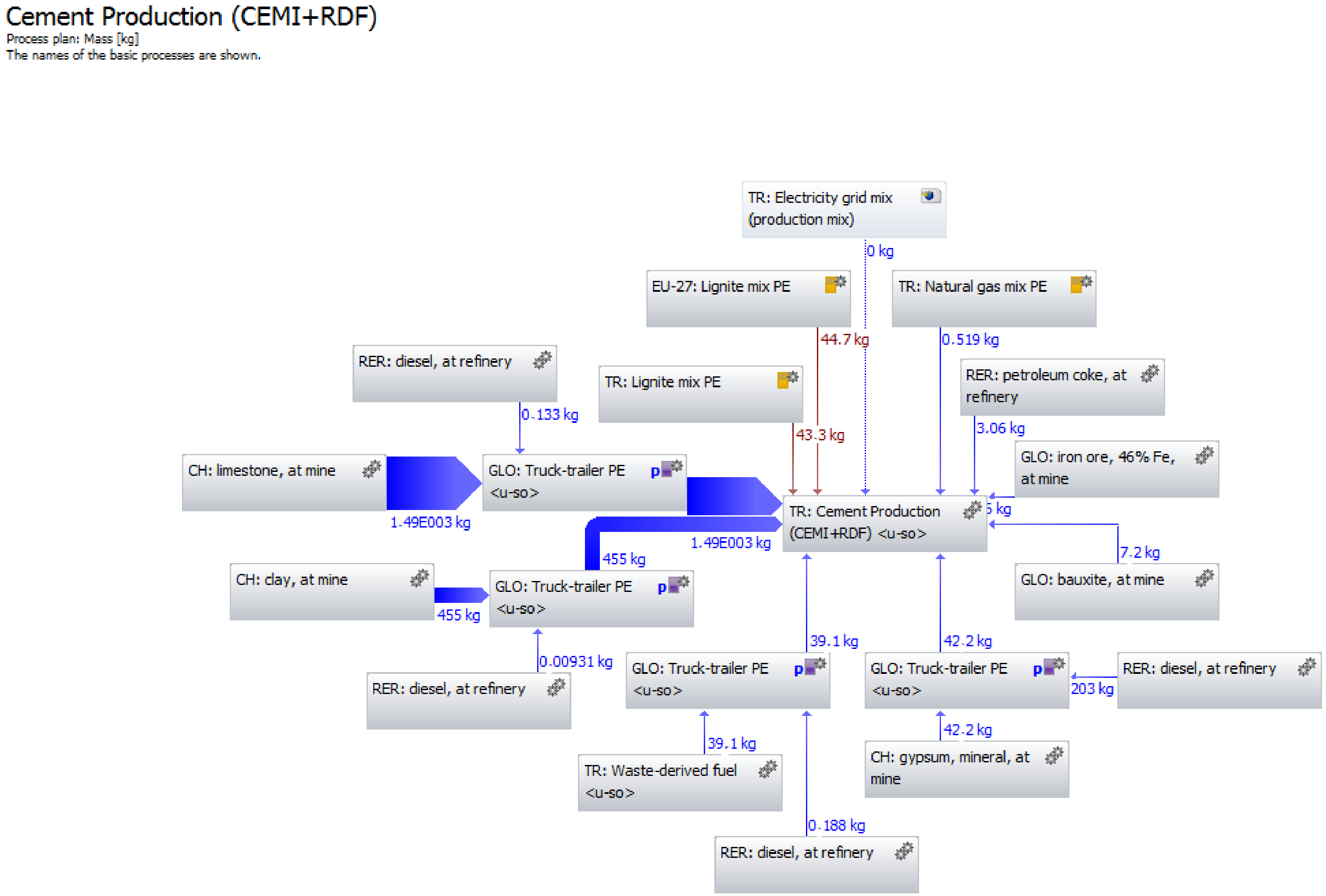


Figure 3.3. Production flow for 1 ton of Portland cement with RDF supplement.

Table 3.5. Inputs for production of 1 ton of Portland cement with RDF supplement.

Inputs	**Quantity**	**Amount**	**Unit**
Bauxite [Non-renewable resources]	Mass	7.2	Kg
Clay [Non-renewable resources]	Mass	455	Kg
Electricity [Electric power]	Energy (net calorific value)	402.984	MJ
Gypsum (natural gypsum) [Non-renewable resources]	Mass	42.2	Kg
Iron ore (56.86%) [Non-renewable resources]	Mass	1.36	Kg
Lignite Eco invent [Lignite (resource)]	Mass	44.7	Kg
Lignite Turkey [Lignite (resource)]	Mass	43.3	Kg
Limestone (calcium carbonate) [Non-renewable resources]	Mass	1492.93	Kg
Natural gas Turkey [Natural gas (resource)]	Mass	0.519	Kg
Petrol coke [Refinery products]	Mass	3.057	Kg
Refuse derived fuel [Production residues in life cycle]	Mass	39.146	Kg

Table 3.6. Outputs for production of 1 ton of Portland cement with RDF supplement.

Outputs	**Quantity**	**Amount**	**Unit**
Cement (CEM I 42.5) [Minerals]	Mass	1000	kg
Carbon dioxide [Inorganic emissions to air]	Mass	746	kg
Carbon monoxide [Inorganic emissions to air]	Mass	0.2886	kg
Dust (unspecified) [Particles to air]	Mass	1.177	kg
Heavy metals to air (unspecified) [Heavy metals to air]	Mass	1.46E-5	kg
Nitrogen dioxide [Inorganic emissions to air]	Mass	1.208	kg
Nitrogen oxides [Inorganic emissions to air]	Mass	0.7484	kg
VOC (unspecified) [Organic emissions to air (group VOC)]	Mass	0.270	kg
HCl [Inorganic emissions to air]	Mass	0.00049	kg
HF [Inorganic emissions to air]	Mass	0.00049	kg
Dioxin/Furan [Organic emissions to air (group Halogenated organic emissions to air)]	Mass	3.00E-12	kg

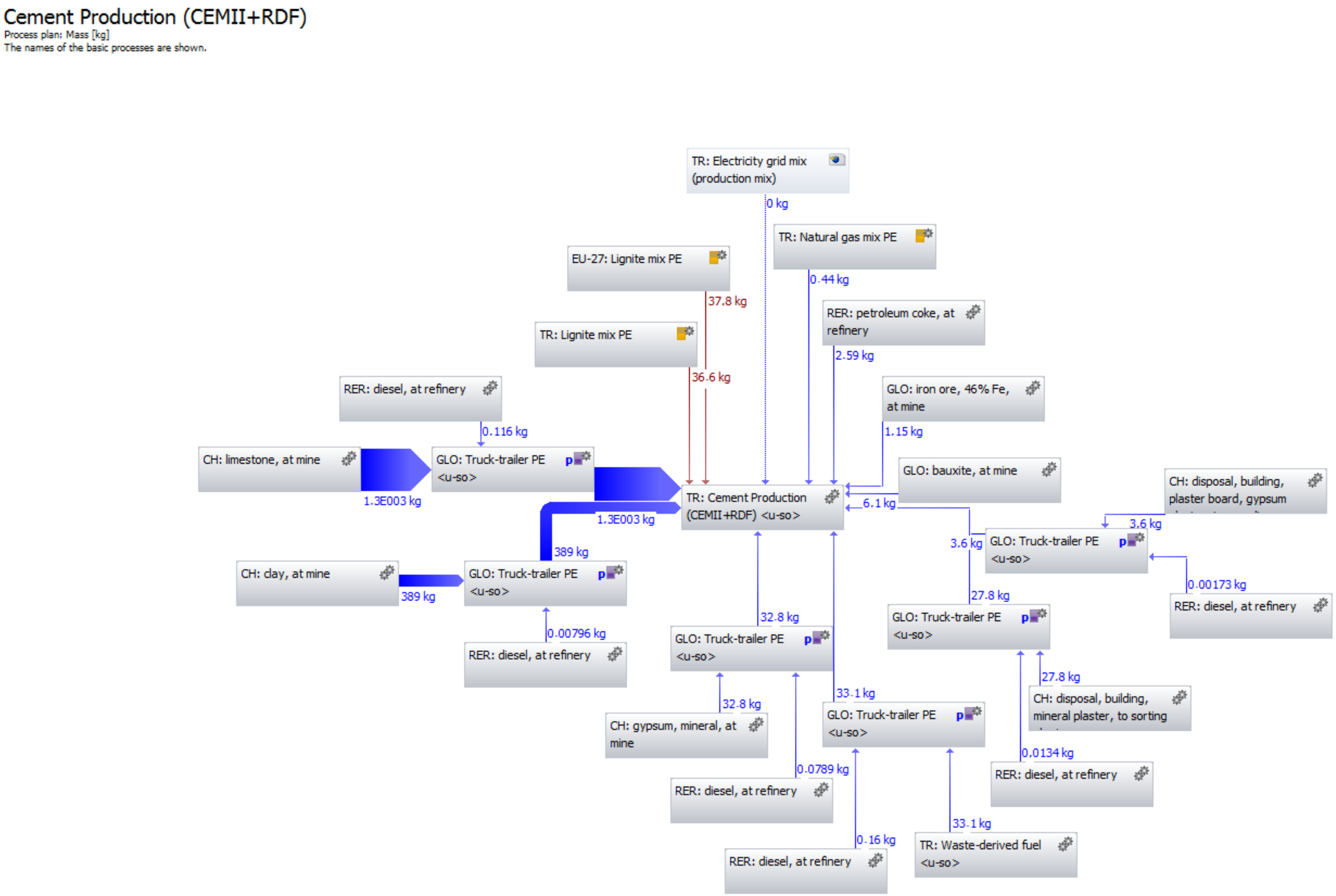


Figure 3.4. Production flow for 1 ton of blended cement.

Table 3.7. Inputs for production of 1 ton of blended cement with RDF supplement.

Inputs	**Quantity**	**Amount**	**Unit**
Bauxite [Non-renewable resources]	Mass	6.1	Kg
Clay [Non-renewable resources]	Mass	389	Kg
Electricity [Electric power]	Energy (net calorific value)	366.768	MJ
Gypsum [Waste for recovery]	Mass	3.6	Kg
Gypsum (natural gypsum) [Non-renewable resources]	Mass	32.8	Kg
Iron ore (56. 86%) [Non-renewable resources]	Mass	1.15	Kg
Lignite Eco invent [Lignite (resource)]	Mass	37.8	Kg
Lignite Turkey [Lignite (resource)]	Mass	36.6	Kg
Limestone (calcium carbonate) [Non-renewable resources]	Mass	1297.8	Kg
Silica (ceramic waste) [Waste for recovery]	Mass	27.8	Kg
Natural gas Turkey [Natural gas (resource)]	Mass	0.44	Kg
Petrol coke [Refinery products]	Mass	2.587	Kg
Refuse derived fuel [Production residues in life cycle]	Mass	33.15	Kg

Table 3.8. Outputs for production of 1 ton of blended cement with RDF supplement.

Outputs	**Quantity**	**Amount**	**Unit**
Cement (CEM II 42.5) [Minerals]	Mass	1000	kg
Carbon dioxide [Inorganic emissions to air]	Mass	630.7	kg
Carbon monoxide [Inorganic emissions to air]	Mass	0.2442	kg
Dust (unspecified) [Particles to air]	Mass	1.177	kg
Heavy metals to air (unspecified) [Heavy metals to air]	Mass	1.23E-5	kg
Nitrogen dioxide [Inorganic emissions to air]	Mass	1.022	kg
Nitrogen oxides [Inorganic emissions to air]	Mass	0.6332	kg
VOC (unspecified) [Organic emissions to air (group VOC)]	Mass	0.241	kg
HCl [Inorganic emissions to air]	Mass	0.00041	kg
HF [Inorganic emissions to air]	Mass	0.00042	kg
Dioxin/Furan [Organic emissions to air (group Halogenated organic emissions to air)]	Mass	2.81E-12	kg

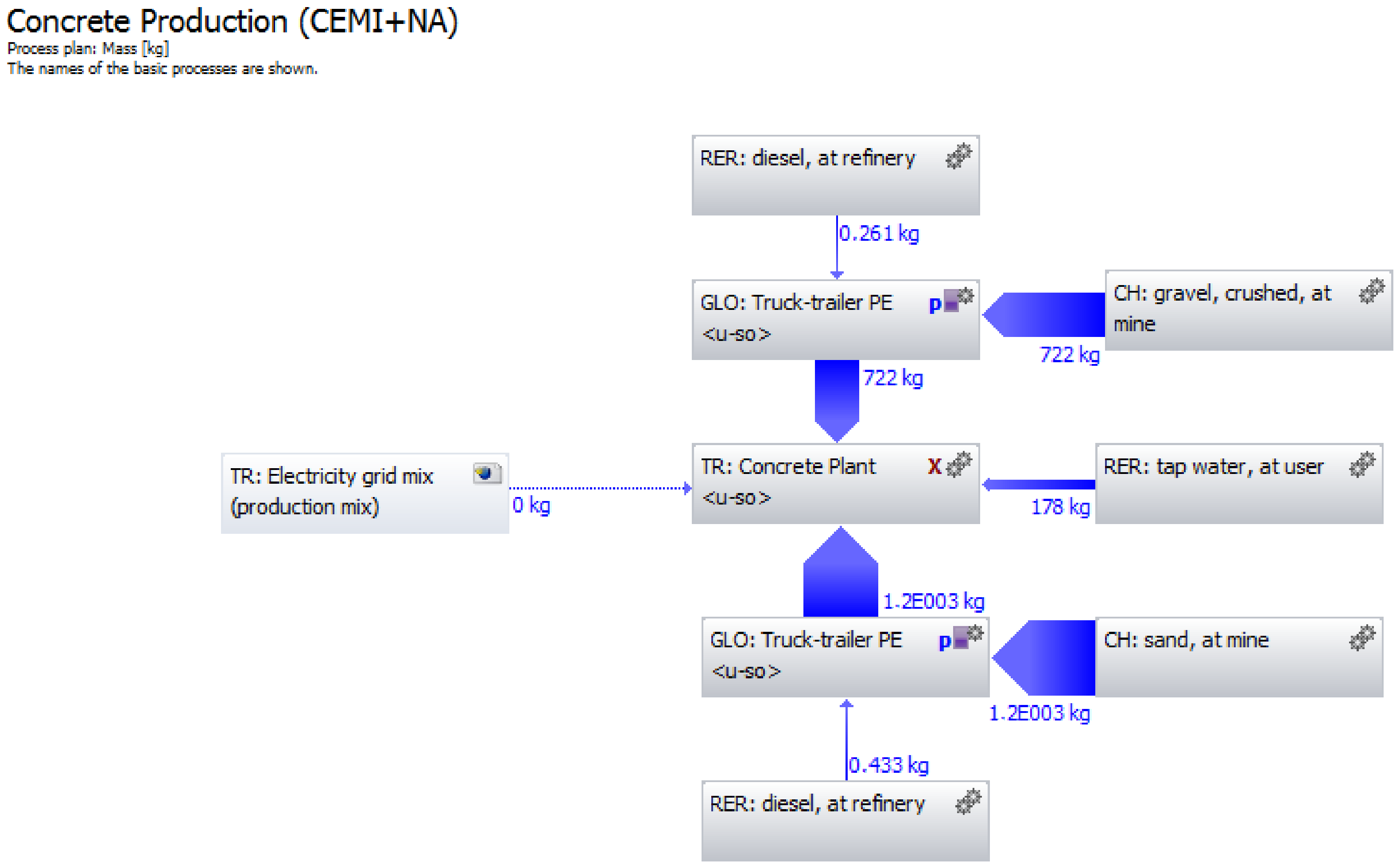


Figure 3.5. Production flow for 1 m^3 of concrete and natural aggregates.

Table 3.9. Inputs for production of 1 m^3 of concrete consisting of Portland cement and natural aggregates.

