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Comparative Life Cycle Assessment among Various Scenarios for Reducing the Environmental Impacts from the Myanmar Cement Industry

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Table of Contents

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Abstract

The study assesses the environmental impacts of the Myanmar cement industry with the approach of life cycle assessment (LCA) and identifies hotspots to come up with appropriate mitigation options for enhancing the environmental performance of the cement industry in Myanmar. Eight cement plants in Mandalay region, Myanmar were visited for data collection. The document presents environmental LCAs of specific cement plants using the ReCiPe 2016 method. Results showed that emissions of CO2, NOx, SO2 and PM2.5 mainly from the clinker production step and from fossil fuel consumption for energy (electricity and transportation) are key contributors to environmental impacts from cement industry in the country. Major impacts from the Myanmar cement industry include climate change, photochemical oxidant formation: ecosystem quality, particulate matter formation, terrestrial acidification, and fossil resource scarcity. Comparative LCAs were then performed including a base scenario and five alternative scenarios developed mostly focusing on energy efficiency and the use of alternative fuels and materials. It was observed that the options employed in the scenarios led to a significant reduction in emissions and major environmental impacts. Above all, the ideal scenario was found to enable a decrease in emissions of CO2 by 10-50%, NOx by 5-23%, SO2 by 4-20% and PM2.5 by 6-22% compared to a base scenario. This resulted in a reduction of major environmental impacts by 10-50% for climate change, 6-27% for photochemical oxidant formation: ecosystem quality, 7-22% for particulate matter formation, 6- 22% for terrestrial acidification and 8-64% for fossil resource scarcity.

Keywords: Cement, Emissions, Impacts, Life Cycle Assessment, Myanmar, Sustainability

မြန်မာ့ဘိလပ်မြေထုတ်လုပ်မှုလုပ်ငန်းမှ ပတ်ဝန်းကျင်အပေါ် သက်ရောက်မှုများကို လျှော့ချဆောင်ရွက်မည့်နည်းလမ်းများအား ဖြစ်စဉ်တလျှောက် နှိုင်းယှဉ်သုံးသပ်ခြင်း

