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Life cycle assessment of a cement plant in Naypyitaw, Myanmar

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ABSTRACT

Cement production accounts for about 5% of the total anthropogenic CO_2 emissions and 12–15% of the global energy use from the industrial sector. The impact on climate change and natural resource depletion are among the key concerns of the cement industry. Cement demand has been growing rapidly in many developing countries due to a booming construction sector spurred by rapid urbanization. Myanmar is one of these countries and has started to privatize its cement industry to meet the growing domestic demand. This study aims to assess the environmental impacts of Ordinary Portland Cement (OPC) production in Myanmar using Life Cycle Assessment (LCA) for the Max Myanmar Cement Plant in Naypyitaw. The LCA examines the entire cement production chain, using two alternative scenarios for fuel substitution. The results suggest that conventional cement production has adverse environmental impacts, with the calcination stage being responsible for most impacts. Calcination accounts for 89%, 95% and 97% of the effect for the climate change, acidification, and eutrophication impact categories respectively. Fuel switching from the coal dominating mix to 100% natural gas can decrease environmental impacts for most mid-point impact categories, such as climate change (68% reduction), acidification potential (83% reduction), and eutrophication potential (96% reduction).

1. Introduction

Cement is one of the most widely used and produced construction materials globally (Worrell et al., 2001; WBCSD, 2009). Even though cement production increased significantly between 2010 and 2014 (from 3280 Mt to 4290 Mt), it has remained relatively stable since then (4100 Mt in 2019) (IEA, 2020). However, cement production is projected to increase globally to 4682 Mt yr^{-1} in 2050 (IEA, 2018). Rapid urbanization drives cement production in many parts of the world, and most notably in developing countries (Chen et al., 2014). As a result, cement manufacturing has become a focal point of ongoing efforts to develop sustainable construction materials to enhance urban sustainability (WBCSD, 2009; Imbabi et al., 2013; Pacheco-Torgal et al., 2014).

Cement production is very energy-intensive, requiring large amounts of fossil fuels for the decomposition of limestone to calcium oxide (Worrell et al., 2001; Wang et al., 2009; Ali et al., 2011). According to Summerbell et al. (2016), the cement industry contributes to about 5% of the total anthropogenic CO_2 emissions and accounts for 12–15% of the global energy use from the industrial sector (Aranda-Usón et al., 2012). Coal is a commonly used fuel for calcination in many countries (especially developing countries) but emits large amounts of greenhouse gases (GHGs). Overall, the calcination process contributes as much as 50% of the total CO_2 emissions from cement production, with the rest coming from fuel combustion in the kiln (Nadal et al., 2009; Feiz et al., 2015; Cao et al., 2016). The amount of clinker used (i.e., the main ingredient in cement production) is proportional to the CO_2 emissions. For example, as the clinker to cement ratio increased at an average rate of 1.6% annually (from 2014 to 2018), there was a proportional increase in direct CO_2 emissions (IEA, 2020).

Besides GHG emissions, cement production emits many other atmospheric pollutants (especially due to coal use) such as carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matter (PM), among others (Humphreys and Mahasenan, 2002; Ali et al., 2011; Karagiannidis, 2012; Schorcht et al., 2013). The mining of raw materials

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also causes natural resource depletion (Phair, 2006), land degradation (Al-Dadi et al., 2014), and air pollution (Josa et al., 2007).

Many studies have assessed the environmental impacts of cement production, but they have been rather different in terms of methods, system boundaries, environmental impacts, and variables (e.g., the composition of raw materials, types of technology, and fuels) (Martos and Schoenberger, 2014). Life Cycle Assessment (LCA) is one of the most widely used methods for assessing the environmental impacts of cement production (Huntzinger and Eatmon, 2009; Boesch and Hellweg, 2010; Lu, 2010; Amrina and Vilsi, 2015). LCA studies have compared the environmental impacts of cement production across different types of cement (Boughrara, 2014; Feiz et al., 2015) and production stage (Gracia-Gusano et al., 2015). Many LCA studies modeled different scenarios for substituting raw materials and fuels, as a means of reducing the adverse environmental impacts of cement production (Hong and Li, 2011; Strazza et al., 2011; Aranda-Uson et al., 2012; Gracia-Gusano et al., 2015), or identifying the best available technology (Valderrama et al., 2012). However, it is relatively difficult to make complete comparisons between LCA studies due to their different functional units and impact assessment methods (e.g., Josa et al., 2004; Huntzinger and Eatmon, 2009; Chen et al., 2010; Aranda-Uson et al., 2012; Valderrama et al., 2012) (see Section 4).

Myanmar is one of the developing countries where accelerated urbanization (WBG, 2019a) goes in tandem with a booming cement industry spurred by infrastructure development. In 2014–2015, the construction sector grew by 8%, with a simultaneous increase in the demand for building materials (WBG, 2015), including cement (Fig. S1, Supplementary Electronic Material). With approximately 40% of Myanmar's cement demand being met through imports (WBG, 2019b), the national government started privatizing cement plants under the Ministry of Industry in 2013 to boost domestic production (WBG, 2015). It was expected that the high sustained cement demand for the development of special economic zones, housing, and commercial buildings will push national cement production to as high as 12 Mt in 2030 (IPSOS, 2013).