Inputs	**Quantity**	**Amount**	**Unit**
Cement (CEM I 42.5) [Minerals]	Mass	276	kg
Electricity [Electric power]	Energy (net calorific value)	17.7192	MJ
Gravel [Non-renewable resources]	Mass	722	kg
Sand [Non-renewable resources]	Mass	1200	kg
Water [Water]	Mass	178	kg

Table 3.10. Outputs for production of 1 m^3 of concrete consisting of Portland cement and natural aggregates.

Outputs	**Quantity**	**Amount**	**Unit**
Ready-mix concrete [Minerals]	Mass	2365	kg
Dust (> PM10) [Particles to air]	Mass	0.0648	kg
Dust (PM2.5 - PM10) [Particles to air]	Mass	0.0246	kg
Dust (PM2.5) [Particles to air]	Mass	0.0234	kg

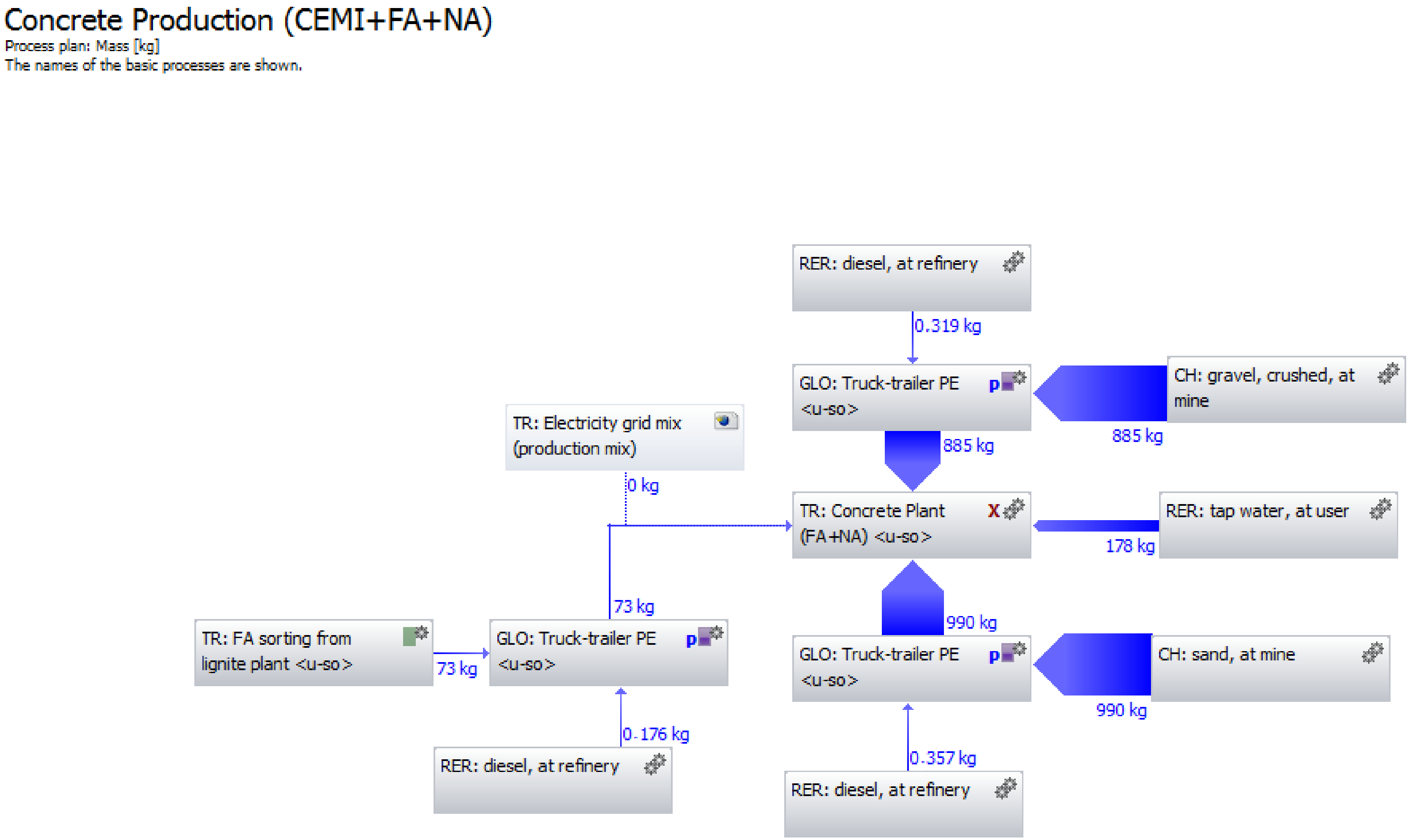


Figure 3.6. Production flow for 1 m^3 concrete consisting of Portland cement, fly ash and natural aggregates.

Table 3.11. Inputs for production of 1 m^3 concrete consisting of Portland cement, fly ash and natural aggregates.

Inputs	Quantity	Amount	Unit
Cement (CEM I 42.5) [Minerals]	Mass	243	kg
Electricity [Electric power]	Energy (net calorific value)	17.55	MJ
Fly ash (unspecified) [Waste for recovery]	Mass	73	kg
Gravel [Non-renewable resources]	Mass	885	kg
Sand [Non-renewable resources]	Mass	990	kg
Water [Water]	Mass	178	kg

Table 3.12. Outputs for production of 1 m^3 concrete consisting of Portland cement, fly ash and natural aggregates.

Outputs	Quantity	Amount	Unit
Ready-mix concrete [Minerals]	Mass	2365	kg
Dust (> PM10) [Particles to air]	Mass	0.0648	kg
Dust (PM2.5 - PM10) [Particles to air]	Mass	0.0246	kg
Dust (PM2.5) [Particles to air]	Mass	0.0234	kg

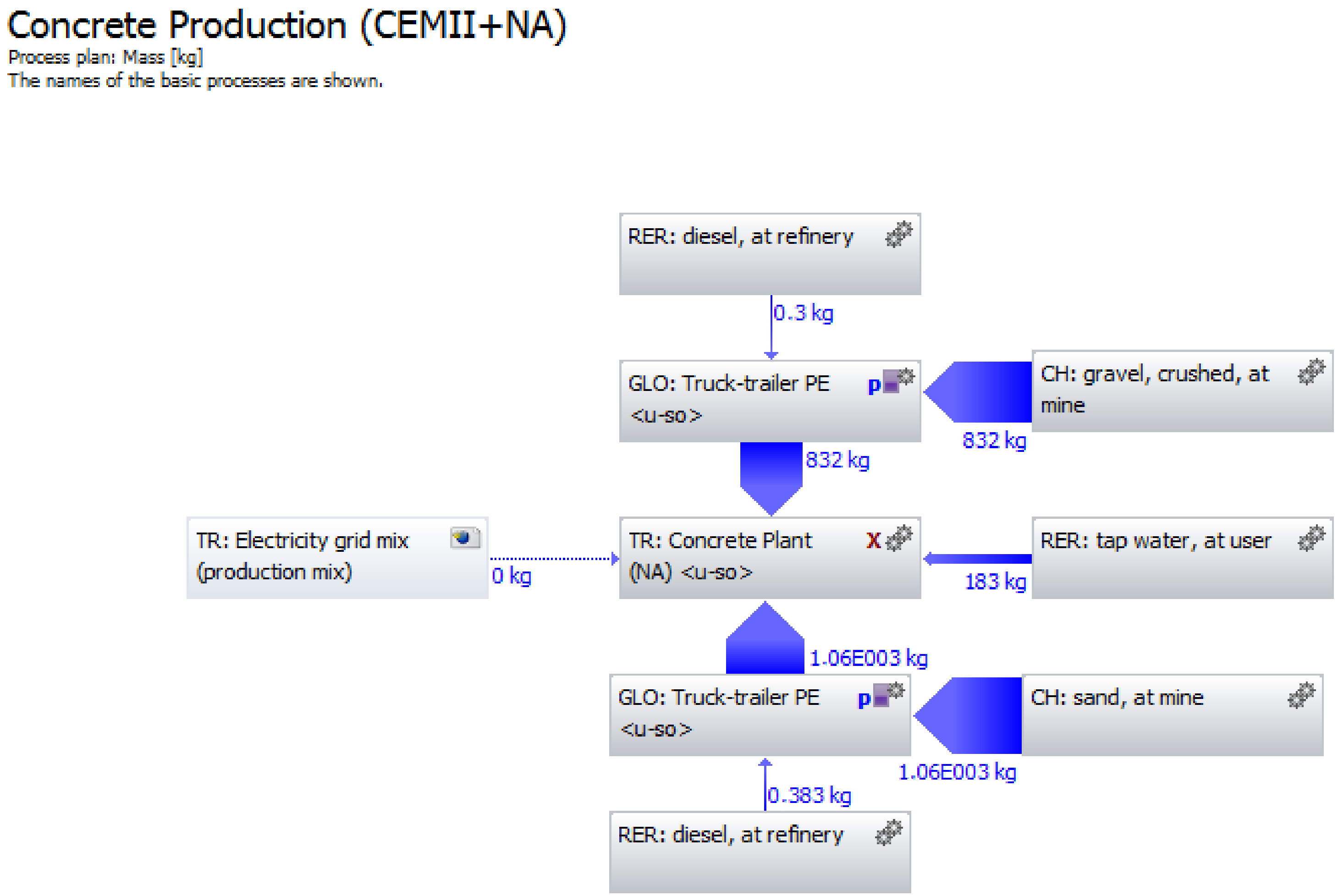


Figure 3.7. Production flow for 1 m^3 concrete consisting of blended cement with RDF supplement and natural aggregates.

Table 3.13. Inputs for production of 1 m^3 concrete consisting of blended cement and natural aggregates.

Inputs	**Quantity**	**Amount**	**Unit**
Cement (CEM II 42.5) [Minerals]	Mass	315	kg
Electricity [Electric power]	Energy (net calorific value)	17.6112	MJ
Gravel [Non-renewable resources]	Mass	832	kg
Sand [Non-renewable resources]	Mass	1060	kg
Water [Water]	Mass	183	kg

Table 3.14. Outputs for production of 1 m^3 concrete consisting of blended cement and natural aggregates.

Outputs	**Quantity**	**Amount**	**Unit**
Ready-mix concrete [Minerals]	Mass	2365	Kg
Dust (> PM10) [Particles to air]	Mass	0.0648	Kg
Dust (PM2.5 - PM10) [Particles to air]	Mass	0.0246	Kg
Dust (PM2.5) [Particles to air]	Mass	0.0234	Kg

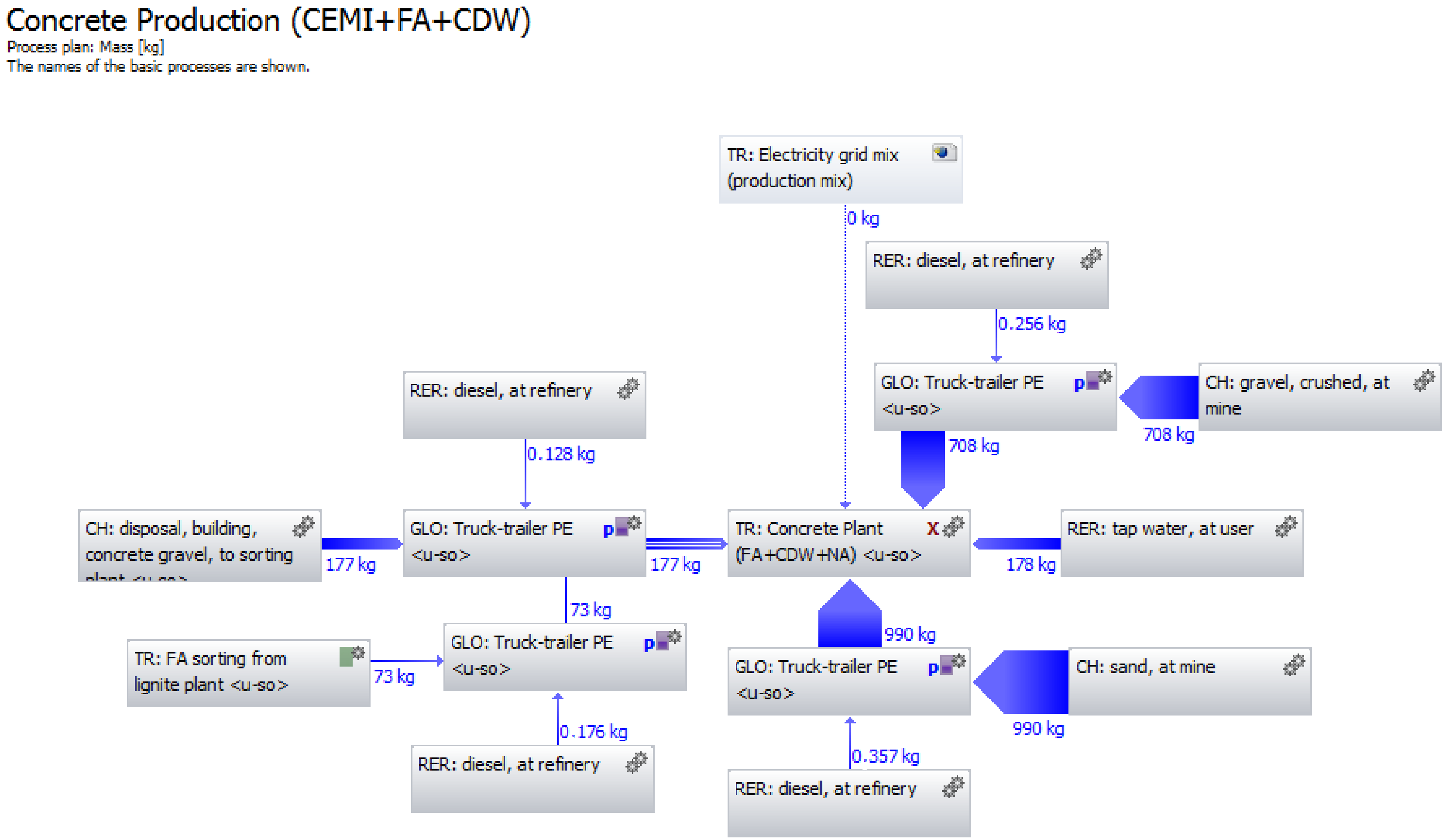


Figure 3.8. Production flow for 1 m^3 concrete consisting of Portland cement, fly ash and CDW as aggregates.

Table 3.15. Inputs for production of 1 m^3 concrete consisting of Portland cement, fly ash and CDW as aggregates.

Inputs	**Quantity**	**Amount**	**Unit**
Cement (CEM I 42.5) [Minerals]	Mass	243	Kg
CH: disposal, building, concrete gravel, to sorting plant [Recycling]	Mass	177	Kg
Electricity [Electric power]	Energy (net calorific value)	17.55	MJ
Fly ash (hard coal) [Waste for recovery]	Mass	73	Kg
Gravel [Non-renewable resources]	Mass	708	Kg
Sand [Non-renewable resources]	Mass	990	Kg
Water [Water]	Mass	178	Kg

Table 3.16. Outputs for production of 1 m^3 concrete consisting of Portland cement, fly ash and CDW as aggregates.