သန့်ဇင်ထွန်း၊ လက်ထောက်ညွှန်ကြားရေးမှူး
ပတ်ဝန်းကျင်ထိန်းသိမ်းရေးဦးစီးဌာန

စာတမ်းအကျဉ်း

တင်ပြပါစာတမ်း၌ (ဘဝစက်ဝန်း)ဖြစ်စဉ် တလျှောက်သုံးသပ်ခြင်း (Life Cycle Assessment) နည်းလမ်းအား အသုံးပြု၍ မြန်မာ့ဘိလပ်မြေ ထုတ်လုပ်မှုလုပ်ငန်းကြောင့် ပတ်ဝန်းကျင်အပေါ် သက်ရောက်နိုင်မှုများနှင့် အဆိုပါ သက်ရောက်မှုများကို ဖြစ်စေသော အဓိကအကြောင်းရင်းများအား ရှာဖွေဖော်ထုတ်ခြင်းများဆောင်ရွက်ခဲ့ပါသည်။ ထို့နောက် တွေ့ရှိသည့် အချက်များအပေါ် မူတည်လျက် သက်ရောက်မှု လျှော့ချရေးနည်းလမ်းများအား ပုံဖော်ဆောင်ရွက်သွားခြင်းဖြင့် မြန်မာ့ဘိလပ်မြေ ထုတ်လုပ်မှု လုပ်ငန်းများအတွက် ပိုမိုကောင်းမွန်သော ပတ်ဝန်းကျင်ဆိုင်ရာ ဆောင်ရွက်မှုများ ရရှိစေရေးရည်ရွယ်ပါသည်။ သုတေ သန အတွက် လိုအပ်သောအချက်အလက်များ စုဆောင်း ရန် မြန်မာနိုင်ငံ၊ မန္တလေးတိုင်းဒေသ ကြီး အတွင်းရှိ ဘိလပ်မြေစက်ရုံ ၈ ရုံသို့ ကွင်းဆင်းလေ့လာ ဆောင်ရွက်ခဲ့ပါသည်။ ကောက်ယူ ရရှိသော အချက်အလက်များမှတဆင့်ဘိလပ်မြေထုတ်လုပ်မှု လုပ်ငန်းများကြောင့် ဖြစ်ပေါ်နိုင်သော ပတ်ဝန်းကျင်ဆိုင်ရာ သက်ရောက်မှုများအား ReCiPe 2016 နည်းစနစ် အား အသုံးပြု၍ ခန့်မှန်း ဖော်ထုတ်ခဲ့ပါသည်။ သုတေသနဆောင်ရွက်မှု ရလဒ်များအရ မီးသင့်ကျောက် (ကလင်ကာ) ပြုလုပ်ခြင်း၊ လျှပ်စစ်စွမ်းအင်အသုံးပြုရမှုပို့ဆောင်ရေးလုပ်ငန်းများအတွက် သုံးပြုရသောရုပ်ကြွင်း လောင်စာများလောင်ကျွမ်းမှု စသည်တို့မှ ထွက်ရှိသော CO_2၊ NO_2၊ SO_2 နှင့် $PM_{2.5}$ စသည့် ထုတ်လွှတ်အခိုးအငွေ့များသည် ပတ်ဝန်းကျင်အပေါ် သက်ရောက်မှုဖြစ်စေသည့် အဓိကအရာများ ဖြစ်ကြောင်း၊ မြန်မာ့ဘိလပ်မြေ ထုတ်လုပ်မှုကဏ္ဍကြောင့် ဖြစ်ပေါ် သောအဓိက ပတ်ဝန်းကျင်ဆိုင်ရာ သက်ရောက်မှုများမှာ ရာသီဥတု ပြောင်းလဲခြင်း (climate change)၊ ဂေဟာစနစ်ဆိုင်ရာ အရည်အသွေးများအား ထိခိုက်ပျက်စီးစေသော photochemical oxidant များ ဖြစ်ပေါ်ခြင်း (photochemical oxidant formation: ecosystem quality)၊ အမှုန်အမွှားများဖြစ် ပေါ်ခြင်း (particulate matter formation)၊ မြေလွှာ၏ ဓာတု အရည်အသွေးများပြောင်းလဲ၍ အက်ဆစ်

ခ‌ေတ်ဖြစ်ထွန်းခြင်း (terrestrial acidification) နှင့် ပြည်လည် ပြည့်ဖြိုးမြဲမဟုတ်သော ရုပ်ကြွင်း သယံဇာတများ ရှားပါးပျက်စီးခြင်း (fossil resource scarcity) တို့ဖြစ်ကြောင်း သိရှိရပါသည်။ ဆက်လက်၍ တွေ့ရှိချက်များအပေါ် မူတည်လျက် ပတ်ဝန်းကျင်အပေါ် သက်ရောက်မှု နည်းပါး စေသောအခြား နည်းလမ်း ၅ မျိုး အား ရှာဖွေဖော်ထုတ်ခဲ့ပြီး ၎င်းနည်းလမ်း ၅မျိုးအား ဘိလပ်မြေ စက်ရုံများ၌ ပေါင်းစပ် ထည့်သွင်းအသုံးပြုထားရှိမှု ရလဒ်များနှင့်အချက်အလက် ကောက်ယူ ခဲ့သော ဘိလပ်မြေစက်ရုံများ၏ မူလအခြေအနေ (base scenario) ဆိုင်ရာ ရလဒ်တို့အား နှိုင်းယှဉ်သုံးသပ်ခြင်း ဆောင်ရွက်ခဲ့ပါသည်။ နည်းလမ်းတစ်မျိုးစီသည် ဘိလပ်မြေ ထုတ်လုပ်မှု ကြောင့် ဖြစ်သော အဓိက ထုတ်လွှတ်အခိုးအငွေ့များနှင့် ပတ်ဝန်းကျင်အပေါ် သက်ရောက်မှု များအား သိသာ လျော့ကျစေနိုင်ပါသည်။ သို့သော် နှိုင်းယှဉ်ချက်များအရ စံပြနမူနာနည်းလမ်း (ideal scenario) အား ဆောင်ရွက်ခြင်းဖြင့် အကောင်းဆုံး လျော့ချနိုင်ကြောင်း၊ ၎င်း၏ ရလဒ် များအား ဘိလပ်မြေ စက်ရုံ များ၏ မူလအခြေအနေဆိုင်ရာ ရလဒ်များနှင့် နှိုင်းယှဉ်ပါက CO_2 ထုတ်လွှတ်မှု အား ၁၀ မှ ၅၀ ရာခိုင်နှုန်းခန့်၊ NO_x ထုတ်လွှတ်မှုအား ၅ မှ ၂၃ ရာခိုင်နှုန်း ခန့်၊ SO_2 ထုတ်လွှတ်မှုအား ၄ မှ ၂၀ ရာခိုင်နှုန်းခန့်၊ $PM_{2.5}$ ထုတ်လွှတ်မှုအား ၆ မှ ၂၂ ရာခိုင် နှုန်း ခန့်ထိ လျှော့ချနိုင်ပြီး အကျိုးဆက် အနေဖြင့် အဓိကကျသော ပတ်ဝန်းကျင်ဆိုင်ရာ သက်ရောက်မှုများ ဖြစ်သည့် climate change အား ၁၀ မှ ၅၀ ရာခိုင်နှုန်းခန့်၊ photochemical oxidant formation: ecosystem quality အား ၆ မှ ၂၇ ရာခိုင်နှုန်းခန့်၊ particulate matter formation အား ၇ မှ ၂၂ ရာခိုင်နှုန်းခန့် terrestrial acidification အား ၆ မှ၂၂ ရာခိုင်နှုန်းခန့် နှင့် fossil resource scarcity အား ၈ မှ ၆၄ ရာခိုင်နှုန်းခန့်အထိ လျှော့ချ နိုင်ကြောင်း တွေ့ရှိရပါသည်။