Even though the use of emission reduction techniques and alternative materials in cement production has been rather advanced in developed countries, Myanmar still follows conventional manufacturing processes, which involve the mining/quarrying of raw materials (e.g., limestone, clay), raw meal preparation, calcination (clinker production), and finally cement preparation (see section 2.1). Portland cement (which consists of 95% clinker) accounts for most of the domestic production using coal and natural gas as fuels for the calcination process (ADB, 2015). Due to the expansion of cement production (Fig. S1, Supplementary Electronic Material), the cement industry has become the second largest domestic consumer of coal, accounting for 69% of coal consumption in the industrial sector in 2013–14 (NEMC, 2015; ADB, 2016) (Fig. S2, Supplementary Electronic Material).

The above implies that cement production is likely to have significant negative environmental impacts in Myanmar, which are likely to further increase alongside the expanding cement production. However, with a few exceptions (Tun et al., 2020), there is a lack of robust scientific studies about the environmental impacts of cement production in Myanmar. Such evidence gaps need to be bridged in order to understand better the environmental impacts of cement production across its different stages, as well as to optimize the use of raw materials and energy to mitigate these impacts.

This paper aims to (a) assess the environmental impacts of cement production in Myanmar using LCA and (b) identify possible options to mitigate these impacts. The focus of the analysis is the cement plant of the Max Myanmar Company located in Lewe Township, Naypyitaw. The study considers both process and energy-related emissions. Apart from the assessment of the environmental impacts of current cement production practices (which is a rather underexplored topic in Myanmar), an original aspect of the study is the modelling of two scenarios emphasizing fuel use during the calcination process to identify possible mitigation options (Section 2.5). This is because natural gas use has significantly lower GHG and air pollutant emissions compared to coal, with studies suggesting that a switch from coal to natural gas in calcination kilns could help in mitigating the environmental impacts of cement production (Wilson and Staffel, 2018). This also reflects studies arguing that fossil fuel substitution will be the safest mitigation option in cement manufacturing, as the use of alternative materials directly relates to cement type and strength, both of which depend on the market demand (Garcia-Gusano et al., 2015), which is currently geared towards conventional cement options in Myanmar (ADB, 2015).

Section 2 outlines the adopted methods, underlying data, and scenarios. Section 3 presents the main results across a series of environmental impacts and energy use scenarios. Section 4 discusses the outputs of this LCA alongside other studies (Section 4.1) and identifies possible implications and recommendations for enhancing the sustainability of cement production in Myanmar (Section 4.2).

2. Material and methods

In accordance with the ISO 14040 standard (ISO, 2006), we followed the four major stages of LCAs, namely: (a) goal and scope definition, (b) life cycle inventory (LCI), (c) life cycle impact assessment (LCIA), and (d) interpretation and communication of the main results. Although, the actual methodological approaches of LCAs vary according to the technology and raw materials used in cement production (Van Oss and Padovani, 2002, 2003), the entire cement production process follows four basic steps, namely raw material extraction, raw meal preparation, calcination, and cement production. Section 2.1 explains the detailed process of cement production. Section 2.2 defines the system boundary and scope of this study. Section 2.3 outlines the collection of input/output data within the system boundary. Section 2.4 analyzes the inventory and assesses the environmental impacts over the entire cement production chain. Section 2.5 highlights the alternative scenarios for energy use during the calcination stage to facilitate the comparison of the impacts of different fuels.

2.1. Cement production process

The first stage of cement production is the extraction of raw materials from quarries and their transportation to cement plants. The raw materials, namely limestone, clay, laterite, and gypsum are quarried in their respective mining areas and transported to the cement plant through different means depending on the context (e.g. a conveyor belt, truck, boat, train). The raw materials extraction involves the use of explosives for mining. Diesel used by heavy machinery and trucks is the main energy input for drilling, crushing, and transportation of the raw material extraction.

The second stage involves the preparation of the raw meal. The mined limestone is usually crushed in two stages, first with a jaw crusher and then by a hammer crusher to reduce the particle size to about 25 mm. Clay and laterite are grounded with impact crushers before mixing with limestone. Then all raw materials (i.e., limestone, clay, and laterite) are fed to the raw mill at required proportions and milled to a mixture called ‘raw meal’. This mixture is dried in cyclone separators using the hot gas released from the kiln. At this stage, the coarse particles are also channeled back to the raw mill for grinding, and the fine particles are conveyed to the raw mill silo for blending and storage. Electricity is the main energy used during the raw meal preparation stage.

The third stage consists of the calcination process, which requires the use of large amounts of energy in lime kilns. Depending on cement type, the mixture of raw materials is grounded and exposed to a high temperature within the kiln to form the clinker through a chemical reaction. There are different types of kilns such as shaft kilns, wet rotary kilns, semi-wet rotary kilns, new suspension pre-heater, and pre-calciner kilns (Pardo et al., 2011). Currently, the most common method is the dry process with preheater and pre-calciner kiln (IEA, 2018), which consumes a relatively lower amount of energy compared to the wet process.

Before entering the kiln, the raw meal is fed to preheater cyclones for drying and partial calcination. The hot air from the kiln is passed to the pre-heater for drying through bottom-up processes. The water content is first reduced and about one-third of the raw meal's weight is lost through the formation of oxides and CO_2 release in the atmosphere. Approximately 60–65% of the primary calcination takes place in the pre-calciner utilizing almost 40% of the fuel energy. Kilns usually use coal and natural gas fuel mixes, heating the raw meal to about 1400–1500 °C. This stage is not only the most energy-intensive throughout the cement production process, but also the highest GHG-emitting one. After leaving the kiln, the hot clinker is cooled down in air quenching coolers (AQC), which also serve to recover and channel the heat to the pre-heater and cyclone separators.