Outputs	**Quantity**	**Amount**	**Unit**
Ready-mix concrete [Minerals]	Mass	2365	Kg
Dust (> PM10) [Particles to air]	Mass	0.0648	Kg
Dust (PM2.5 - PM10) [Particles to air]	Mass	0.0246	Kg
Dust (PM2.5) [Particles to air]	Mass	0.0234	Kg

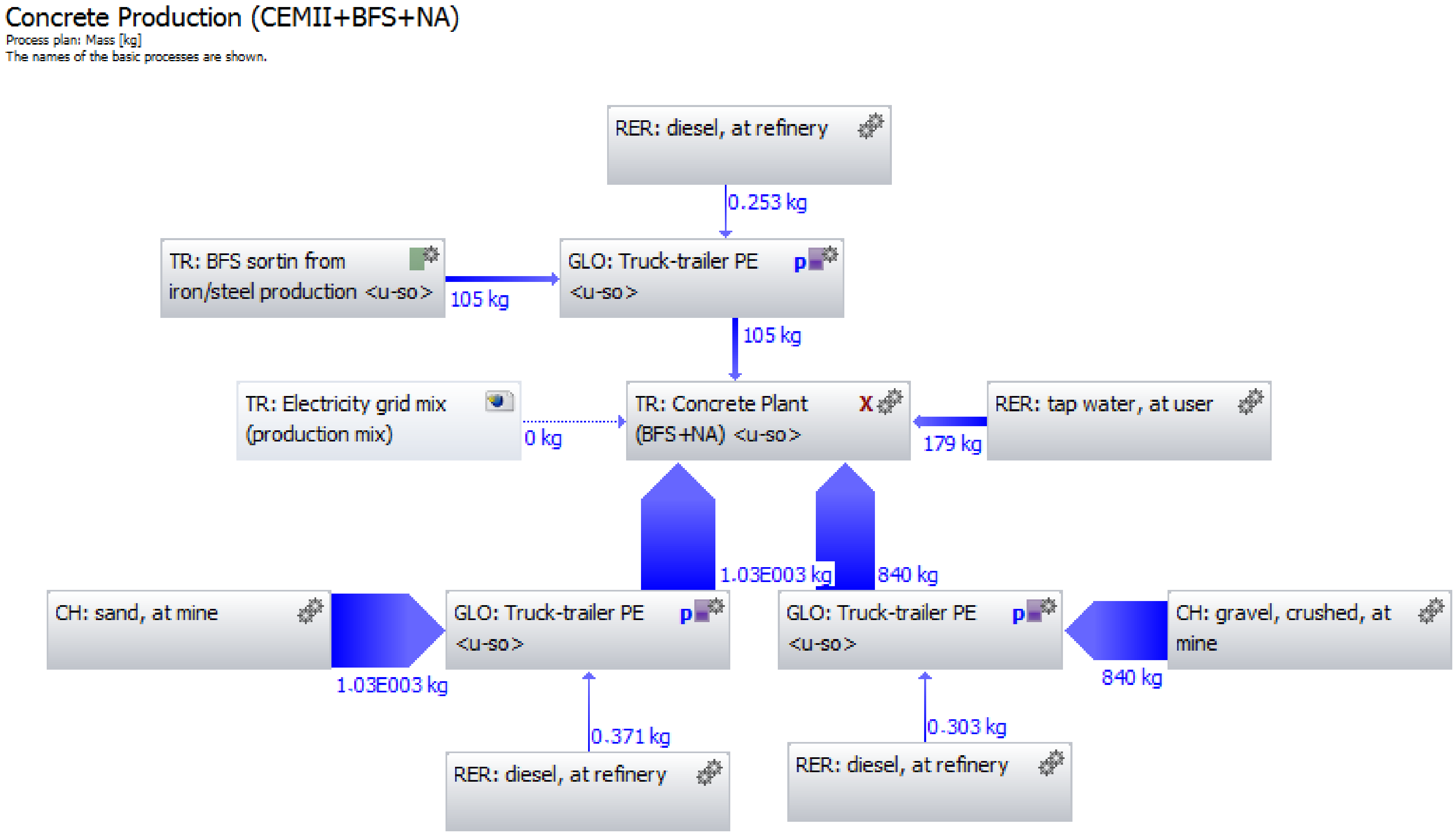


Figure 3.9. Production flow for 1 m^3 concrete consisting of blended cement, blast furnace slag and natural aggregates.

Table 3.17. Inputs for production of 1 m^3 concrete consisting of blended cement, blast furnace slag and natural aggregates.

Inputs	**Quantity**	**Amount**	**Unit**
Blast furnace slag [Waste for recovery]	Mass	105	kg
Cement (CEM II 42.5) [Minerals]	Mass	219	kg
Electricity [Electric power]	Energy (net calorific value)	17.5212	MJ
Gravel [Non-renewable resources]	Mass	840	kg
Sand [Non-renewable resources]	Mass	1027	kg
Water [Water]	Mass	179	kg

Table 3.18. Outputs for production of 1 m^3 concrete consisting of blended cement, blast furnace slag and natural aggregates.

Outputs	**Quantity**	**Amount**	**Unit**
Ready-mix concrete [Minerals]	Mass	2365	Kg
Dust (> PM10) [Particles to air]	Mass	0.0648	Kg
Dust (PM2.5 - PM10) [Particles to air]	Mass	0.0246	Kg
Dust (PM2.5) [Particles to air]	Mass	0.0234	Kg

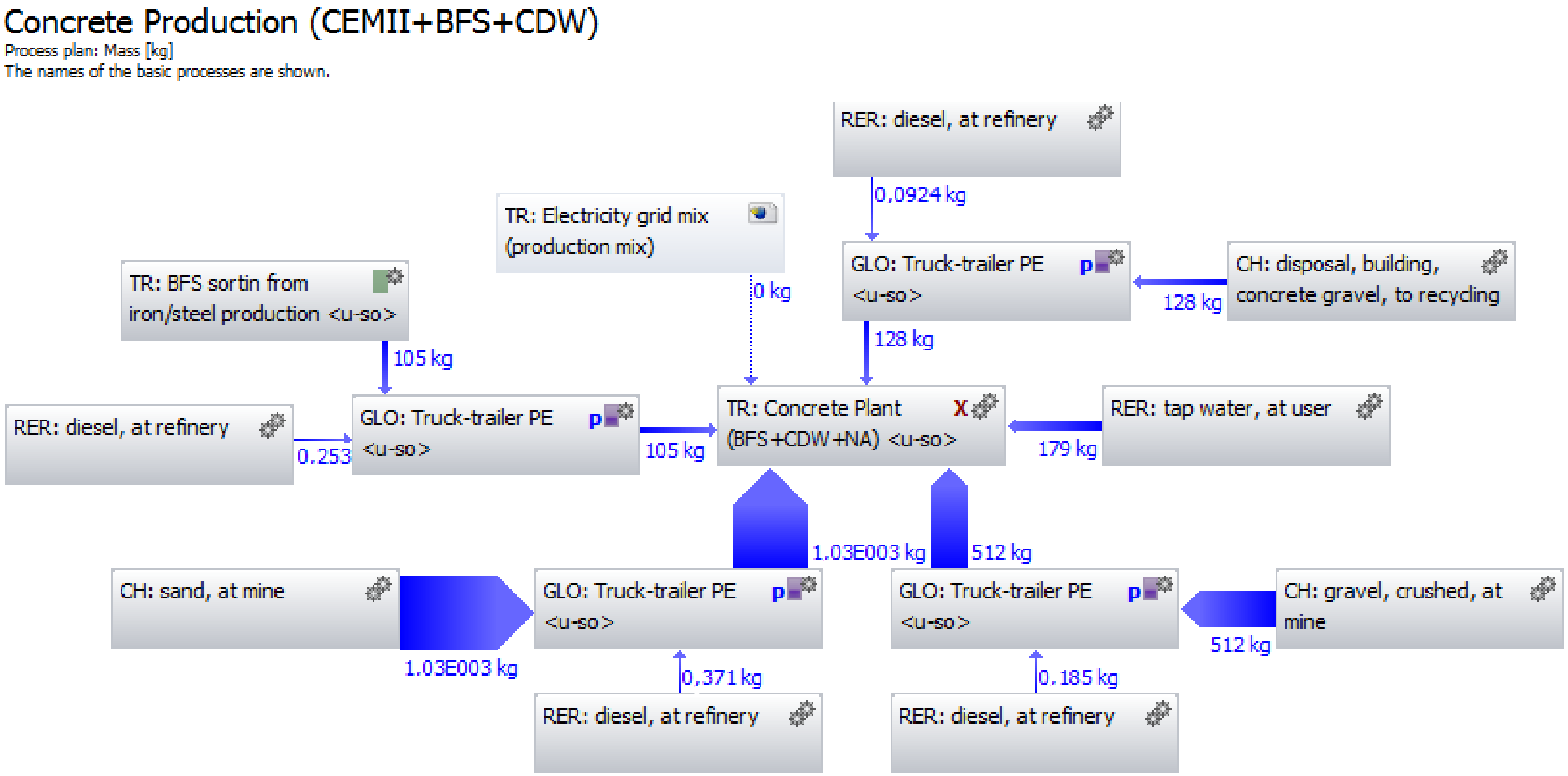


Figure 3.10. Production flow for 1 m^3 concrete consisting of blended cement, blast furnace slag and CDW as aggregates.

Table 3.19. Inputs for production of 1 m^3 concrete consisting of blended cement, blast furnace slag and CDW as aggregates.

Inputs	**Quantity**	**Amount**	**Unit**
Blast furnace slag [Waste for recovery]	Mass	105	Kg
Cement (CEM II 42.5) [Minerals]	Mass	219	Kg
CH: disposal, building, concrete gravel, to sorting plant [Recycling]	Mass	128	Kg
Electricity [Electric power]	Energy (net calorific value)	17.5176	MJ
Gravel [Non-renewable resources]	Mass	512	Kg
Sand [Non-renewable resources]	Mass	1027	Kg
Water [Water]	Mass	179	Kg

Table 3.20. Outputs for production of 1 m^3 concrete consisting of blended cement, blast furnace slag and CDW as aggregates.

Outputs	**Quantity**	**Amount**	**Unit**
Ready-mix concrete [Minerals]	Mass	2365	Kg
Dust (> PM10) [Particles to air]	Mass	0.0648	Kg
Dust (PM2.5 - PM10) [Particles to air]	Mass	0.0246	Kg
Dust (PM2.5) [Particles to air]	Mass	0.0234	Kg

4. RESULTS AND DISCUSSION

4.1. Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) phase is evaluation of potential environmental impacts of the resources and releases of the surveyed system. This phase delivers essential information for the evaluation by associating the inflows and outflows resulted from the inventory analysis with specific environmental impact categories. Environmental impact categories for this study are selected with regards to product category rules for concrete. Impact categories considered in this study are shown in Table 4.1.

Abiotic Depletion Potential (ADP) (elements): impact from depletion of scarce non-renewable resources (minerals, metals), expressed in comparison to the element antimony

Abiotic Depletion Potential (ADP) (fossil): impact from depletion of fossil fuel resources such as oil or natural gas, expressed using their net calorific value. Characterization factors are based on the net calorific value (MJ) of the fossil fuel resource.

Global Warming Potential (GWP): Deals with all GHGs that may cause the earth's temperature to rise and have an adverse effect on the ecosystem and human health and material welfare, global warming, measured using the equivalent carbon dioxide emission over a 100 year time horizon.

Acidification Potential (AP): Covers all impacts on soil, water, organisms, ecosystems & materials by acidifying pollutants (e.g., SO_2, NO_X, NH_X), measured in kg of sulphur dioxide equivalent.

Eutrophication Potential (EP): Covers all impacts of excessively high environmental levels of macronutrients (N, P) causing a shift in species composition and an elevated biomass production in aquatic and terrestrial ecosystems, disturbing the balance between species, measured in kg phosphate equivalent.

Table 4.1. Life cycle impact categories for this study.

Impact Category	**Scale**	**Examples of LCI Data (i.e. classification)**	**Parameter**	**Parameter unit expressed**
Global Warming	Global	Carbon dioxide (CO_2) Carbon monoxide (CO) Nitrogen dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydro chlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global warming potential, GWP (100 years). Characterisation Factors: International Panel for Climate Change 4th Assessment Report, 2007.	kg CO_2 eq.
Acidification for soil and water	Regional Local	Sulphur oxides (SOx) Nitrogen oxides (NOx) Hydrochloric acid (HCl) Hydrofluoric acid (HF) Ammonia (NH_4)	Acidification potential of soil and water, AP.	mole H+ eq./kg SO_2 eq.
Eutrophication	Local	Phosphate (PO_4) Nitrogen oxide (NO) Nitrogen dioxide (NO_2) Nitrates (NO_3) and Ammonia (NH_4)	Eutrophication potential, EP.	mole N eq./kg PO_4 eq.
Photochemical ozone creation	Local	Non-methane hydrocarbon (NMHC)	Formation potential of tropospheric ozone, POCP.	kg NMVOC eq./kg Ethane eq.
Human Toxicity	Local	All toxic substances releases to air, water, and soil	Human Toxicity potential, HTP.	kg 1.4-Dichlorobenzene
Depletion of abiotic resources-elements Depletion of abiotic resources-fossil fuels	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Abiotic depletion potential (ADP-elements) for non-fossil resources Abiotic depletion potential (ADP-fossil fuels) for fossil Resources	kg Sb eq. MJ, net calorific value

Photochemical Ozone Creation Potential (POCP): Also known as summer smog, indicates the potential capacity of an oxidizing photochemical substances, such as volatile organic compounds (VOCs) and carbon monoxide (CO) to produce ozone in the presence of nitrogen oxides (NO_X) which frees ozone in the low atmosphere, measured relative to Ethane (C_2H_4). The effect of solar radiation on oxidizing photochemical substances gives rise to reactions between the oxidizing photochemical compounds and hydroxyl radicals (OH^-).

Human Toxicity Potential (HTP): Covers the impact on human health of all toxic substances emitted to air, water and soil, measured in kg 1.4-Dichlorobenzene equivalent (PCR, 2013 and Marinkovic et al., 2010).

The data summarized in the inventory phase have been interpreted through classification, characterization, normalization and weighting by using GaBi6 software. LCIA mainly includes determination of the environmental impact categories, classification and characterization. Normalization and weighting are optional steps. Classification links the input and output parameter of the inventory to the impact categories. For instance, CO_2 and methane is defined in terms of Global Warming Potential. Characterization provides the calculation of LCI results impacts. The potential impact of CO_2 and methane on global warming is calculated by using conversion factors. Normalization express the magnitude of an impact indicator data in a way that can be compared among total effect of a given reference, i.e. normalization is used for comparison of different impact categories while weighting assigns relative values to the different impact categories based on their perceived importance or relevance.

Life Cycle Impact Assessment (LCIA) has been conducted using characterization factors from CML 2001-April 2013 methodology. Global warming potential (in kg CO_2-eq.), acidification (in kg SO_2-eq.), photochemical oxygen formation (in kg ethane-eq.), abiotic depletion (elements) (in kg Sb-eq.), abiotic depletion (fossil) (MJ.), eutrophication (kg phosphate-eq.) and human toxicity potential (in DCB-eq.) are considered as environmental impact categories. The priority has been given to GHG emissions due to the CO_2 intensity of the cement production.

4.1.1. Results for Cement Production

4.1.1.1 Classification In this step, LCI results are organized and combined to the related impact categories. As an initial step, prior to characterization, impact categories of global warming, acidification, eutrophication, photochemical oxidant formation and abiotic depletion of fossils and elements are determined by considering the emissions from a cradle-to-gate life-cycle of concrete mixtures. The emissions and the impacts of emissions on the environment in terms of environmental impact categories with classification units for this study are given in Table 4.2.

Table 4.2. Classifications of emissions to impact categories for this study.

Impact Category	**Resource or Emission**	**Unit**
Global warming (GWP)	CO_2	kg CO_2-eqv.
Acidification (AP)	NO_X, HCl, HF SO_2	kg SO_2-eqv.
Photochemical ozone creation (POCP)	CO, NOx, VOCs, Dioxins/furans	kg ethane-eqv.
Eutrophication (EP)	NO_X	kg PO_4^{3-}-eqv.
Human toxicity potential (HTP)	Heavy metals, Dioxins/furans, VOCs, CO	kg DCB-eqv.
Abiotic depletion (fossil)	Fossils	MJ
Abiotic depletion (elements)	Minerals, metals	kg Sb-eqv

The emissions from ordinary Portland cement (CEM I) production, ordinary Portland cement (CEM I) production with RDF supplement and limestone blended cement (CEM II) production with RDF supplement is shown in Table 4.3.

When ordinary Portland cement (CEM I) and limestone blended cement (CEM II) in the case of RDF use is compared, the contribution of clinker substitutes in terms of energy and material use have been calculated as 11% and 10%, respectively. The contribution of using RDF in production of CEM I has reached to 18% regarding energy savings. The combined savings through RDF supplement and clinker substitutes have been 29% in terms of energy consumption. Figure 4.1 and 4.2 illustrate required energy and material resources in different cement production scenarios.