Comparative Life Cycle Assessment among Various Scenarios for Reducing the Environmental Impacts from the Myanmar Cement Industry

1. Introduction

Construction industry has a significant impact on the environment, consuming approximately 40% of worldwide natural resources subsequently leading to environmental pollution and biological damages from the extraction activities of these resources (Gursel 2014). Besides, it has been identified that about 40% of the global GHG emissions come from energy consumption by the building sector (Gan et al. 2017). Concrete has been widely used as an important building material due to its readily accessible constituents and its distinct properties such as user friendliness, strength, and durability (Damtoft et al. 2008, Nagrockiene et al. 2017). Cement, a major component of concrete, is also the most widely used man-made material for buildings and infrastructure in the world. Cement production and consumption is somewhat related to the economic growth of a particular area, and the cement industry also creates certain job opportunities and provides economic benefits to its related sectors (Devi et al. 2017). However, being an energy and resource intensive industry, cement manufacturing is associated with various environmental issues such as global warming, air pollution, acidification, resource depletion, and land use change (Morsali. 2016).

Ali et al. (2011) indicated that the cement industry is responsible for about 7% of the global anthropogenic carbon dioxide (CO_2) emissions. In the manufacture of cement, around half of the CO_2 is released during the decarbonation of limestone (calcination process) and another half comes from energy uses such as fossil fuels, electricity, etc. (Huntzinger and Eatmon 2009). The Cembureau Activity Report (2019) estimated that global cement production had reached 3.99 billion tonnes in 2018. Without any action, increasing cement production will lead to higher emissions of CO_2. Furthermore, the cement industry is a major contributor to emissions of dust/ particulate matter (PM), sulphur oxides (SO_x), nitrogen oxides (NO_x) and carbon monoxide (CO) as well as heavy metals (Tang et al. 2018 and Marceau et al. 2006).

1.1 Cement industry in Myanmar

Growing urbanization has led to an increase in the demand for construction materials. Karstensen and Saha (2017) estimated that infrastructure development and increasing foreign investments would raise the construction activity in Myanmar by about 10% per annum, subsequently accelerating both the production and consumption of cement in the country. There are 17 cement plants in Myanmar using 23 cement kilns (11 wet-process and 12 dry-process kilns) with a total production capacity of approximately 9 Mta (million tonnes per annum). Table 1 shows the number and production capacity of currently operating cement plants and upcoming cement facilities around the states and regions of the country.