The fourth (and final) stage, blends the clinker with gypsum, and then grounds the mixture at the cement mill (IEA, 2018). The Ordinary Portland Cement (OPC) usually consists of 95% clinker and 5% gypsum (Cankaya and Pekey, 2015). The mixture eventually leaving the cement mill is a grey fine powder, which is stored in silos before being supplied to the market in bags or bulk-loaded trucks.

Currently, the Max Myanmar Cement Plant, which is the focus of this study, produces Ordinary Portland Cement (OPC) following the process outlined above. It has a capacity of 2100 t d^{-1} and uses electricity from a 13 KV national grid line, which is sourced from hydropower. The plant uses limestone and other raw materials extracted from nearby quarries and transported by trucks. The fuel mix for thermal energy in the kiln consists of 90% coal and 10% natural gas, but according to the plant personnel, there is scope for fuel switch considering fuel availability and environmental concerns (Section 2.5).

2.2. *Goal and scope definition*

As outlined in Section 1, the goal of this LCA is to evaluate the environmental performance of cement production in the Max Myanmar Cement Plant, and model two scenarios for the fuel used in the calcination stage. In determining the system boundaries, LCAs should consider the entire life cycle of products/services, starting from the acquisition of raw materials to waste disposal ('cradle to grave' approach). However, it is practically challenging to consider all stages if a product has various applications in its final use stage. Thus, many cement production LCAs follow the 'cradle to gate' or the 'gate to gate' approach (Josa et al., 2004; Cankaya and Pekey, 2015), which considers the stages between raw material extraction and product manufacturing or product transformation respectively. Due to the various applications of cement, most of the relevant LCAs follow a 'cradle to gate' approach.

Hence, this study also adopted the 'cradle to gate' approach, examining the four major stages (Section 2.1). Fig. 1 shows the main inputs and outputs of each stage, specifying the system boundaries. The consumption and disposal of cement (e.g., kiln dust as construction material) were not considered in this study. The functional unit was 1 tonne of OPC, while cement infrastructure (i.e., buildings, plant, and equipment) and energy and water consumption for office operation was beyond the scope of the analysis.

2.3. *Life cycle inventory*

The development of a life cycle inventory involves the quantification and compilation of all data related to the inputs, outputs, energy use, and generated waste to produce a functional unit of the product within the investigated system boundary (Gursel et al., 2014). Following the system boundary outlined in Section 2.2, we collected the data about raw materials, energy, and fuel use on-site at the Max Myanmar Cement Plant. This was achieved through multiple interviews with key personnel who provided the necessary information in February and September 2018. The secondary data was obtained from the Ecoinvent database

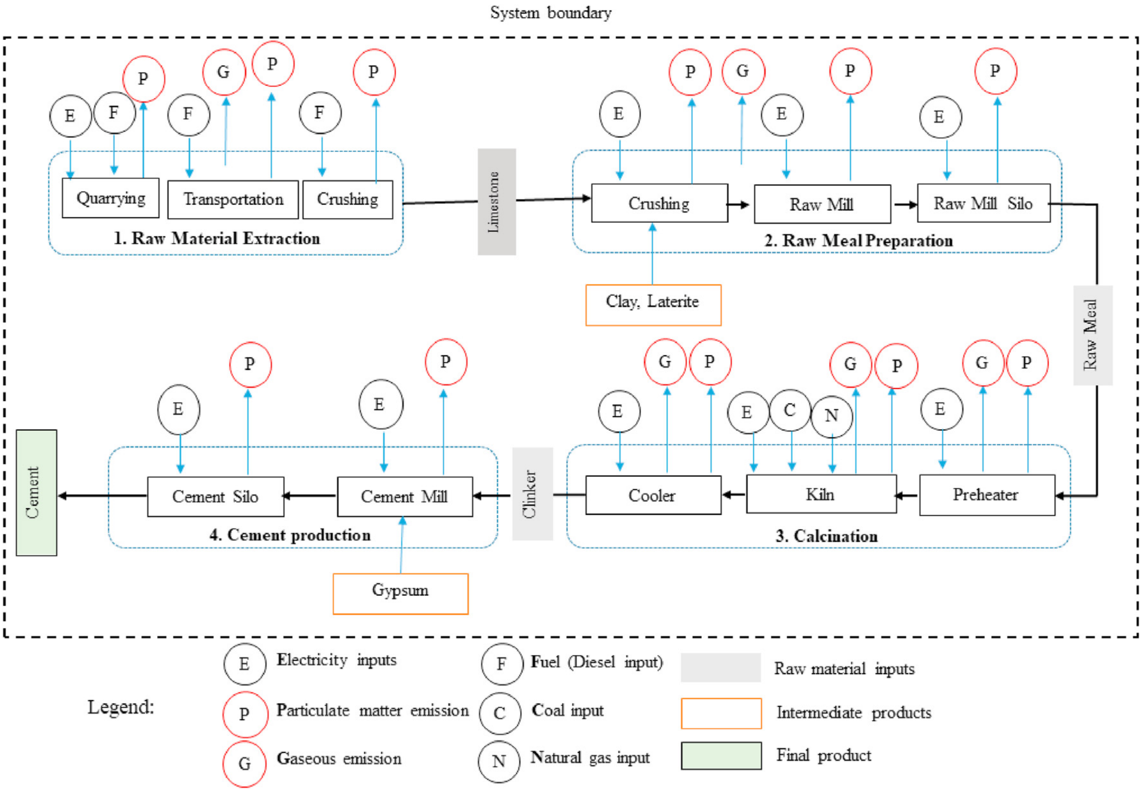

Fig. 1. System boundaries of cement production.
Note: Electricity (E) is used to drive electric motors; diesel fuel (F) is used for transportation and the operation of heavy equipment (e.g., crushers, drillers); coal (C) and natural gas (N) are used for the production of thermal energy and heat during processing (esp. calcination).