Table 4.3. The emissions from surveyed cement production scenarios.

Emissions to air (kg/ton-cement)	**CEM I**	**CEM I with RDF**	**CEM II with RDF**
Heavy metals to air	0.000256	0.000246	0.000226
Carbon dioxide	901.4	876.6	745.9
Carbon monoxide	0.518	0.347	0.296
Nitrogen dioxide	1.076	1.209	1.023
Nitrogen monoxide	0.006	0.012	0.009
VOCs	0.297	0.270	0.241
Particles to air	1.570	1.566	1.515
HCl	0.00047	0.00049	0.00041
HF	0.00048	0.00049	0.00042
Dioxin/Furan	0.000026	0.000028	0.000023

The main emission streams in cement production are fuel use and raw material calcination. Inventory analysis has showed that CO_2 dominates the emissions associated with the cement production as it is expected. CO_2 emissions emitted from fossil fuels have been decreased by approximately 3% when RDF is used as energy substitute in fuel mix for 1 ton of cement. The evaluation of CEM I and CEM II while using RDF have indicated additional 14.5% reduction in CO_2 for CEM II. The major released emissions to air are shown in Figure 4.3.

The change in CO, NO and NO_2 emissions has been examined as well. CO, NO and NO_2 emissions stem from the fuel combustion in order to adjust required temperature for the calcination of raw materials. While CO, HCl, HF, heavy metals and VOC emissions have been decreased by 33%, 1%, 2%, 4% and 9% respectively by using RDF, NO_2 and NO emissions have been increased by 12% and 7%, respectively. The chemical composition of RDF may change according to the different waste supply. Therefore, fluctuations on NO and NO_2 emissions and related environmental impact categories are expected. In addition, Particulate matter has decreased by 3% with respect to the use of clinker substitutes.

As it iss mentioned before, almost all of SO_2 emissions generated from combustion is fixed in the semi-product; clinker. SO_2 emissions mainly stems from selected electricity process. Since SO_2 emissions have very low values considering the whole system, it has limited meaning for this study.

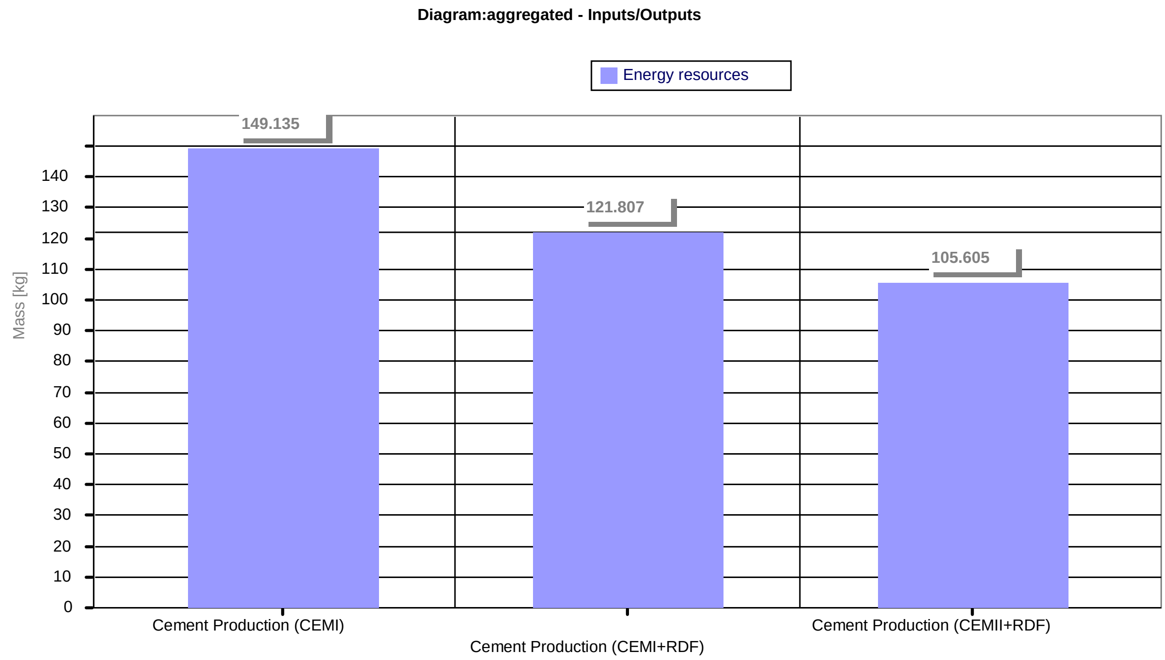


Figure 4.1. The energy use for CEM I, CEM I-RDF and CEM II-RDF

<u>4.1.1.2. Characterization</u> Direct comparison of LCI results within the impact categories is made through the characterization step. GaBi6 calculates the contribution of the emissions to each impact category and classifies the emissions into relevant categories for cement production scenarios. Table 4.4 illustrates the quantified LCA characterization results for the production of ordinary Portland cement (CEM I); the production of ordinary Portland cement (CEM I) produced by using RDF in fuel mix and the production of ready-mix concrete from blended cement with limestone substitution (CEM II) produced by using RDF in fuel mix.

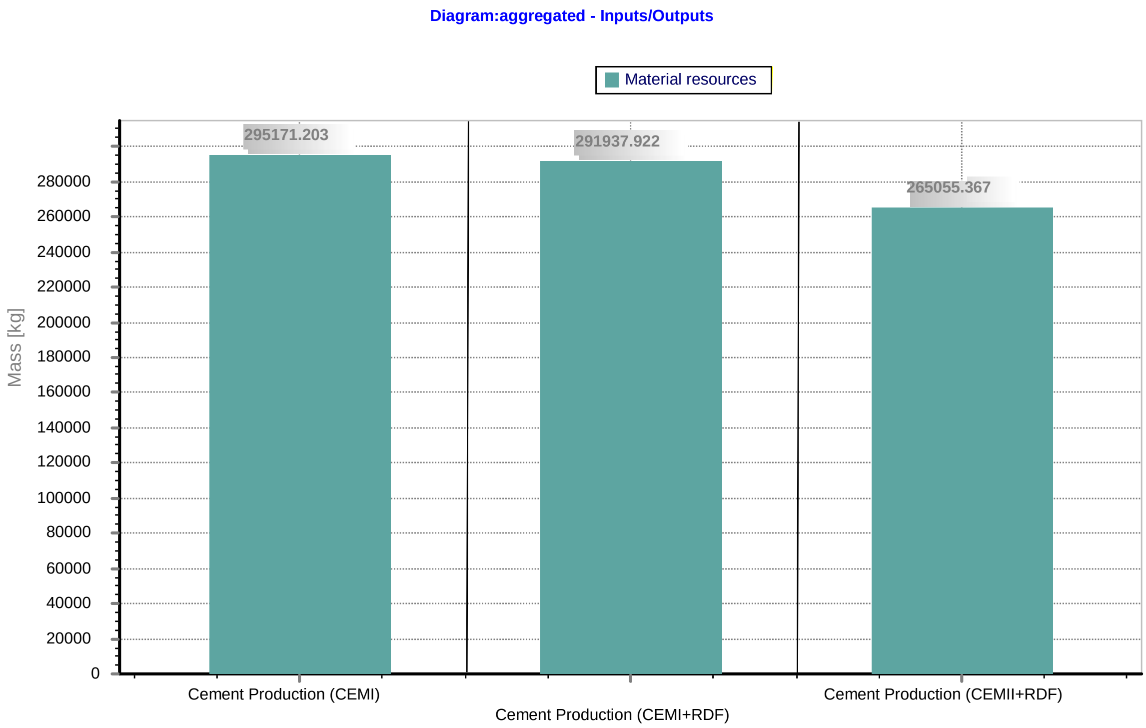
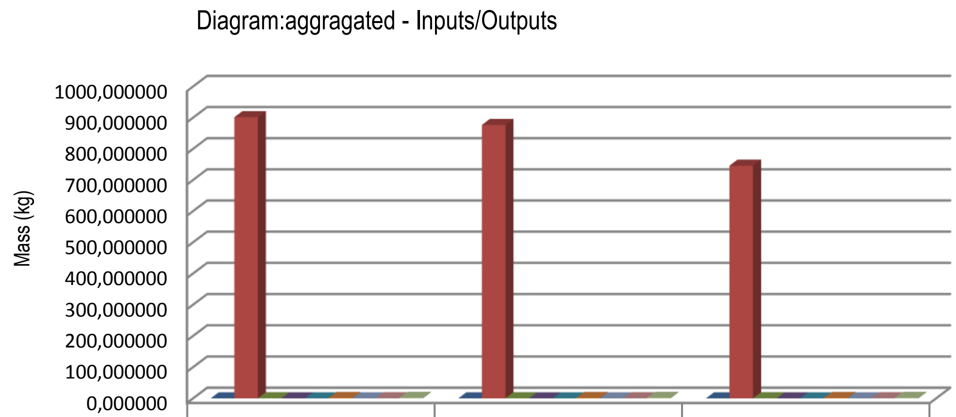


Figure 4.2. The material use for CEM I, CEM I-RDF and CEM II-RDF.

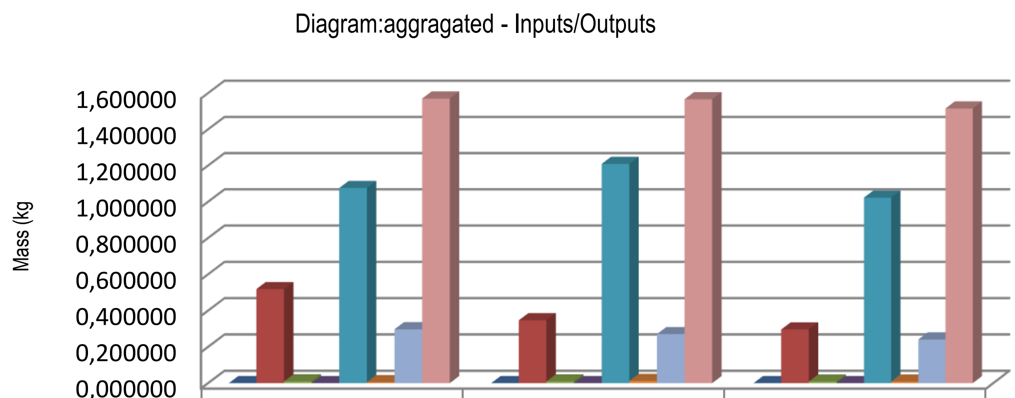
The high energy consumption of clinker production is the main source of environmental impact regarding GWP. The results have indicated that the fuel shift from fossils to RDF proceeds as approximately 3% reduction in GWP parallel to CO_2 reduction and 10.5% reduction in ADP (fossils). However, 17.5% increase in both AP and EP due to the NO_X emissions originated from the chemical composition of RDF used. Besides, HTP has decreased by 9% and POCP has decreased by 11%.

As Figure 4.5 illustrates, CEM II examined more environmentally friendly. GWP, ADP (elements), ADP (fossil), AP, EP, HTP and POCP has decreased by 17%, 22%, 26%, 5%, 4,5%, 15.5% and 20%, respectively. The substitution of 1 kg of clinker with limestone has reduced the carbon dioxide emissions of cements by around 0.9 kg CO_2 eq/t-cement because the trigger effect of reduction in both fuel consumption and the amount of raw materials that would otherwise introduced to calcination reaction. If 1 kg of the energy input is substituted by RDF, the carbon footprint is then reduced by about 0.6 kg CO_2 eq/t-cement. Therefore, the potential environmental benefits from clinker substitution can be indicated as much more substantial than fuel substitution in clinker production on a mass by mass basis.



	CEMI	CEMI+RDF	CEMII+RDF
Heavy metals to air	0,000256	0,000246	0,000226
Carbon dioxide	901,4	876,6	745,9
Carbon monoxide	0,518	0,347	0,296
Hydrogen chloride	0,01006	0,00995	0,00904
Hydrogen fluoride	0,000266	0,000260	0,000236
Nitrogen dioxide	1,076	1,209	1,023
Nitrogen monoxide	0,006	0,012	0,009
Organic emissions to air (group VOC)	0,297	0,270	0,241
Particles to air	1,570	1,566	1,515

Figure 4.3. The major emissions of different cement production scenarios.



	CEMI	CEMI+RDF	CEMII+RDF
Heavy metals to air	0,000256	0,000246	0,000226
Carbon monoxide	0,518	0,347	0,296
Hydrogen chloride	0,01006	0,00995	0,00904
Hydrogen fluoride	0,000266	0,000260	0,000236
Nitrogen dioxide	1,076	1,209	1,023
Nitrogen monoxide	0,006	0,012	0,009
VOC group	0,297	0,270	0,241
Particles to air	1,570	1,566	1,515

Figure 4.4. The major emissions of different cement production scenarios (CO_2 excl.).

Table 4.4. The characterization results for different cement production scenarios.

Environmental quantities (CML2001 - Apr. 2013)	Unit	CEM I	CEM I+RDF	CEM II+RDF
Abiotic Depletion (ADP elements)	[kg Sb-eq.]	0.0015	0.0015	0.0012
Abiotic Depletion (ADP fossil)	[MJ]	2518	2125	1862
Acidification Potential (AP)	[kg SO_2-eq.]	0.550	0.622	0.525
Eutrophication Potential (EP)	[kg Phosphate-eq.]	0.141	0.160	0.135
Global Warming Potential (GWP 100 years)	[kg CO_2-eq.]	907.2	881.8	750.5
Human Toxicity Potential (HTP inf.)	[kg DCB-eq.]	7.681	7.191	6.487
Photochemical Ozone Creation Potential (POCP)	[kg Ethene-eq.]	0.058	0.053	0.047

4.1.1.3. Normalization The goal of normalization is to refer the impact scores to a common reference to help us to compare different environmental impacts of the analysed product system. Therefore, calculation is made by dividing the LCIA results of each impact category by the reference value. This reference value reflects the total impact from the emissions, extractions, radiations and land use, per impact category for EU25+3 over a year (Monteiro and Freire, 2012). The results have no unit that allows comparison of impact potentials. Normalization results present a suitable form for the final weighting a decision-making, as well. In this study, EU25+3, year 2000 CML, IPCC, ReCiPe (person equivalents) option has been used for normalization step. Normalization results for cement production scenarios are demonstrated in Figure 4.6. The normalization results have indicated that the potential impact of abiotic depletion of elements exceeds the potential impact of global warming. The results have revealed the importance of clinker substitutes which decreases the required clinker amount and accordingly the required limestone and clay amount. ADP (elements), GWP, and ADP (fossil) have decreased by 22%, 17% and 26%, respectively in the case of adding clinker substitutes. Moreover, the normalization