In 2017, about 1.98 Mt (million tonnes) cement were produced (Myanmar Statistical Yearbook, 2018). Based on the capacity of existing plants and forthcoming facilities, it is anticipated that the production of cement is going to double over the next few years. Cement plants in Myanmar use their own clinker, and portland cement represents over 99% of the cement produced in the country (Myanmar's Initial National Communication report, 2012).

The Myanmar's INC report (2012) also indicates that cement production is one of the major CO_2 emission sources from the industrial sector. In 2000, it was estimated that the cement sector alone emitted 203.23 Gg CO_2 equivalent, representing about 44% of the GHG emissions from Industrial Processes and Product Use (IPPU sector). This was projected to increase with the growing demand and production in cement (Myanmar's INC report, 2012).

Table 1. Regional distribution of cement plants in Myanmar (2017 data)

State/ Region	Existing cement plants		Upcoming cement facilities	
	Number	Production Capacity (Mta)	Number	Production Capacity (Mta)
Mandalay	8	4.17	6*	7.90
Shan	3	0.74	1*	1.20
Magway	2	0.34		
Nay Pyi Taw	1	0.63		
Mon	1	1.75	2**	2.15
Kayin	1	1.44		
Ayeyarwaddy	1	0.36		
Total	17	9.43		11.25

* Upgrading/ extending cement kilns inside current cement plants
** Newly constructed cement plants
Note: Table adapted from Karstensen and Saha (2017).

1.2 Review of the environmental impacts from the cement industry

Life Cycle Assessment (LCA) is one of the most commonly used assessment tools for evaluating potential environmental impacts of a product over the whole period of its life from raw materials acquisition, through manufacturing and delivery, to use, reuse, recycling or disposal at the end of its useful life. LCA can assist in identifying pollution shifts among various processes of products or services, assessing possible subsequent impacts, developing proper plans for better environmental performance, as supporting information to decision-makers for strategic planning, priority setting and layout of products or services and for eco-labelling (ISO 14040:2006). Several studies employing the LCA concept have been carried out to investigate the environmental impacts of different cement products and various cement manufacturing processes around the world (Stafford et al. 2016, Morsali. 2016, García-Gusano et al. 2015, Li et al. 2015, Feiz et al. 2015, Chen et al. 2014, Valderrama et al. 2012, Hong et al. 2011, Boesch and Hellweg 2010).

Wang et al. (2013) identified five major factors influencing greenhouse gas (GHG) emissions from cement production, viz. energy emission factor, energy structure, energy intensity, cement production activity, and clinker production activity. Of these, cement production activity and clinker production activity mainly dominate the increasing GHG emissions. CO_2 emissions contribute the most to global warming caused by the cement industry, in the range between 98% and 100%. Other GHGs, such as CH_4 and N_2O, show less influence despite their higher characterization factors (Josa et al. 2007, Gutierrez et al. 2017). Marceau et al. (2006) conducted a life cycle inventory (LCI) of portland cement manufactured in the United States and discussed that limestone calcination and fuel combustion in the clinker production stage accounted for 60% of total CO_2 emissions (553 kg per tonne of cement) and 39% of total CO_2 emissions (365 kg per tonne of cement), respectively. Clinker accounts for most impacts of cement production (Zabalza et al. 2011), and environmental impacts related to the cement industry are directly proportional to the clinker content in cement (Huntzinger and Eatmon 2009). Rosyid et al. (2020) identified that global warming and acidification impacts related to an Indonesian cement facility were attributed mainly to the kiln process activities. Feiz et al. (2015) compared the Global Warming Potential of three cement products with varying clinker contents; and it was observed that product with less clinker possessed the lowest value. Chen et al. (2014) indicated that significant environmental impacts from the cement industry include (1) global warming and (2) respiratory inorganics, which are concerned with direct emissions from coal and limestone consumption, and (3) non-renewable energy, which is attributable to the consumption of energy (i.e., electricity and coal).