(Ecoinvent Center, 2010), which is one of the best available databases for LCAs (Martínez-Rocamora et al., 2016). The software SimaPro 8.1.1.16 was used for data analysis, and the emission data was calculated based on the emission factors of the US Environmental Protection Agency (EPA, 2004). Table 1 contains the inventory data for each major stage of cement production normalized for the functional unit used in this study (i.e., 1 tonne of cement) (Section 2.2).

Raw materials, electricity, and fuel are the main inputs in the cement production process. Data related to transport and the use of explosives and fuel during the raw material extraction stage was computed as appropriate. Other raw materials are outsourced, with the relevant data related to the quantity and transport provided by the company. The transportation data was calculated as the transport distance multiplied by the required quantity of raw materials (tkm). Energy use in the plant was divided into electricity and thermal energy. The electricity was sourced from the national grid line, which in Myanmar is mainly generated through hydropower. Crushing, conveying, grinding and machine operation required electricity, while the calcination process used a fuel mix consisting of coal (90%) and natural gas (10%) to produce the required thermal energy (Table 1, Section 2.3).

The main outputs of cement production are atmospheric emissions, with almost no solid waste generation except for cement kiln dust (Section 2.2). The calcination stage is responsible for most emissions (Josa et al., 2004; Petek Gursel et al., 2014), mainly PM, CO, CO_2, SO_2, and NO_x. The GHG emissions considered in this study included CO_2, CH_4, and N_2O, which are mainly emitted during calcination (Josa et al., 2007; Valderrama et al., 2012). Fuel combustion emits NO_x through the oxidation of chemically-bound nitrogen in the fuel and the thermal fixation of nitrogen in the combustion air, with the latter generated in both the pre-heater and kiln. SO_2 is mainly emitted during calcination, with the overall level of emissions depending on the fuel's sulfur content. Fuel combustion also emits other pollutants but in smaller quantities, such as volatile organic compounds (VOCs), which are generally measured as total organic compounds (TOC). Dust and particulate matter (PM) are emitted during quarrying, grinding, conveying, milling of raw materials, and storage. Other pollutants are emitted throughout cement production, but at smaller quantities, and include HF, HCl, PCDD/F (TOC), and some metals (Cd, Hg, Tl, As, Sb, Pb, Cr, Co, Cu, Mn, Ni, V) (Schneider et al., 2011; Schorcht et al., 2013). Due to the low levels of emissions of these pollutants, they were not considered in this study. Finally, as the solid waste generated during cement production was reused (Stafford et al., 2016b), we did not consider solid waste as an output in this study.

Table 1
Life cycle inventory.

Inputs	Amount	Outputs	Amount
Raw material extraction			
Explosives (ton)	3.900×10^{-4}		
Diesel (L)	1.610×10^{0}		
Raw meal preparation			
Limestone (ton)	1.313×10^{0}	Particulate matter (g)	4.061×10^{0}
Clay (ton)	1.875×10^{-1}		
Laterite (iron ore) (ton)	6.250×10^{-2}		
Electricity (kWh)	2.674×10^{1}		
Calcination			
Raw meal (ton)	1.562×10^{0}	Particulate matter (g)	7.438×10^{-1}
Coal (MJ)	6.411×10^{3}	Carbon monoxide (CO) (g)	4.594×10^{-1}
Natural gas (MJ)	65.941×10^{2}	Carbon dioxide (CO_2) (g)	8.438×10^{2}
Electricity (kWh)	60.164×10^{1}	Nitrogen oxides (NOx) (g)	2.250×10^{0}
		Sulfur dioxide (SO_2) (g)	2.531×10^{-1}
Cement preparation			
Clinker (ton)	9.375×10^{-1}	Particulate matter (g)	2.410×10^{-2}
Gypsum (ton)	6.250×10^{-1}		
Electricity (kWh)	4.775×10^{1}		

Source: Max Myanmar Cement plant, Naypyitaw.

2.4. Life cycle impact assessment (LCIA)

In this study, we used the ReCiPe (H) approach for mid-point impact assessment consisting of 18 mid-point impact categories. The mid-point impacts include climate change (CC), ozone depletion (OD), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial acidification (TA), freshwater and marine eutrophication (FE and ME respectively), metal and fossil depletion (MRD and FD respectively), human toxicity (HT), terrestrial, freshwater and marine ecotoxicity (TET, FET and MET respectively) (Goedkoop et al., 2012). These mid-point impact categories can be categorized into local, regional, and global effects, with (a) resource depletion and gaseous emission as the main local effects, (b) acidification and eutrophication as the main regional effects, and (c) climate change as the main global effect.

2.5. Alternative scenarios for energy use

As outlined in Section 2.3, the factory uses a fuel mix consisting of 90% coal and 10% natural gas in the kiln. However, when considering the large environmental impact associated with energy use in the kiln (Section 1) and the possibility of fuel switch as identified by plant personnel (Section 2.1), we developed two alternative scenarios for energy use in the kiln, namely (a) 100% natural gas (Scenario 1), and (b) 100% coal (Scenario 2).