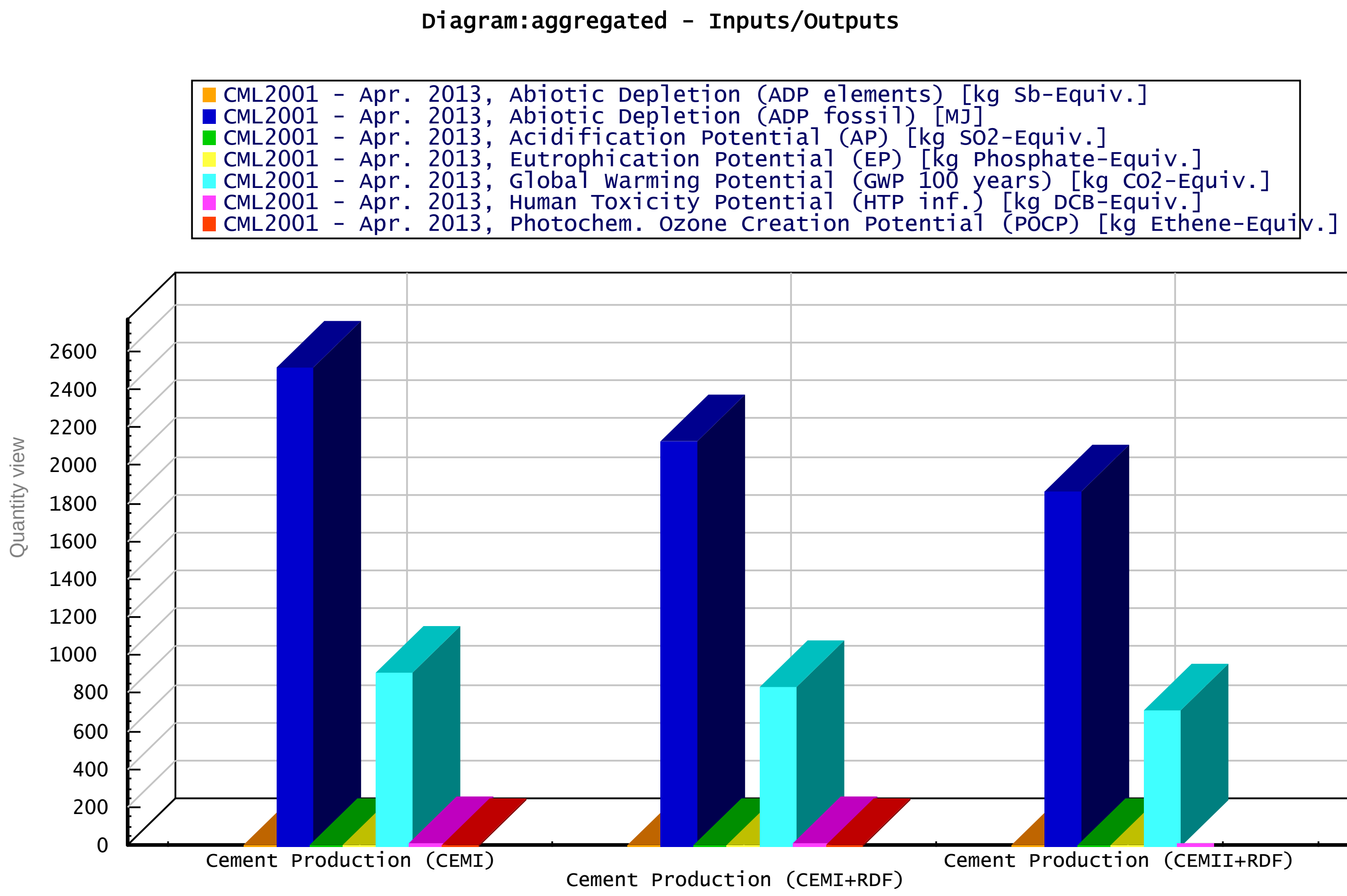


Figure 4.5. Comparative environmental impacts potentials of different cement production scenarios.

results for acidification potential reflect that the chemical composition of fuel mix should be precisely arranged to keep NOx emissions under control. AP has increased by 13% when RDF is used for the same cement mix and decreased by 4.5% when clinker substitutes is used due to the lower amount of required energy parallel to the lower amount of calcined raw material.

4.1.1.4. Weighting. The goal of the weighting step is to assign the relative amounts of normalization results to the different impact categories based on their perceived importance or relevance. The weighting results of different cement production scenarios have appeared similar to normalization results in this study. However, GWP has dominated ADP (elements) due to the relative importance of climate change. Figure 4.7 illustrates the weighting results.

4.1.2. Results for Concrete Production

4.1.2.1 Classification Scenario 5 and Scenario 8 have performed similar in terms of resource consumption according to use of clinker substitutes, waste-derived fuel and cement replacements agents. Extra saving in terms of material consumption has been obtained by CDW with respect to less consumption of natural aggregates. However, in the overall evaluation, the contribution of CDW has been very limited. Moreover, in Scenario 7, energy substitution, replacement of cement with fly ash and utilizing CDW as aggregates in concrete mix have created dramatic chance in terms of resource consumption.

A relative increase in energy consumption has been observed in Scenarios 4 and 6 due to the absence of energy substitution. In comparison to Scenario 2, not being used of RDF has resulted in an increase in energy use for Scenario 4 and Scenario 6 although the cement amounts are lower than the base scenario. Therefore, it can be revealed that the use of RDF is more important than replacement of cement with fly ash in terms of energy consumption for this case.

In comparison to Scenario 5, a relative increase in material resources has been observed for Scenario 6 and Scenario 7. Classification results have demonstrated that

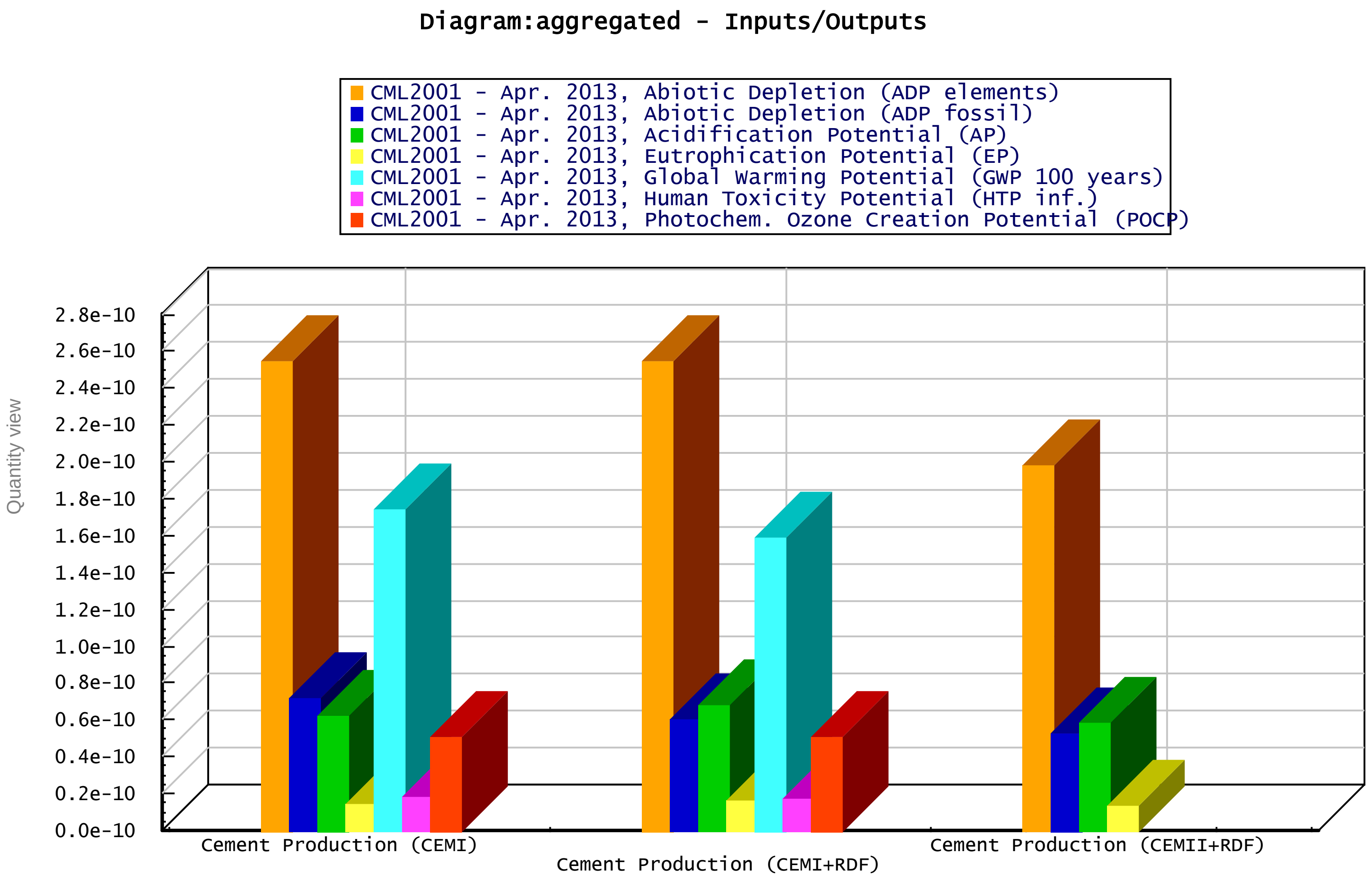


Figure 4.6. Normalization results for different cement production scenarios.

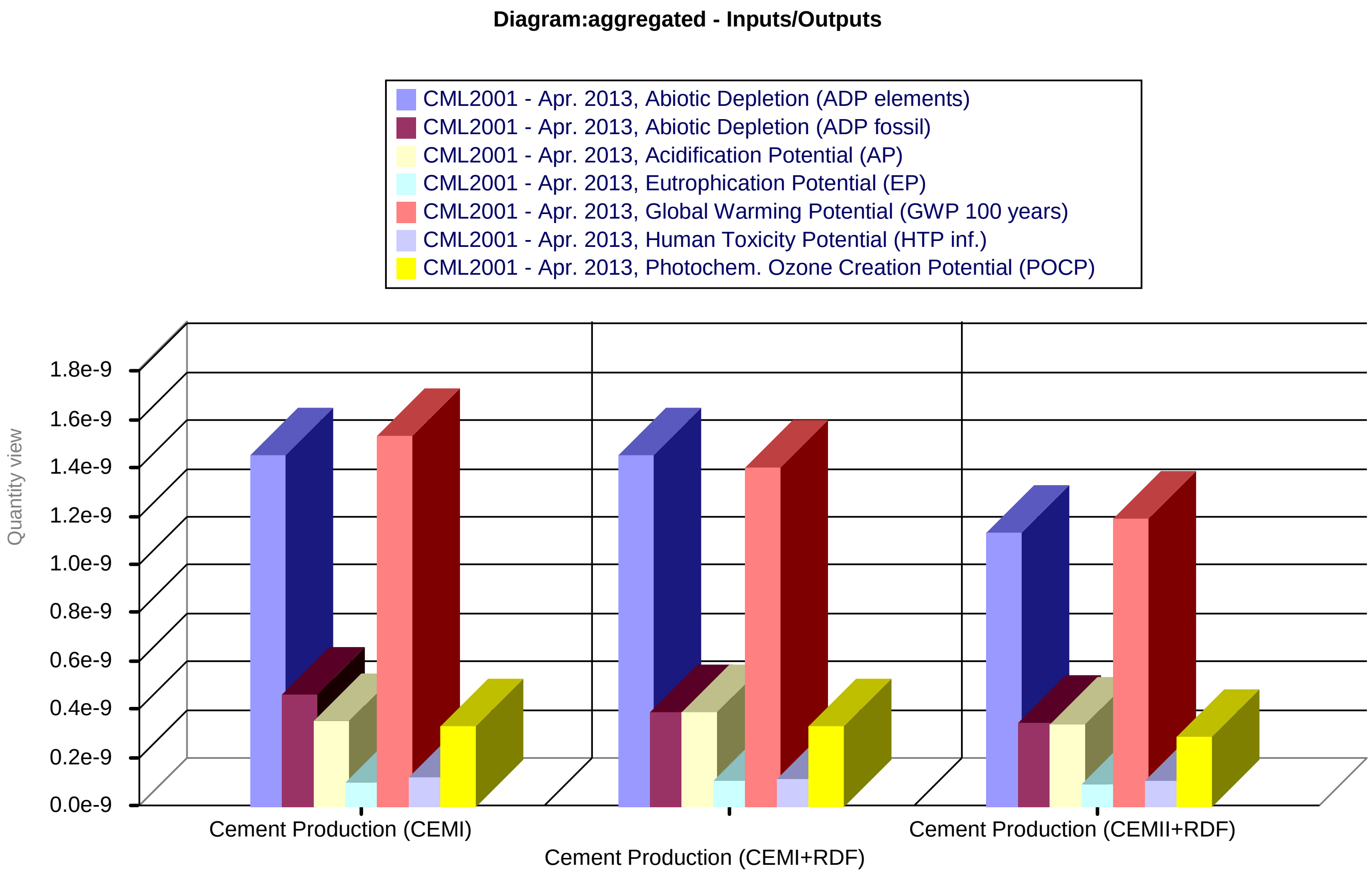


Figure 4.7. Weighting results for different cement production scenarios.

utilization of blast furnace slag is more efficient than utilizing fly ash in terms of resource conservation. On the other hand, it should be underlined that, fly ash has created a significant decrease in both material and energy consumption when it is compared to base scenario. Figure 4.8 and 4.9 shows the inventory results of resource consumption for each concrete production scenarios.

The main emission stream of concrete production is cement production. Therefore, the amount of cement and the energy substitution have been the main determining points of the emissions. Besides, all mixes having lower clinker content have resulted in a reduced carbon footprint than base scenario. Figure 4.10 illustrates the major emissions released to the air with respect to different concrete production scenarios.

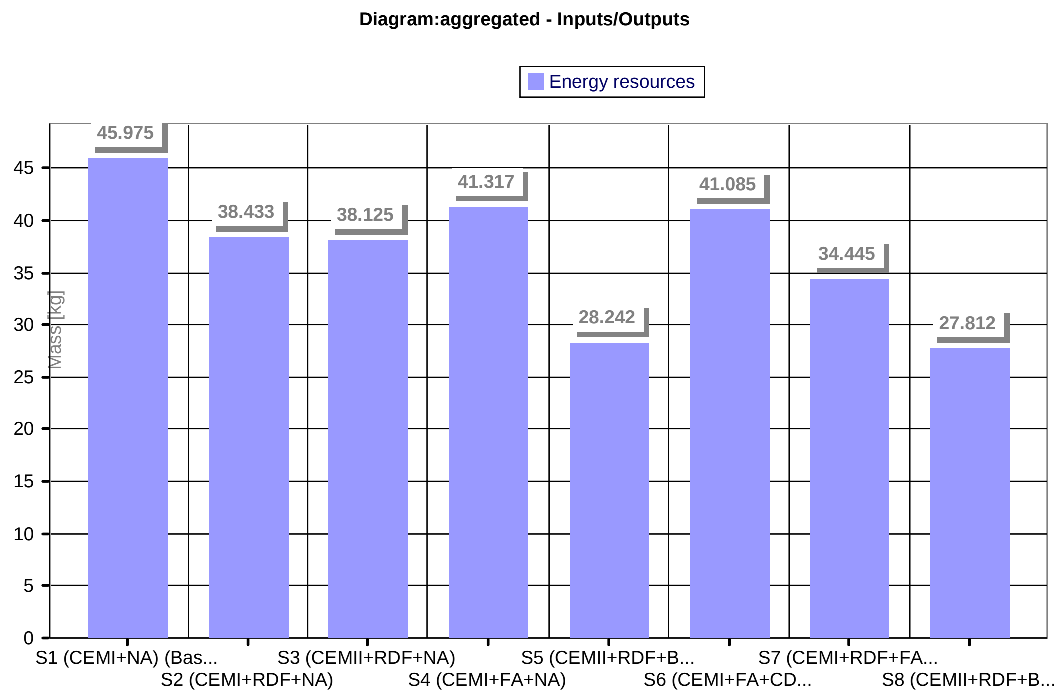


Figure 4.8. The energy resource use for each scenario (S1 – S8).

Special emphasis has been given to CO_2 emissions. Figure 4.12 demonstrates the change in CO_2 with respect to decrease in fossil fuel, clinker ratio in cement and cement ratio in concrete.