García-Gusano et al. (2015) performed a life cycle comparison of five improvement scenarios, viz. thermal efficiency, electrical efficiency, material substitution, fossil fuel substitution and the ideal scenario in which all improvement measures were considered. The results showed that the ideal scenario was the most advantageous to achieve significant reductions in the in the impact categories studied (21 % in climate change, 49 % in acidification, 45 % in photochemical ozone formation, 30 % in human toxicity with cancer effects and 15 % in freshwater eutrophication) followed by material and fossil fuel substitution scenarios. Çankaya and Pekey (2019) discussed that cement production with 3% fuel substitution rate could lead to noticeable impact reduction of 27% in human health, 10% in ecosystem quality, 11% in resources and 1.4% in climate change per tonne of clinker compared to a traditional cement production. Again, Çankaya and Pekey (2020) evaluated the potential environmental impacts from the application of thermal energy substitution and electrical energy efficiency in clinker production through comparing the life cycle results of sixteen scenarios which were developed based on the types of the substituted fuels (dried sludge, refuse derived fuel (RDF), residual oil) and rates of energy substitution (15% and 30% substitution). It was observed that the scenario where RDF was applied to substitute 30% of the thermal energy in the clinker production stage showed the best results in terms of overall environmental burden minimization.

2. Objectives

Applying different impact assessment methods, studies described in sub-section 1.2 assessed the environmental impacts of the cement industry, and it was observed that the magnitude of the impacts generally differed based on the amount of energy and raw materials consumed. Therefore, in order to adopt appropriate improvement measures for the cement industry in a particular area, it is fundamental to specifically conduct an LCA of the industry in that area. In Myanmar, there have not been any scientific studies evaluating the environmental impacts of the cement industry. Hence, this study investigates the environmental impacts from the Myanmar cement industry with the concept of LCA and evaluates the improvement scenarios where energy efficiency and the use of alternative fuels and materials are taken into consideration. The work is notable because it provides relevant information in implementing an action plan to increase the productivity and competitiveness of industrial systems through disaster-and-climate resilience, and low-carbon and green characteristics as mandated in Myanmar Sustainable Development Plan (2018-2030).

3. Materials and Methods

Several studies have employed LCA to determine the environmental impacts from cement production, to prioritize specific impacts from the cement industry, and to analyze and compare various options aiming at reducing impacts from cement production. However, since cement have many end-use applications, there may be some difficulties in performing an entire life cycle (cradle-to-grave) analysis. Therefore, a cradle-to-gate or gate-to-gate approach is preferable. Most cement related LCA studies have been conducted considering a cradle-to-gate approach despite some differences in their respective scope, such as including or excluding raw material quarrying, collection and transportation (Garcia-Gusano et al. 2015, Feiz et al. 2015, Li et al. 2015, Huntzinger and Eatmon 2009).

3.1 Goal and scope

This study focuses on identifying the environmental impacts and hotspots from the Myanmar cement industry based on the data collected over the period 2017-2018 (fiscal year). One tonne of portland cement manufactured in Myanmar using domestic clinker was used as the functional unit. Cradle-to-gate analysis was conducted, limiting the system boundary to raw material extraction, transportation, and manufacturing of the final product, i.e., portland cement, as shown in Figure 1.