The selected scenarios were based on the fact that Myanmar has proven natural gas reserves, which are becoming a major (and more important) component of the national energy mix (IEEJ, 2020). Furthermore, it was expected that the natural gas demand will be triggered by existing oil refineries, and the current paper and cement industries, as well as by new cement plants and metallurgy industries, scaling from 70 mmcf d^{-1} on average in 2014–15 to 150 mmcf d^{-1} in 2015–16 onwards (Agha et al., 2016). Cement plants are in the proximity of the national natural gas pipeline, which makes it rather feasible to use natural gas as fuel in the cement industry. At the same time, the use of natural gas for cement manufacturing will have lower environmental impacts compared to the prevailing use of coal, which bodes well with national efforts to reduce GHG emissions and transition to a green economy (Section 4.2).

3. Results

3.1. Major environmental impact categories

Below, we present absolute values for each environmental impact category (midpoint indicators) using the ReCipe(H) method. Table 2 contains the results from the midpoint impact assessment for each production stage considering the current fuel mix used in the plant (i.e., 90% coal and 10% natural gas) (Section 2.3). The results suggest that almost all impact categories are highly affected by the calcination stage, which accounts for more than 80% of the overall effect for many impact categories such as climate change, terrestrial acidification, freshwater eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, and fossil depletion (Fig. 2, Table 2).

In particular, for the climate change impact category, the calcination stage accounts for 89% (989.7 kg CO_2 eq) of the overall effect, followed by raw material extraction (10%). Conversely, the raw meal preparation and cement preparation processes have a negligible contribution to this impact category. Furthermore, the calcination stage also influences significantly fossil fuel depletion, accounting for 81% of the overall effect (180 kg oil eq). Conversely, raw meal preparation accounts for most of the overall effect (80%, 29 kg Fe eq), for the metal depletion impact category.

The calcination stage also dominates the main regional environmental impact categories, namely acidification and freshwater eutrophication, accounting for 95% and 97% of the overall effect respectively. This is mainly due to the emissions of SO_2, and to a lesser extent NO_x

Table 2
Contribution of the four production stages on mid-point impact categories.

Impact category	Unit	Raw material extraction	Raw meal preparation	Calcination	Cement preparation	Total
Climate change	kg CO_2 eq	1.080×10^2	$6.000 \times 10^{\circ}$	9.897×10^2	$9.700 \times 10^{\circ}$	1.113×10^3
Ozone depletion	kg CFC -11 eq	2.110×10^{-5}	2.000×10^{-7}	5.800×10^{-6}	5.000×10^{-7}	2.76×10^{-5}
Terrestrial acidification	kg SO_2 eq	3.090×10^{-1}	1.300×10^{-2}	$6.098 \times 10^{\circ}$	1.000×10^{-2}	$6.430 \times 10^{\circ}$
Freshwater eutrophication	kg P eq	$8.170 \times$ 10-3	1.2×10^{-4}	2.707×10^{-1}	2.701×10^{-4}	2.792×10^{-1}
Marine eutrophication	kg N eq	$4.420 \times$ 10-2	1.500×10^{-3}	1.713×10^{-1}	1.000×10^{-3}	2.18×10^{-1}
Human toxicity	kg 1, 4-DB eq	3.500×10^1	2.000×10^{-1}	2.178×10^2	$1.000 \times 10^{\circ}$	2.540×10^2
Photochemical oxidant formation	kg NMVOC	3.510×10^{-1}	1.900×10^{-2}	$2.500 \times 10^{\circ}$	1.000×10^{-2}	$2.880 \times 10^{\circ}$
Particulate matter formation	kg PM 10 eq	1.910×10^{-1}	9.600×10^{-2}	$1.913 \times 10^{\circ}$	3.000×10^{-2}	$2.230 \times 10^{\circ}$
Terrestrial ecotoxicity	kg 1,4-DB eq	5.990×10^{-2}	1.000×10^{-4}	1.89×10^{-2}	2.300×10^{-3}	8.120×10^{-2}
Freshwater ecotoxicity	kg 1,4-DB eq	$1.280 \times 10^{\circ}$	3.000×10^{-2}	$4.670 \times 10^{\circ}$	8.000×10^{-2}	$6.060 \times 10^{\circ}$
Marine ecotoxicity	kg 1,4-DB eq	$1.520 \times 10^{\circ}$	2.000×10^{-2}	$4.420 \times 10^{\circ}$	7.000×10^{-2}	$6.030 \times 10^{\circ}$
Ionising radiation	kBq U235 eq	$9.750 \times 10^{\circ}$	1.000×10^{-1}	$8.550 \times 10^{\circ}$	2.000×10^{-1}	1.860×10^1
Agricultural land occupation	m^2a	$2.050 \times 10^{\circ}$	1.000×10^{-2}	1.054×10^1	5.415×10^{-2}	1.265×10^1
Urban land occupation	m^2a	1.180×10^1	1.000×10^{-1}	$6.300 \times 10^{\circ}$	3.000×10^{-1}	1.850×10^1
Natural land transformation	m^2	4.310×10^{-2}	5.800×10^{-3}	5.210×10^{-2}	1.100×10^{-2}	1.120×10^{-1}
Water depletion	m^3	3.970×10^{-1}	7.830×10^{-1}	$2.210 \times 10^{\circ}$	$1.370 \times 10^{\circ}$	$4.76 \times 10^{\circ}$
Metal depletion	kg Fe eq	$4.000 \times 10^{\circ}$	2.900×10^1	$3.100 \times 10^{\circ}$	2.000×10^{-1}	3.630×10^1
Fossil fuel depletion	kg oil eq	4.160×10^1	4.000×10^{-1}	1.830×10^2	$1.000 \times 10^{\circ}$	2.26×10^2