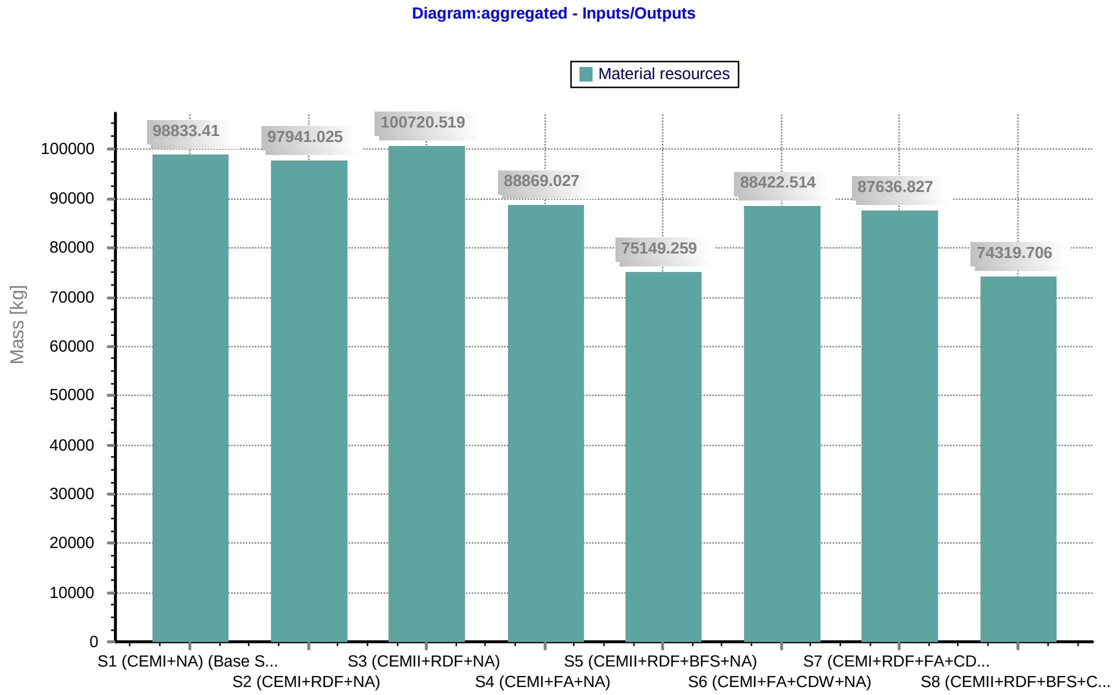
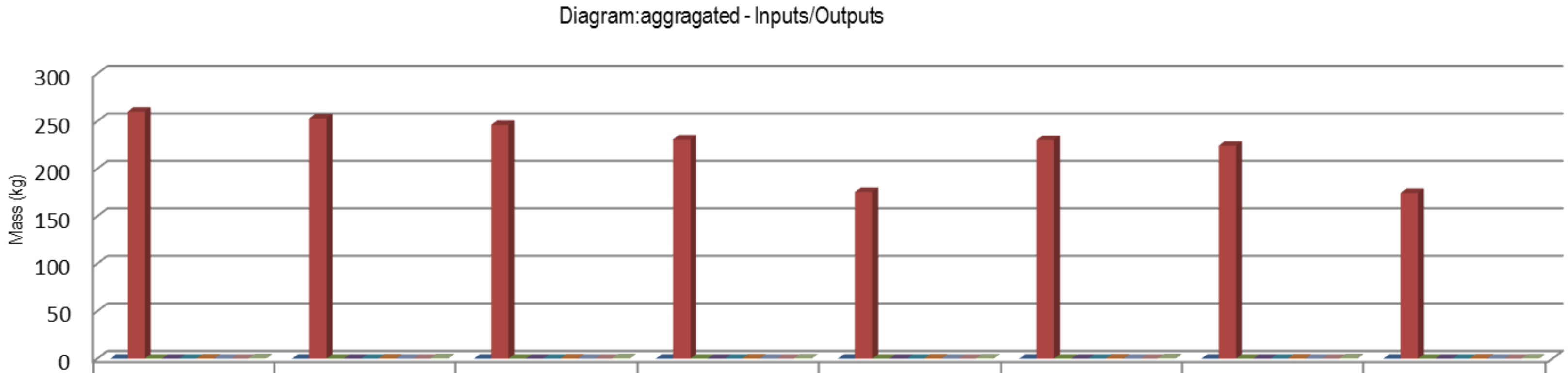


Figure 4.9. The material resource use for each scenario (S1 – S8).

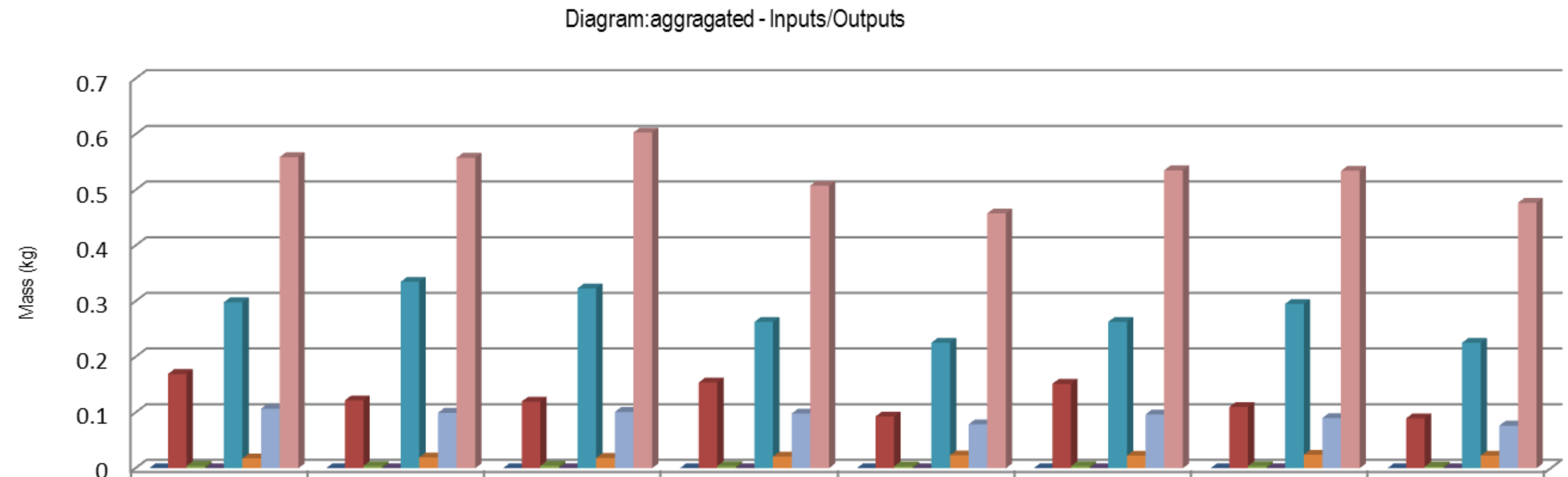
Decreasing the clinker to cement ratio makes significant reduction in CO_2 emissions as a result of calcination process when it is evaluated on a mass by mass basis. However, the amounts of limestone blended cement required for the same quality class of 1 m^3 concrete increases when clinker substitutes are used. Thus, the CO_2 savings gained through limestone blended cement decreases when it is used as concrete. On the other hand, limestone blended cement has created significant reduction in CO_2 levels when it is compared to the base scenario. The evaluation of the scenarios has resulted in up to 33% decrease in in CO_2 emissions.

4.1.2.2. Characterization Generated emissions and material use among the life cycle of 1 m^3 concrete production are calculated for all of the selected impact categories in the characterization. GaBi6 calculates the contribution of the emissions to each impact category and classifies the emissions into relevant categories. Table 4.5 summarizes the quantified LCA characterization results for Base Scenario-Scenario 1; the production of ready-mix concrete from ordinary Portland cement (CEM I) and natural aggregates, Scenario 2; the production of ready-mix concrete from ordinary Portland cement produced



	S1 (CEMI+NA) (Base Scenario)	S2 (CEMI+RDF+NA)	S3 (CEMII+RDF+NA)	S4 (CEMI+FA+NA)	S5 (CEMII+RDF+BFS+NA)	S6 (CEMI+FA+CDW+NA)	S7 (CEMII+RDF+FA+CDW+NA)	S8 (CEMII+RDF+BFS+CDW+NA)
Heavy metals to air	0.000298427	0.000295766	0.00031132	0.000308606	0.000289963	0.000274787	0.000272444	0.000228222
Carbon dioxide	260.0	253.1	246.2	230.9	175.4	230.4	224.4	174.4
Carbon monoxide	0.169	0.122	0.120	0.154	0.093	0.152	0.110	0.090
Hydrogen chloride	0.004141815	0.004111503	0.004282499	0.003913107	0.003414717	0.003748685	0.003721998	0.003110996
Hydrogen fluoride	0.000119006	0.000117544	0.000122007	0.00011314	9.95E-05	0.000107911	0.000106623	8.99E-05
Nitrogen dioxide	0.298	0.335	0.323	0.263	0.226	0.263	0.295	0.226
Nitrogen monoxide	0.018	0.020	0.019	0.021	0.023	0.023	0.024	0.023
VOC group	0.1071	0.0997	0.1013	0.0985	0.0791	0.0968	0.0903	0.0767
Particles to air	0.559	0.558	0.603	0.508	0.458	0.535	0.534	0.477

Figure 4.10. The major emissions released to the air for the scenarios S1-S8.



	S1 (CEMI+NA) (Base Scenario)	S2 (CEMI+RDF+NA)	S3 (CEMII+RDF+NA)	S4 (CEMI+FA+NA)	S5 (CEMII+RDF+BFS +NA)	S6 (CEMI+FA+CDW +NA)	S7 (CEMII+RDF+FA+ CDW+NA)	S8 (CEMII+RDF+BFS +CDW+NA)
Heavy metals to air	0.000298427	0.000295766	0.00031132	0.000308606	0.000289963	0.000274787	0.000272444	0.000228222
Carbon monoxide	0.169	0.122	0.120	0.154	0.093	0.152	0.110	0.090
Hydrogen chloride	0.004142	0.004112	0.004282	0.003913	0.003415	0.003749	0.003722	0.003111
Hydrogen fluoride	0.000119006	0.000117544	0.000122007	0.00011314	9.95E-05	0.000107911	0.000106623	8.99E-05
Nitrogen dioxide	0.298	0.335	0.323	0.263	0.226	0.263	0.295	0.226
Nitrogen monoxide	0.018	0.020	0.019	0.021	0.023	0.023	0.024	0.023
VOC group	0.1071	0.0997	0.1013	0.0985	0.0791	0.0968	0.0903	0.0767
Particles to air	0.559	0.558	0.603	0.508	0.458	0.535	0.534	0.477

Figure 4.11. The major emissions released to the air (S1-S8) (excl. CO_2).

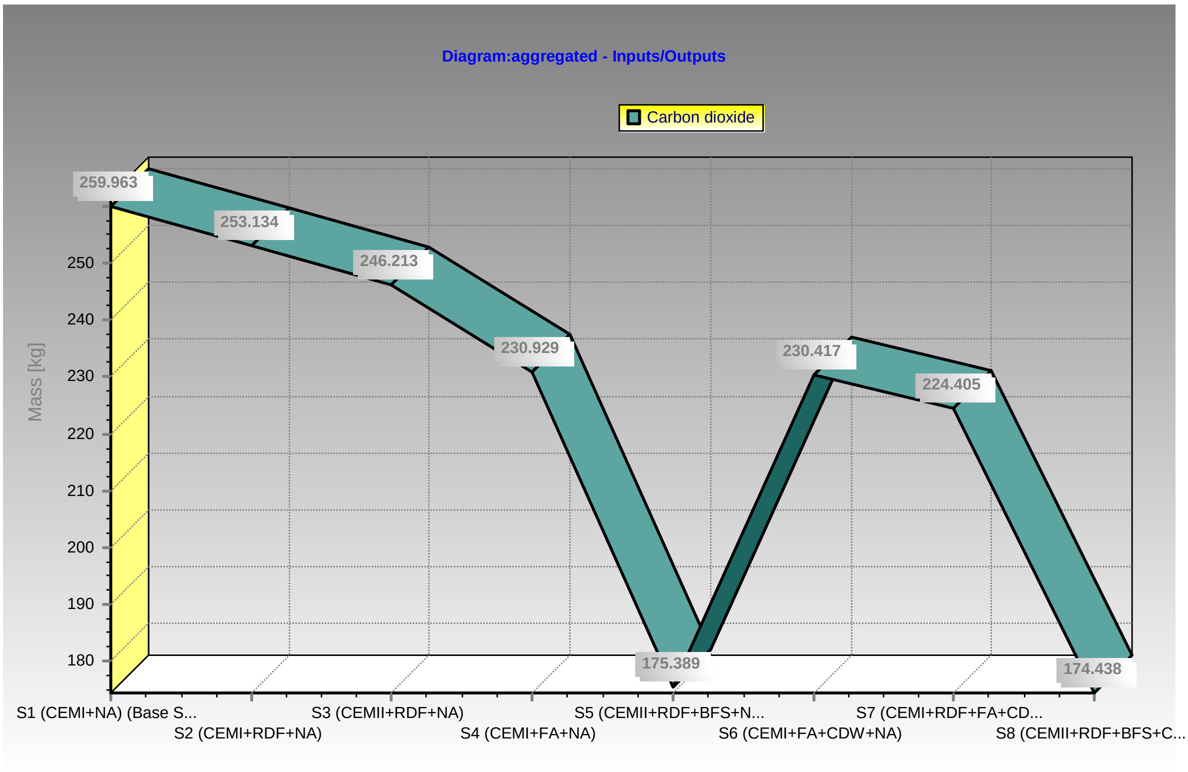


Figure 4.12. The change in CO_2 emissions.

by RDF supplement in fuel mix and natural aggregates, Scenario 3; the production of ready-mix concrete from blended cement (CEM II) produced by RDF supplement in fuel mix and natural aggregates, Scenario 4; the production of ready-mix concrete from ordinary Portland cement (CEM I) and utilizing fly ash and natural aggregates, Scenario 5; the production of ready-mix concrete from blended cement (CEM II) produced by RDF supplement and utilizing slag and natural aggregates, Scenario 6; the production of ready-mix concrete from ordinary Portland cement (CEM I) and utilizing construction and demolition waste as aggregates substitutes, fly ash for cement replacement and natural aggregates Scenario 7; the production of ready-mix concrete from ordinary Portland cement (CEM I) produced by RDF supplement and utilizing construction and demolition waste as aggregates substitutes, fly ash for cement replacement and natural aggregates and Scenario 8; the production of ready-mix concrete from blended cement (CEM II) produced by RDF supplement and utilizing construction and demolition waste as aggregates substitutes, blast furnace slag for cement replacement and natural aggregates. Characterization results are given in Table 4.5 and Figure 4.13.

Table 4.5. Environmental impacts of selected scenarios for concrete production.