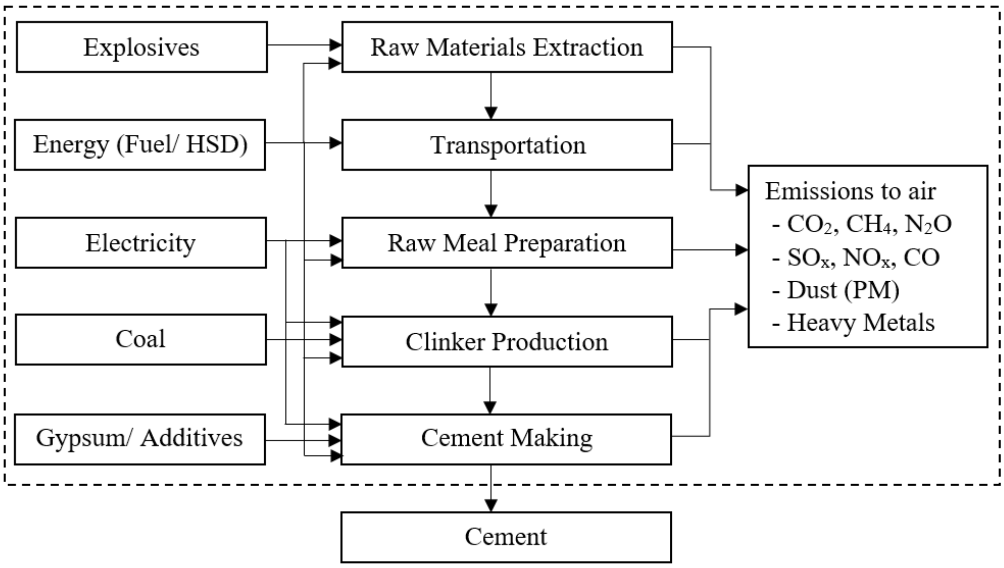

Figure 1. Cradle-to-gate system boundary showing the production of cement in Myanmar

3.2 Life cycle inventory (LCI) and impact assessment (LCIA)

Input and output data of the studied system were collected and quantified with reference to the goal and scope of the study. Table 1 shows that 8 cement plants (2 wet process and 6 dry process plants) in Mandalay region has the production capacity of 4.17 Mta, accounting for about 44% of the whole cement production capacity in the country. Out of these 8 plants, 2 plants (plants A and B) apply the wet-process technology for cement production whereas the others (plants C, D, E, F, G and H) are dry-process plants. Among the 6 dry-process plants, plants C and D produce more cement than any other plants. These 2 plants have installed waste heat recovery (WHR) systems which are able to recover 35 kWh and 40 kWh of electricity per tonne clinker, respectively. Plants E and F are moderately operated plants while old dry process plants, plants G and H, manufacture lower amount of cement. All the cement plants use grid electricity except plant D which generates electric power from its coal fired power plant (CFPP).

All input data (raw materials, energy, electricity and transportation) were collected from these 8 cement plants, except for data about quarrying of raw materials (limestone, iron ore, clay, gypsum, etc.) and coal which were adapted from Ditsele (2010), Norgate et al. (2010), Suárez et al. (2016), Kittipongvises (2017) and Md. Hossain et al. (2017). However, collected data relating to factors such as plant capacity, applied processes and technologies (reflecting energy structure and energy consumption), and maintenance procedures are site-specific and variable. Therefore, to ensure a better representativity, LCAs were specifically performed for the 8 selected cement plants. Figure 1 shows the five steps considered for estimating emissions from portland cement production, namely raw material extraction, transportation to cement plant, and manufacturing process, including, raw meal preparation, clinker production and cement making. All activities considered in each production step are listed in Table 2. Raw materials and energy inputs were collected to analyze the emissions from each individual step. Emissions were estimated using emission factors from IPCC (2006) guidelines, EMEP/ EEA air pollutant emission inventory guidebooks (European Environmental Agency, 2019) and the US EPA, Detonation of explosives; An AP-42 update (US EPA, 1979). Life cycle inventory (LCI) data of portland cement productions by different cement plants are presented in Appendix 1. Estimated emissions are then assigned to related impact categories using the ReCiPe 2016 method (Hierarchist perspective). Characterization factors and detailed methodology of the ReCiPe 2016 method are available at www.lcia-recipe.net.

Table 2. Activities considered in the manufacture of portland cement

Production step	Process/ activity considered for emissions estimation and impact assessment
Raw material extraction	Quarrying of raw materials such as limestone, clay, iron ore, etc. (emissions from fuel production, fuel combustion, electricity, explosives detonation and fugitive emissions)
Raw material transportation	Transportation of raw materials to cement plant (emissions from fuel production and fuel combustion)
Raw meal preparation	On-site transportation, electricity, grinding/ homogenizing (emissions from fuel production, fuel combustion, electricity generation and raw meal process)
Clinker	Coal extraction, coal transportation, on-site transportation, coal

production	combustion, electricity, calcination (emissions from extraction, transportation and burning of coal, fuel production, fuel combustion, electricity generation, calcination process)
Cement making	Gypsum extraction, transportation of gypsum/ other additives, fuel production, fuel combustion, electricity, cement milling (emissions from gypsum extraction, fuel production, fuel combustion, electricity generation and milling process)

3.3 Description of the alternative scenarios

Findings from LCAs of the 8 cement plants were taken as a base scenario (S_0) for the cement industry in the country. Besides, taking into consideration energy efficiency, and the use of alternative raw materials and fuels, the document introduces five alternative scenarios (S_1-S_5) in order to reduce the environmental impacts from the Myanmar cement industry. Comparative LCAs among different scenarios were then performed to evaluate how individual scenarios contribute to reducing major emissions and subsequent environmental impacts.