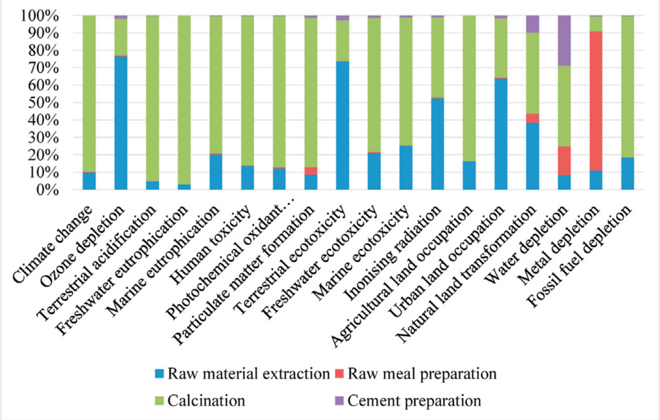

Fig. 2. Contribution (in %) of the four cement production stages on mid-point impact categories.

(Fig. 2, Table 2). However, it is worth noting that marine eutrophication is significantly affected by the raw material extraction stage due to ammonia emission from explosives, contributing to about 21% of the overall effect for this impact category (Fig. 2, Table 2).

The calcination process is also responsible for approximately 85% of the impact associated with the emission of photochemical oxidants and particulate matter (Fig. 2, Table 2). Raw material extraction is responsible for 76% of the overall effect for the ozone depletion impact category, with the contribution of the other stages being rather small. The raw material extraction stage also accounts for more than 50% of the overall effect for the terrestrial ecotoxicity and ionising radiation impact categories. In particular, for all three of the above-mentioned impact categories, limestone extraction and transport contribute by far most of the impact from the raw material extraction stage, with the contribution of clay and laterite extraction/transport being rather minimal (<3%). However, laterite extraction plays a much more important role for the metal depletion and particulate matter formation impact categories, accounting for approximately 87% and 32% respectively of the impact associated with the raw material extraction stage.

3.2. *Impacts of alternative fuel use in the cement industry*

The current fuel mix consisting of coal (90%) and natural gas (10%) (Section 2.3) emits 1.012 $tCO_2\ t_{clinker}^{-1}$. Following the two alternative scenarios (Section 2.5), a fuel switch to purely natural gas (Scenario 1) will reduce CO_2 emission to 0.320 $tCO_2\ t_{clinker}^{-1}$, while a switch to coal (Scenario 2) will increase emissions to 1.067 $tCO_2\ t_{clinker}^{-1}$. Similarly, when using only natural gas, the overall climate change impact will reduce to 0.335 $tCO_2eq\ t_{cement}^{-1}$, whereas it will increase to 1.153 $tCO_2eq\ t_{cement}^{-1}$ when using only coal.

This pattern of increasing impact, from Scenario 1 (lowest), to Baseline (middle) and Scenario 2 (highest) is observed for most impact categories. Some of the more noteworthy possible mitigation effects of Scenario 1 compared to the Baseline include impact categories such as climate change (−68.1%), freshwater eutrophication (−96.0%), marine eutrophication (−70.9%), terrestrial acidification (−83.0%), particulate matter emissions (−77.1%), human toxicity (−79.4%), freshwater ecotoxicity (−60.3%) and marine ecotoxicity (−66.2%) (Table 3).

However, there are some impact categories that a fuel switch to pure natural gas (Scenario 1) might have the opposite effects compared to the Baseline, with ozone depletion (+26.9%) and fossil fuel depletion (+44.5%) (Table 3). As it will be discussed in Section 4.1 this increase is associated with the emission of ozone depleting species in the natural gas distribution system.

4. Discussion

4.1. *Synthesis of results and comparison with other studies*

The scope, system boundaries, production technologies, energy/material flows in supply chains, and underlying assumptions vary widely between different LCAs of cement production. Thus, the direct comparison of the environmental impacts may be difficult between individual LCA studies. Considering this acknowledgement, Table S1 (Supplementary Electronic Material) juxtaposes the major environmental impacts, impact assessment methods, and functional units of the present analysis with previous LCA studies of cement production in Brazil (Stafford et al., 2016a), Europe (Stafford et al., 2016b), China (Chen et al., 2014), Spain (Garcia-Gusano et al., 2015), China/Japan (Li et al., 2015) and Myanmar (Tun et al., 2020).

When it comes to the broader LCA literature, climate change has been one of the most widely-studied impact categories, and in accordance with most studies, we found that the calcination process is the major source of GHG emissions (Vatopoulos and Tzimas, 2012; Benhelal et al., 2013; Chen et al., 2014; Uwasu et al., 2014; Zhang et al., 2014; Ammenberg et al., 2015; Feiz et al., 2015). In our study, the calcination stage accounts for approximately 89% of the effects for the climate change impact category, with the total emissions amounting to 1.02 $tCO_2\ t_{cement}^{-1}$. These emissions are comparable to other LCAs, which have ranged between 0.6 and 1.0 $tCO_2\ t_{cement}^{-1}$ (Huntzinger and Eatmon, 2009; Moya et al., 2010; Valderrama et al., 2012; Pacheco-Torgal et al., 2014; Uwasu et al., 2014; Feiz et al., 2015) (Table S1, Supplementary Electronic Material).

Table 3
Effect of different fuel mixes for the calcination stage.