Category	Unit	S1	S2	S3	S4	S5	S6	S7	S8
Abiotic Depletion (ADP elements)	kg Sb eq.	0.00045	0.00045	0.00040	0.00040	0.00029	0.00040	0.00039	0.00028
Abiotic Depletion (ADP fossil)	MJ	847.4	739.1	739.8	774.1	572.4	767.7	672.3	560.3
Acidification Potential (AP)	kg SO_2 eq	0.166	0.186	0.179	0.151	0.133	0.152	0.169	0.133
Eutrophication Potential (EP)	kg PO_4 eq.	0.042	0.047	0.046	0.038	0.034	0.039	0.043	0.034
Global Warming Potential (GWP 100 years)	kg CO_2 eq.	261.8	254.8	247.9	232.6	176.7	232.1	225.9	175.7
Human Toxicity Potential (HTP)	kg DCB eq.	5.514	5.378	5.561	5.461	4.950	5.055	4.936	4.186
Photochemical Oxidant Creation (POCP)	kg Ethane eq.	0.013	0.012	0.012	0.010	0.005	0.009	0.008	0.005

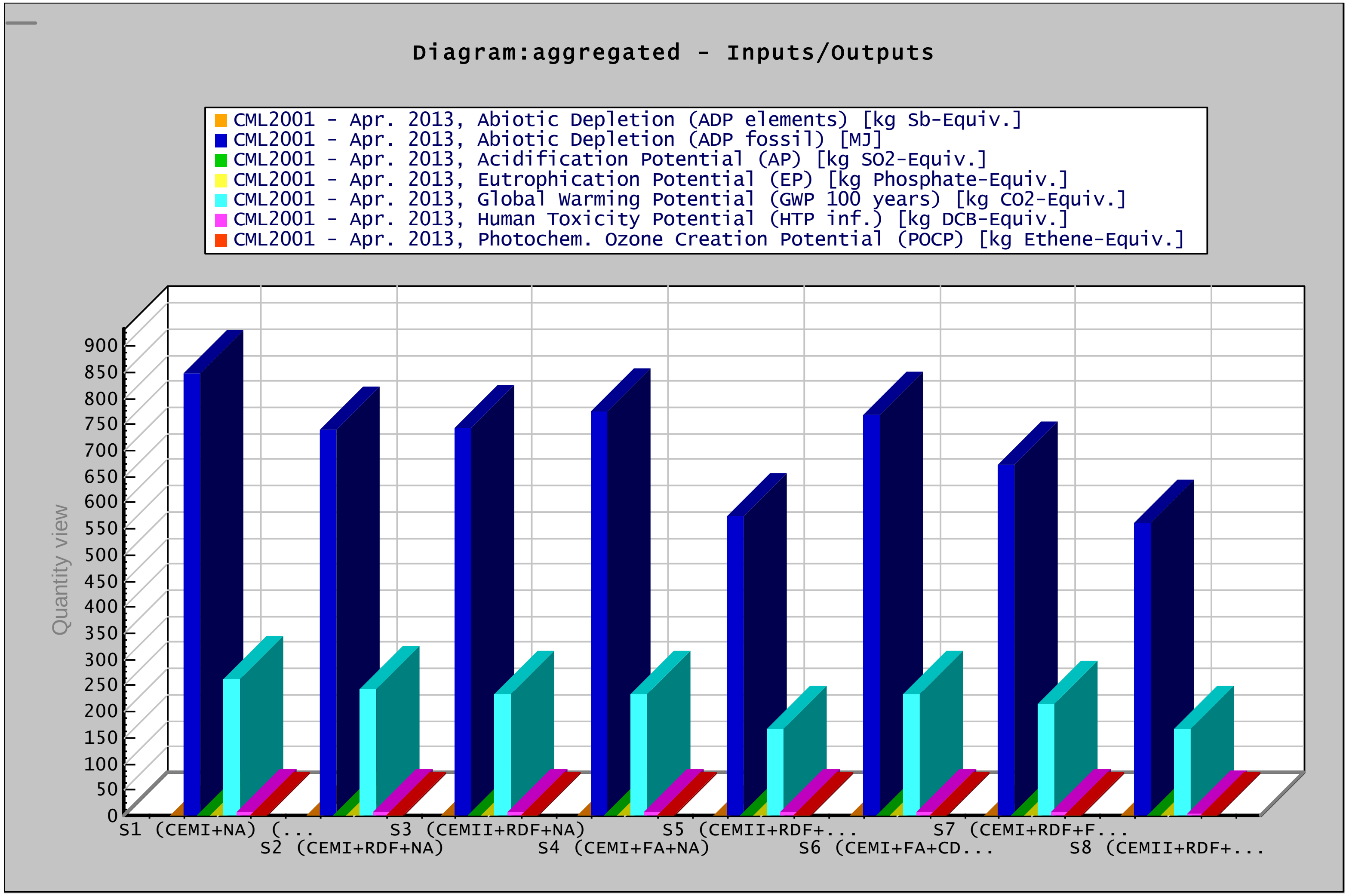


Figure 4.13. Characterization results of the scenarios S1 - S8.

The total GWP, ADP (elements and fossils), AP, EP, HTP and POPC for each of the concrete mixes involve direct and supply-chain emissions from all the quarrying, production, and transportation processes taking place in the system boundary. For comparison, Scenario 1 represents the base scenario which is the production of 1 m^3 concrete with 100% by weight of ordinary Portland cement (CEM I) and conventional fossil fuel use. Having a total of 260 kg of CO_2-eq, Scenario 1 has caused the highest amount of GWP. With the integrated approach of energy substitution by RDF, decreasing amount of Portland cement and increasing amount of SCM including limestone and blast furnace slag, GWP from 1 m^3 of concrete can be as low as 33% of the base scenario.

The impact of RDF can be summarized as 13% reduction in ADP fossils; 3% reduction in GWP, 3% reduction in HTP and 10% in reduction POCP; 12% increase in both AP and EP. The increase in AP and EP categories has occurred due to the increased level of NOx emissions generated from the chemical composition of RDF.

The reduction in clinker amount leads to additional savings in terms of ADP (elements) and GWP by 10% and 3%. In comparison to the base scenario, Scenario 3 contributes to environmental savings by 10%, 13%, 6% and 9% in ADP (elements), ADP (fossils), GWP and POCP respectively. However, more of the blended cement was required to perform an equivalent strength characteristic. Although the clinker content in CEM II-concrete (243 kg) is lower than the clinker content in CEM I-concrete (251 kg), the increased consumption of electricity due to the increased amount of CEM II has result in a 0.1% decrease in ADP (fossils) savings obtained through clinker substitutes. Gathering the two effects in brief, ADP (fossils) has given almost the same results for CEM I-concrete and CEM II- concrete. The increased amount of cement in concrete mix has also result in increase in AP and EP by 8%. HTP remains the same. GWP savings through clinker substitutes in concrete has declined in comparison to that of in cement because the eliminated clinker amount through substitutes has decreased. If the same amount of cement were used in both CEM I concrete and CEM II concrete, the eliminated amount would be 39 kg; however, for 1 m^3 of concrete it is 8 kg. On the other hand, it can be seen that environmental savings from clinker substitutes exceeds the savings from RDF supplement by about 3% in terms of GWP because of the decreased amount of clinker in concrete mix.

Considering that the main environmental problem about cement and concrete production is their contribution to GWP, it can be concluded that cements with lower clinker content is very favourable from a greenhouse gas emission perspective. Blended cements have low impacts due to less embodied energy and less embodied equivalent CO_2 emissions, in general. The substitution of 14% of clinker leads to reduce GWP of one cubic meter of concrete by around 7 kg CO_2-eq and when 21% of the energy input is substituted by RDF, the carbon footprint is then reduced by about 7 kg per one cubic meter of concrete. The total savings through Scenario 3 is then, 14 kg CO_2-eq.

Replacement of 1 kg of fly ash has resulted in reduction of GWP by 0.4 kg CO_2-eq. Fly ash used as 12% by weight replacements of cement decreases GWP by 11%, ADP (elements) by 10%, ADP (fossils) by 9%, AP by 9%, EP by 9% and POCP by 24%.

Replacement of 1 kg of blast furnace slag results in reduction of GWP by 0.7 kg CO_2-eq. Blast furnace slag used as 30% by weight replacements of cement has additional savings in terms of GWP, ADP (elements), ADP (fossil), AP, EP, HTP and POCP by 27%, 26%, 20%, 28%, 28%, 11% and 50%, respectively when it is compared with Scenario 3. In comparison to the base scenario, Scenario 5 decreases GWP by 33%; ADP (elements) by 36%; ADP (fossils) by 32%, AP by 20%; EP by 20%; HTP 10% and POCP by 59%.

In overall, 1 kg of clinker substitutes has reduced by 0.2 kg CO_2-eq and 1 kg RDF substitutes has reduced by 0.6 kg CO_2-eq while 1 kg of fly ash and blast furnace slag have reduced by 0.4 and 0.7 kg CO_2-eq, respectively. The decrease in savings from 1 kg of clinker substitutes in 1 m^3 of concrete in comparison to the savings in 1 ton of cement is due to the fact that the ratio of clinker substitutes in 1 m^3 of concrete is less than which of 1 ton of cement. Moreover, additional electricity consumption in parallel with the increase in cement portion in concrete mix leads such a reduction in environmental savings.

20% substitution of CDW has little contribution in terms of selected environmental impact categories except HTP because of the additional disposal activities. The environmental savings through CDW and the negative effect of disposal activities has nearly balanced the impacts. However, in HTP impact category, significant savings have been observed. The additional savings through CDW in terms of HTP are due to the additional dust emissions while extraction of aggregates. HTP has decreased by 14% when Scenario 5 and Scenario 8 are compared. Besides, 20% substitution of CDW has 2% contribution in terms of ADP (elements) and ADP (fossil). Moreover, it should be emphasized that utilization of CDW in concrete production has considerable contributions to waste and landscape management solutions. In Scenario 8; 128 kg of CDW and in Scenarios 6 and 7; 177 kg of CDW per cubic meters of concrete is avoided from landfilling.

The results revealed that concrete products with a 30% share of granulated blast furnace slag from the steel/iron industry had the best climate performance through decreasing GWP by 33%. The overall results shows that for a given performance measure, energy substitution by RDF, improvements in mix design as well as selection of materials make it possible to reduce GWP representing the CO_2 intensity of concrete mixes.

4.1.2.3. Normalization As it is mentioned before; normalization is a way to compare contribution of different environmental impact categories to the overall environmental problem. In this study, the normalization results indicate that ADP (elements), GWP and ADP (fossils) are the main contributors of environmental concerns.

Scenarios 5 and 8 represent the best performances considering the overall environmental impacts. The normalization results EU25+3, year 2000. CML, IPCC, ReCiPe (person equivalents) are illustrated in Figure 4.14.

Scenario 2 has provided 3% and 13% savings in GWP and ADP (fossils) respectively. ADP (elements) has stood the same. Scenario 3 has achieved 10%, 13% and 6% savings in ADP (elements), ADP (fossils) and GWP, respectively. However, AP has again increased with these options. Therefore, the chemical composition of RDF should be defined carefully in waste to energy systems.

In comparison to Scenarios 1 and 3, Scenario 4 and 5 demonstrate the additional improvements gained through decreasing cement content. In comparison to base scenario, Scenario 4 has provided 11%, 9% and 11% in ADP (elements), ADP (fossils) and GWP, respectively through the introduction of fly ash. Scenario 5 can be compared with Scenario

3 to illustrate the net savings gained through utilization of blast furnace slag. In terms of ADP (elements), ADP (fossils) and GWP; Scenario 5 achieves additional reduction by 26%, 19% and 27%, respectively in comparison to Scenario 3. Moreover, Scenarios 4 and 5 have performed better than both Scenarios 2 and 3 in all environmental impact categories.

The general pattern of environmental savings in Scenario 6 is highly similar to Scenario 4. In Scenario 6, 12% decrease in ADP (elements), 9% decrease in ADP (fossils) and 14% decrease in GWP have been observed.

Scenario 7 has been assessed as the third best scenario after Scenario 8 and Scenario 5 considering the overall environmental impacts. Scenario 7 has demonstrated 12%, 21% and 14% of reduction in ADP (elements), ADP (fossils) and GWP, respectively.

Scenario 8 has the best environmental performance. ADP (elements), ADP (fossils), and GWP have been decreased by 38%, 34% and 33%.

4.1.2.4. Weighting Weighting reflects the relative importance of different life cycle impact assessment categories. In this study, weighting results have been calculated for PE LCIA Survey 2012 (Europe; incl. CML 2013) and the most important environmental impact categories have been revealed as GWP, ADP (elements) and ADP (elements). Weighting results are illustrated in Figure 4.15.

In this study, weighting results of different concrete production scenarios have been similar to normalization results. The positive influence of the integrated approach for eco-designed concrete have been observed in terms of GWP, ADP (elements) and ADP (elements) which are the highest environmental impact categories according to weighting results. Considering GWP, Scenario 2 contributes by 3%, Scenario 3 contributes by 6%, Scenario 4 contributes by 11%, Scenario 5 contributes by 33%, Scenario 6 contributes by 12%, Scenario 7 contributes by 14% and Scenario 8 contributes by 33%. Considering ADP (elements), Scenario 3 contributes by 10%, Scenario 4 contributes by 11%, Scenario 5 contributes by 36%, Scenario 6 contributes by 12%, Scenario 7 contributes by 12% and Scenario 8 contributes by 38%. Scenario 2 has remained almost the same. Considering

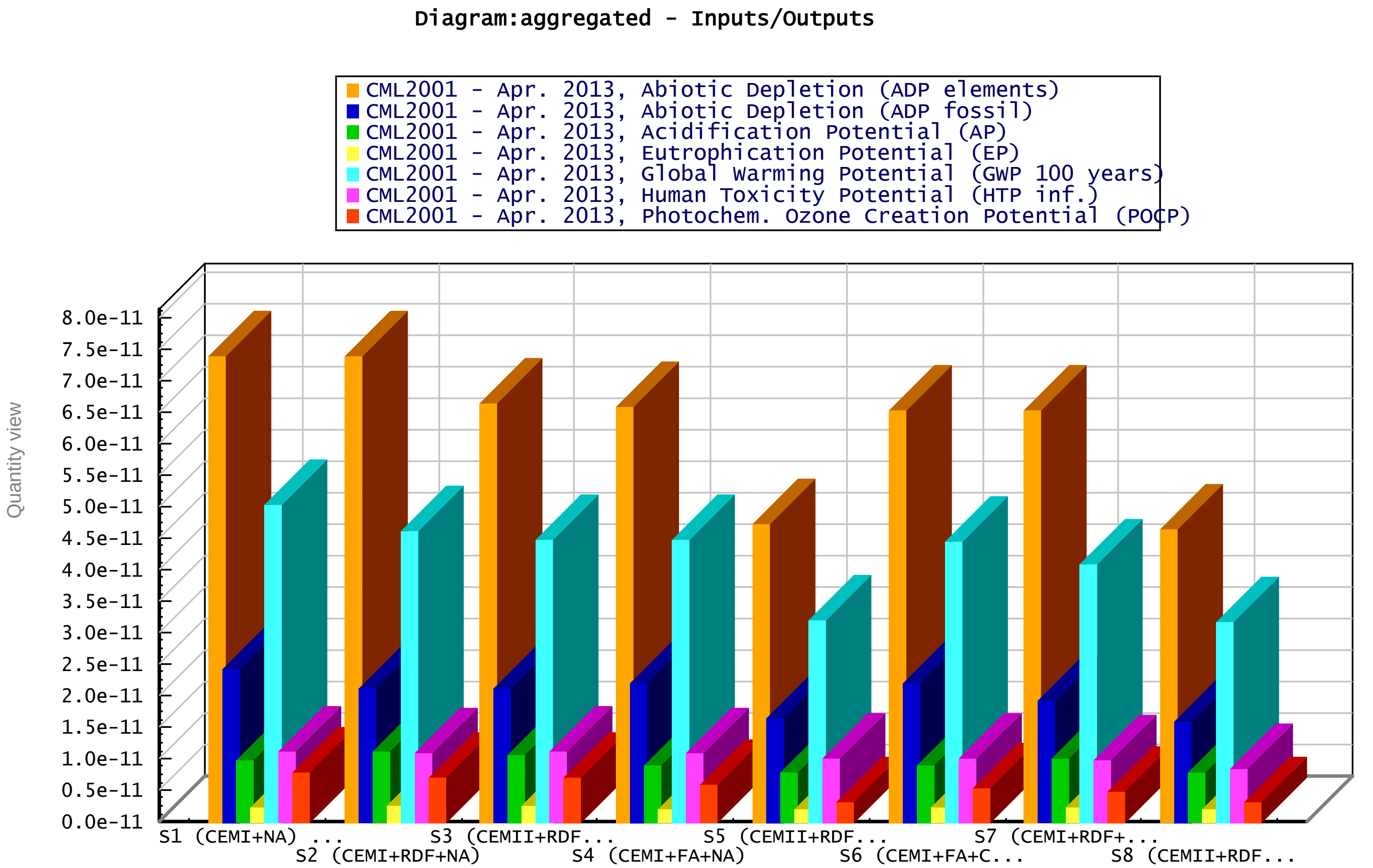


Figure 4.14. Normalization results of the scenarios S1 - S8.

ADP (fossils), Scenario 2 contributes by 13%, Scenario 3 contributes by 13%, Scenario 4 contributes by 9%, Scenario 5 contributes by 32%, Scenario 6 contributes by 9%, Scenario 7 contributes by 21% and Scenario 8 contributes by 34%.

Scenario 5 which represents the progressive impacts of clinker substitutes, RDF and reduction of cement amount in concrete mix performs almost the same as Scenario 8 which additionally contains CDW utilization.