Impact category	Unit	Baseline (mixed fuel)	Scenario 1 (100% natural gas)	Scenario 2 (100% coal)	Scenario 1 (% change from Baseline)	Scenario 2 (% change from Baseline)
Climate change	kg CO_2 eq	1.112×10^{3}	3.552×10^{2}	1.163×10^{3}	−68.1	4.6
Ozone depletion	kg CFC-11 eq	2.760×10^{-5}	3.503×10^{-5}	2.561×10^{-5}	26.9	−7.2
Terrestrial acidification	kg SO_2 eq	6.427×10^{0}	1.094×10^{0}	6.882×10^{0}	−83.0	7.1
Freshwater eutrophication	kg P eq	2.792×10^{-1}	1.122×10^{-2}	3.057×10^{-1}	−96.0	9.5
Marine eutrophication	kg N eq	2.181×10^{-1}	6.342×10^{-2}	2.337×10^{-1}	−70.9	7.5
Human toxicity	kg 1,4-DB eq	2.533×10^{2}	5.231×10^{1}	2.723×10^{2}	−79.4	7.5
Photochemical oxidant formation	kg NMVOC	2.877×10^{0}	7.576×10^{-1}	3.079×10^{0}	−73.7	7.0
Particulate matter formation	kg PM_{10} eq	2.231×10^{0}	5.110×10^{-1}	2.385×10^{0}	−77.1	6.9
Terrestrial ecotoxicity	kg 1,4-DB eq	8.122×10^{-2}	7.410×10^{-2}	8.020×10^{-2}	−8.8	−1.3
Freshwater ecotoxicity	kg 1,4-DB eq	6.053×10^{0}	2.402×10^{0}	6.304×10^{0}	−60.3	4.2
Marine ecotoxicity	kg 1,4-DB eq	6.032×10^{0}	2.039×10^{0}	6.394×10^{0}	−66.2	6.0
Ionising radiation	Kg Bq U235 eq	1.862×10^{1}	1.176×10^{1}	1.923×10^{1}	−36.8	3.3
Agricultural land occupation	m^2a	1.268×10^{1}	2.392×10^{0}	1.362×10^{1}	−81.1	7.4
Urban land occupation	m^2a	1.844×10^{1}	1.232×10^{1}	1.907×10^{1}	−33.2	3.4
Natural land transformation	m^2	1.125×10^{-1}	1.054×10^{-1}	1.101×10^{-1}	−6.3	−2.1
Water depletion	m^3	4.762×10^{0}	4.604×10^{0}	4.795×10^{0}	−69.3	0.7
Metal depletion	kg Fe eq	3.628×10^{1}	3.496×10^{1}	3.638×10^{1}	−3.6	0.3
Fossil fuel depletion	kg oil eq	2.258×10^{2}	1.253×10^{2}	2.270×10^{2}	−44.5	0.5

Note: Mixed fuel denotes the current fuel used in the cement plant consisting of 90% coal and 10% natural gas.

However, the emission of other GHGs is relatively small compared to the overall CO_2 emissions, with the GHG emission levels from the calcination process primarily depending on fuel type and combustion process (Phair, 2006; Moya et al., 2010; Schorcht et al., 2013).

Terrestrial acidification (a regional environmental impact) is mainly linked to the emissions of SO_2 and NO_x during fuel combustion, primarily for calcination and secondarily for transport (Pacheco-Torgal et al., 2014; Tun et al., 2020). In our study, coal combustion contributed to 92% of acidification impacts, which is similar to other studies (e.g., Stafford et al., 2016b). However, the fuel mix during electricity generation can also affect acidification potential if fossil fuels dominate this mix (Garcia-Gusano et al., 2015; Stafford et al., 2016b). Further to fuel combustion, the ammonia-based explosives used for raw material extraction contribute significantly to freshwater eutrophication (FE) and marine eutrophication (ME), as identified in other cement LCAs (Stafford et al., 2016a).

At present, the studied cement company uses pure raw materials, at around 1.56 tonnes of limestone per tonne of OPC. The substitution of raw materials and clinker can be a possible avenue to increase the sustainability of cement production, considering that the extraction of limestone affects substantially terrestrial ecotoxicity and aquatic eutrophication (Section 3.1) (Puertas et al., 2008; Chen et al., 2014; Li et al., 2015). Similarly, alternative fuels such as tires, sewage sludge, and biomass can reduce fossil fuel consumption during cement production (Worrell et al., 2008; Hong and Li, 2011; Chen et al., 2010b; Schorcht et al., 2013). It has been suggested that the use of alternative materials can decrease by 10–13% terrestrial ecotoxicity and aquatic eutrophication, while fossil fuel replacement can decrease by 33–37% acidification and photochemical oxidant formation (but increase by 10% freshwater eutrophication) (Garcia-Gusano et al., 2015). However, alternative raw materials can affect the type and strength of cement (Garcia-Gusano et al., 2015).

We estimated that the mixed fuel used for calcination (90% coal and 10% natural gas) is responsible for the emission of 1.013 $tCO_2\ t_{clinker}^{-1}$, which is on par with other cement plants in the region (Tun et al., 2020). If the clinker is acquired externally, all impact categories would be affected to some degree by transportation (Stafford et al., 2016a). Otherwise, fossil fuel combustion offers the highest potential to reduce GHG emissions and mitigate most major environmental impacts, as it contributes disproportionally more to most impact categories (Section 3.1).

The cement company has been planning to use solely natural gas for thermal energy in the future (Scenario 1, Section 2.3 and 2.5), which is expected to reduce the overall emissions by around 0.320 $tCO_2\ t_{clinker}^{-1}$ or 0.328 $tCO_2\ t_{cement}^{-1}$, reducing significantly the overall environmental burden of cement production (Section 3.2). Conversely fuel switch to coal (Scenario 2) will increase emissions to 1.062 $tCO_2\ t_{clinker}^{-1}$ or 1.067 $tCO_2\ t_{cement}^{-1}$ (Section 3.2). Thus it is expected that the overall climate change impact will be reduced by 68.1% for Scenario 1 and increased by 4.6% for Scenario 2. In particular the switch to 100% natural gas is expected to have a mitigating for most environmental impact categories, with the most prominent exception being ozone depletion (Section 3.2). Studies have linked this to halons 1211 and 1301 emitted in the natural gas pipeline distribution system (Atilgan and Azapagic, 2015; Günkaya et al., 2016), as well as to the refrigerants used in the natural gas extraction and separation (Usapein and Chavalparit, 2017).

Finally, it should be noted that the impact assessment results are highly dependent on the assessment context, with differences in inventory possibly having a significant effect on the overall results. Thus, the context-specificity of both the raw material extraction and the electricity use might affect the comparability of our results with other global contexts. For the former, the raw material extraction was undertaken close to the cement plant, which meant that the effect of transportation is relatively small for many impact categories when compared to other literature (e.g., Stafford et al., 2016a). Similarly, the electricity generation in Myanmar is 100% based on hydropower, so its contribution is relatively small across almost all impact categories.

4.2. Policy implications and recommendations

At the individual company/factory level, the cement plant uses rather conventional production technologies and a fuel mix dominated by coal (90%). There are some ongoing efforts and discussions within the specific company to increase the fraction of natural gas in the energy mix. Such a fuel shift is associated with lower environmental impacts for most impact categories (Table 3), and thus should be considered carefully. In addition, there should be further investments in pollution mitigation technologies. Currently, the cement plant uses three bag-filters and is planning to increase this number, as a means of reducing particulate matter emissions. Although this is a positive development, we recommend further investments in emission control options, for example by adopting denitrification and desulfurization options in addition to baghouse filters and electro-statistic precipitators (Chen et al., 2014).

At the national level, it is important to consider carefully the increasing environmental impacts of cement production and put in place policies to mitigate them. Currently, Myanmar has embarked on a green economy transition through the development of a coordinated policy framework (Helen and Gasparatos, 2020). A key pillar of these efforts is to improve the performance of efficiency-based sectors (NEMC, 2015) such as cement manufacturing (UNEP, 2011). However, the increasing prominence of cement manufacturing in the industrial sector (Section 1) and the lack of adoption of modern production methods, suggest the ever-increasing aggregate environmental impact of the sector. For example, if we extrapolate the results of this study, the projected national cement production will be responsible for the emission of 12.24 $MtCO_2eq$, which will affect significantly the low-carbon growth of the industrial sector by 2030 that has emerged as a major government policy priority (MONREC, 2017). Considering the ongoing privatization of the cement industry there should be strong efforts from the national government to regulate the sector's environmental impacts and to provide incentives for adopting pollution mitigation technologies. For the former, there should be stronger monitoring and evaluation of environmental impacts, including strengthening the nascent Environmental Impact Assessment (EIA) regime in the country not only to capture properly the expected impacts but also to ensure the implementation of the appropriate mitigation options (Sano et al., 2016). For the latter, there should be economic incentives for the adoption of pollution mitigation options and the increased adoption of natural gas in the energy mix of cement plants.

Finally, switching from fossil-based fuels to alternative and renewable fuels (e.g., biomass, waste), increasing energy efficiency, and substituting raw materials could potentially reduce the GHG emissions from the cement industry (Rahman et al., 2013; Papanikola et al., 2019; Scrivener et al., 2018). However, even though the use of waste in cement kilns can be an environmentally sound option, it depends on the waste availability (e.g., seasonal fluctuation), logistics and operational cost (e.g., collection, storage, transportation), and technological options (Zieri and Ismail, 2019). In addition, the chemical composition of waste also has to be analysed to monitor the content of hazardous substances such as chlorine, mercury, and cadmium (PIED, 2014), while waste-heat recovery systems in cement plants need to be further investigated. Therefore, further research would be needed to appreciate the feasibility of such solutions in Myanmar (Tun et al., 2020), including establishing their costs in terms of marginal abatement cost.

5. Conclusion

This study assessed the environmental impacts of cement production in Myanmar using an LCA approach and modeled different alternative fuel scenarios for thermal energy use. Overall, the study identified that current cement production practices are responsible for multiple environmental impacts such as GHG emissions, acidification, and eutrophication, among others. The calcination stage is responsible for most of these impacts, contributing around 89% of the overall effect for the climate change impact category. Replacing the current fuel mix with pure natural gas for thermal energy generation during calcination has a large CO_2 emission reduction potential. Indeed, when compared to the baseline, such a shift can have positive mitigation effects for most impact categories with the exception of ozone depletion. Such mitigation effects would be crucial for ensuring that the increasing cement production in Myanmar does not compromise the current efforts to transition to a green economy.

However, there is a need for further research, including research on the (a) large-scale/national level impacts of cement production; (b) economic feasibility of increased natural gas use for cement production (c) potential and impacts of other options for thermal energy (e.g., biomass. municipal solid waste), and (d) potential and impacts of alternative materials in cement production to reduce the clinker ratio.

Author contributions

Ei Thwe: Conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing original draft, visualization, project administration, funding acquisition.

Dilip Khatiwada: Conceptualization, methodology, writing – reviewing and editing, supervision.

Alexandros Gasparatos: Conceptualization, resources, writing – reviewing and editing, supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2020.100007.

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