Scenario 3, 4 and 6 have similar contribution in terms of GWP and ADP (elements). So, it means that the cumulative effect of clinker substitutes and RDF corresponds to the effect of fly ash as a cement replacement agent.

4.2.The Impact of Different Types of Cement Concrete on LEED Certification

Scenario 8 and Scenario 5 have the sharpest environmental savings among the life cycle scenarios of different cement and concrete production schemes. The evaluation of the eco-designed concretes from Scenario 8 in terms of LEED v4 green building rating system is summarized in Table 4.6. Totally, 10 credits can be obtained through the eco-designed concrete.

4.2.1. Materials and Resource

LEED material and resource category focuses on improving environmental performance and resource efficiency through the regional materials, reusing or recycling of major structural components and disposal of construction waste to minimize the embodied energy and other impacts.

The main idea of this category is to lower the life cycle impact of a building, to perform better than industry baselines in terms of source and composition of raw materials and to document it under environmental product declarations, corporate sustainability report or health product declarations. The total points can be gained within this category is calculated as 9 points.

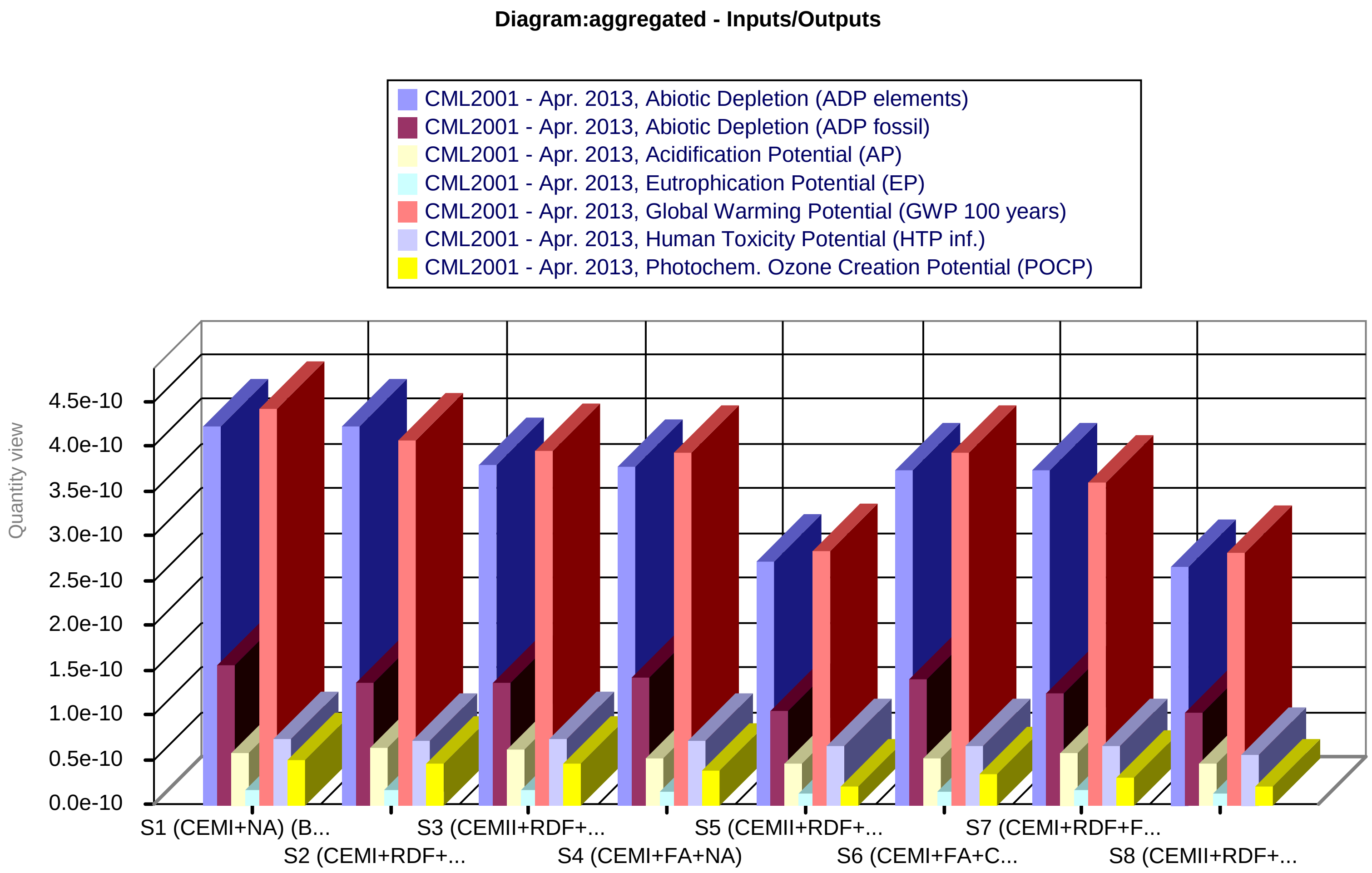


Figure 4.15. Weighting results of the scenarios S1 - S8.

4.2.1.1. Building Impact Reduction. Due to the fact that concrete that have been produced under these schemes enables to lower the life cycle impact of a building, 3 points can be gained through whole-building life-cycle assessment. The eco-designed concrete achieved 38%, 34%, 33%, 20%, 20%, 24% and 59% reduction in ADP (elements), ADP (fossils), GWP, AP, EP, HTP and POCP impact categories, respectively. However, for a precise evaluation, the decrement in GWP, ADP (elements), ADP (fossils), AP, EP and POCP of the relevant building in which eco-designed concrete is used, should be calculated via LCA methodology.

4.2.1.2. Building Product Disclosure and Optimization –Environmental Product Declarations. For disclosure option, it is required to use 20 permanently installed products that disclose impacts using environmental product declarations, corporate sustainability report or health product declarations. Since In LEED v4, concrete products with a unique mix design such as foundations walls, shear walls, bearing walls, columns, beams and slabs are considered to be different products; eco-designed concrete contribute significantly to the 20 required products. 1 point for disclosure option can be obtained if published EPDs are available.

4.2.1.3. Building Product Disclosure and Optimization – Sourcing of Raw Materials. One of the optimization options for obtaining is to 1 point from this category is that all products in the building have demonstrated 25% improvements by cost over base line products in the sourcing of raw materials. Eco-designed concrete from Scenario 8 can contribute to the Recycled Content pathway among the other pathways proposed for meeting this option because Scenario 8 concrete contains blast furnace slag and CDW as recycled materials such as fly ash and slag and in some cases recycled aggregate. Besides, concretes from Scenarios 4, 5, 6 and 7 has also opportunity to contribute this option because of the fly ash, blast furnace slag and CDW contents as recycling material.

Another optimization options for this credit which rewards 1 point is leadership extraction practices. A certain minimum value of building products that performs better than industry baselines for environmental, social and health impacts enables this optimization credit. The value of such products sourced (extracted, manufactured, and purchased) within 160 km of the project site is doubled of their base contributing cost.

Eco-designed concrete performs better than ordinary concrete in all impact categories according to LCA results. In addition concrete is generally manufactured and extracted locally, within 160 km of the site. Therefore, eco-designed concrete can contribute significantly to this option.

4.2.1.4. Building Product Disclosure and Optimization – Material Ingredients. One of the options for meeting this credit requirement is to demonstrate improved life-cycle impacts by optimizing material ingredient chemistry. Concrete is highly low-emitting material which has also one of the lowest levels of VOCs when compared to other commonly used building materials. Besides, the eco-designed concrete achieves 29% reduction in VOC emissions. Therefore, it can likely obtain 1 point from this credit.

4.2.1.5. Construction and Demolition Waste. The eco-designed concrete utilizes CDW in its composition and CDW is avoided from unnecessary landfilling. CDW that is diverted from landfills by recycling into the eco-designed concrete as aggregates can contribute to this credit category if the total weight and volume of waste (returned or unused concrete) diverted from landfills and provide details of how the waste was recycled are stated and delivered to the authorities. 1 point is obtained if 50% of the construction, demolition and land clearing waste are recycled or salvaged, 2 points if 75% is diverted.

4.2.2. Innovation (IN)

Since LEED certification system points out that the increase content of industrial by-products lower both carbon footprint and demand of natural resources, 21% RDF as fuel supplement, 23% clinker substitutes including 4% industrial waste, 12% fly ash and 30% blast furnace slag content for cement replacement and 20% CDW as recycled aggregates can provide innovation credit for eco-designed concrete alternatives.

A decrease in embodied CO_2 in concrete by 40% over typical mixes is one of the pathways in for gaining a LEED point in the Innovation credit category. The eco-designed concrete resulting in 33% reduction in terms of CO_2 emissions has almost accomplished this criterion.

Table 4.6. The eco-designed concretes' contribution to LEED v4.

ECO-DESIGNED CONCRETE (SCENARIO 8)			
Material & Resources		**Total: 13 Points**	**Available: 8 Points**
Prereq.	Storage and collection of recyclables	Required	Out of scope
Prereq.	Construction and demolition waste management planning	Required	Should be considered
Credit	Building life-cycle impact reduction	5	Possible 3 points[1]
Credit	Building product disclosure and optimization - environmental product declarations	2	Possible 1 point[2]
Credit	Building product disclosure and optimization - sourcing of raw materials	2	Possible 2 points[2, 3]
Credit	Building product disclosure and optimization - material ingredients	2	Possible 1 point[2, 4]
Credit	Construction and demolition waste management	2	Possible 1 point
Innovation		**Total: 6 Points**	**Available: 1 Point**
Credit	Innovation	5	Possible 1 point
Credit	LEED accredited professional	1	Out of scope

[1] This credit can be achieved by whole-building life-cycle assessment.

[2] It is required to use 20 permanently installed products that disclose impacts using environmental product declarations, corporate sustainability report or health product declarations.

[3] Total improvement of the all building materials should demonstrate 25% improvement by cost over base line products in the sourcing of raw materials to achieve this credit. Due to the concrete's wide range of applications or functions, it can contribute significantly to this credit score.

[4] Third-party verified corporate sustainability reports (CSR) which include environmental impacts of extraction operations and activities associated with the manufacturer's product and the product's supply chain, are valued as one whole product for credit achievement calculation.

5. CONCLUSIONS

Concrete is a common construction material which has an efficient thermal insulation. However, required high amounts of natural resource and energy for concrete production should be reduced by means of eco-designed concrete.

Concrete manufacturing process consists of two main stages which are cement production and concrete mixing. The environmental load of the concrete manufacturing originates from cement production. Cement production can be divided into three main stages including raw material preparation, clinker processing and finish grinding. Electrical energy usage is allocated into raw materials preparation and finish grinding while thermal energy is engaged in clinker production.

This study focused on the possible improvements concerning the environmental impacts of the cement and concrete production while protecting the required mechanical and durability properties. Additionally, special emphasize has been given to CO_2 reduction in cement and concrete production. It should be underlined that choosing best mode of production requires a multi-dimensional focus. To be able to compare different production scenarios, LCA methodology has been applied. The results from LCIA have indicated that clinker substitutes, co-processing of waste-derived fuels, decreasing cement ratio by SCMs in concrete and replacement of aggregates by CDW reduces the environmental footprint of 1 m^3 of concrete by creating significant reduction in resource and emissions intensity.

GWP results have brought out that decreasing clinker factor by blending limestone and utilizing ceramic waste as clinker substitutes, and co-processing of waste-derived fuels reduce the carbon footprint of a ton of cement significantly. The results favor blended cement (CEM II) between these options because the clinker factor has exceeded RDF supplement in terms of GWP and ADP (elements) which are assessed as the most important aspects of environmental damage according to the weighting results. 1 kg of clinker substitutes has decreased GWP by 0.9 kg CO_2-eq/t-cement and 1 kg of RDF substitutes has decreased GWP by 0.6 kg CO_2-eq/t-cement. Through RDF supplement, 43 kg of waste which replaces 33 kg of fossil fuel is avoided from landfilling. Besides, further investigations may focus on waste to energy systems, replacement of non-carbon neutral waste derived fuels by alternative carbon neutral biomass in fuel mix in order to bring an additional savings in terms of GWP.

Decreasing clinker ratio in cement has significant contribution to all impact categories in an environmental friendly manner. However, the evaluation of CEM I-concrete and CEM II-concrete have revealed the similar ADP (fossils) because the increased mass of CEM II in concrete mix has brought additional electricity consumption. If CEM I or CEM II is subjected to concrete production, then, RDF supplement has performed similar to clinker substitutes in concrete mix. Both of them lead to 7 kg of CO_2-eq reduction in GWP. It should be noted that the contribution of clinker substitutes are much more significant when the evaluation has been preceded on a mass by mass basis. Clinker substitutes have decreased 131 kg CO_2-eq while RDF supplement has decreased 25 kg CO_2-eq.

In Scenario 5 and Scenario 8, dramatic changes in environmental friendly manner have occurred in terms of all impact categories, especially in GWP, ADP (elements), ADP (fossils) and POCP because the decreased amount of cement has contributed significantly to these categories. The third best scenario that benefits the environment in terms of GWP, ADP (fossil), HTP and POCP has been the combination of RDF supplement and decreasing cement content by fly ash addition although AP and EP have increased by 2% because of the significant savings in terms of GWP and ADP (fossils). The results also indicated that the use of RDF has performed better than replacement of cement with fly ash in terms of ADP (fossils) and HTP while replacement of cement with fly ash has left behind RDF supplement in terms of all other environmental impact categories including GWP, ADP (elements), AP, EP and POCP. 1kg of clinker substitutes has decreased GWP by 0.2 kg CO_2-eq/m^3-concrete, 1 kg of RDF substitutes has decreased GWP by 0.6 kg CO_2-eq/m^3-concrete, 1 kg of FA has decreased GWP by 0.4 kg CO_2-eq/m^3-concrete, 1 kg of BFS has decreased GWP by 0.7 kg CO_2-eq/m^3-concrete. Having an amorphous structure and high hydraulicity, blast furnace slag partially substitutes the CaO consumption and decreases the calcination of $CaCO_3$. As a result, it reduces the CO_2 emissions and accordingly GWP.

The impacts of CDW use instead of natural aggregates have been evaluated by comparing Scenario 5 and Scenario 8. 20% substitution of CDW has 2% contribution in terms of ADP (elements) and ADP (fossil). The reduction in HTP is 14% and the other environmental impact categories have remained the same. When Scenario 4 and Scenario 6 are compared, similar trends in changes have been observed. The additional disposal activities and transportation avoids more significant savings. In Scenario 8; 128 kg of CDW and in Scenarios 6 and 7; 177 kg of CDW per cubic meters of concrete is avoided from landfilling.

Overall, In GWP and ADP (fossil) categories, Scenario 2 contributes by 3% and 13%. In GWP, ADP (elements) and ADP (fossil) categories, Scenario 3 contributes by 6%, 10% and 13%; Scenario 4 contributes by 11%, 11% and 9%; Scenario 5 contributes by 33%, 36% and 32%; Scenario 6 contributes by 12%, 12% and 9%; Scenario 7 contributes by 14%, 12% and 21%; and Scenario 8 contributes by 33%, 38% and 34%. In addition to the LCA results, the study has illustrated the avoided landfilling and decrease -even if it is not much- in ADP elements and fossil by means of CDW utilization.

The impact of the best performed scenarios has also been assessed in terms of LEED v4 certification system for new constructions and major renovations. The eco-designed concrete can contribute up to 9 credits for LEED certification system by improving the life cycle environmental performance. In addition, the eco-designed concrete may lower the life cycle impact of a building and performs better than industry baselines in terms of source and composition of raw materials. Besides, concrete is generally manufactured and extracted locally which will bring additional points. Further studies should be made (i) to clarify the share of the eco-designed concrete's life cycle impact among the whole building and (ii) to have deeper understanding of eco-desined concrete's contribution to location & transportation, sustainable sites, water efficiency, energy & atmosphere, indoor environmental quality, integrative process, and regional priority credits.

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