3.3.1 Process modification (S_1)

The scenario considers upgrading the manufacturing process by shifting from a wet kiln to a dry kiln with preheater and precalciner. Upgrading a wet process to a dry process requires a change in equipment along the manufacturing chain, especially the clinker kiln system; and it requires large initial investment cost. However, in order to reduce energy and manufacturing costs, the old and expired wet process cement plants are willing to shift to the dry ones (Energy Technology Systems Analysis Programme, 2010). As of the collected data and related studies (Benhelal et al. 2013, Kajaste and Hurme 2016, Madlool et al. 2011), it was observed that a dry process cement plant generally consumes about 3.05 GJ thermal energy (23-54% less than wet process) and 130 kWh electricity (4-18% less than wet process) for manufacturing one tonne of cement. The scenario entails shifting the 2 wet process plants (plants A and B) to the dry process with precalciner aiming for reducing air pollutant emissions, especially from the application of electricity, and from the extraction, transportation and combustion of coal used for thermal energy, and subsequent impacts.

3.3.2 Increasing the share of clinker substitute (S_2)

Clinker production is the most energy consuming and air pollutants emitting step in the cement industry. With the aim of substituting part of the clinker in making cement, the use of industrial by-products, such as fly ash, slag, etc., as the alternative material is one of the most promising options to reduce emissions from the cement industry (Benhelal et al. 2013, Kajaste and Hurme 2016). Besides, this option indirectly assists in the systematic management of industrial wastes.

LCI data (Appendix 1) describes that the average clinker factor (CF: clinker content in the cement) from the 8 cement plants investigated equates to 0.93 (in the range 0.85-0.97). The European cement standard EN 197-1 defines the criteria for common cements in which

CEM I portland cement includes over 95% clinker and CEM II portland-composite cement consists of 65-94% clinker. In detail, it describes that CEM II portland-fly ash cement (CEM II A) is comprised of 80-94% clinker and 6-20% fly ash including 0-5% additional mineral constituents to be mixed with clinker and fly ash. Whereas CEM II portland-fly ash cement (CEM II B) is made up of 65-79% clinker and 21-35% fly ash together with adjustable 0-5% mineral additives. Therefore, this scenario assumes that the cement industry in Myanmar produces CEM II portland-composite cement with clinker factor (CF) 0.8, i.e., applying 80% clinker and 20% additives (fly ash as the clinker substitute and gypsum). According to this scenario, changes in the raw material constituents of the cement produced in the 8 cement plants investigated and the distance for transporting fly ash from its source to specific cement plants are presented in Appendix 2.

3.3.3 Fuel substitution (S_3)

Conventional fuels, such as coal, pet coke, natural gas, used in the cement kiln can be substituted by alternative fuels such as waste-derived fuels. Examples of the waste materials commonly used as alternative fuels include used tyres, animal residues, sewage sludges, waste oils and other types of waste derived from industrial and municipal sources (Chatziaras et al. 2014). Though several types of waste can be used as alternative fuels, such wastes need to be pretreated before being used in the cement industry. Replacing conventional fuel with waste fuel reduces not only emissions from the cement industry but also the use of fossil resources in cement making, and this constitutes a sound option for the treatment of various waste materials as well. However, before using waste materials as fuels, some basic parameters need to be considered such as local availability, physical and chemical composition, technical possibility, calorific value of the waste materials and a reliable supply chain (European Commission 2013).

The increasing amount of MSW represents an important challenge for sustainable waste management and poses undesirable threats to the environment. The cement industry has become one of the possible options to solve this issue using MSW as alternative fuel to substitute fossil fuels (Rahman et al. 2015). The Waste Management Strategy and Action Plan for Mandalay City (2017-2030) set a plan to produce RDF from MSW that is applicable to cement plants as alternative fuel (MCDC and ECD 2017). It was also discussed that the current waste management practices in Myanmar and increasing production capacity of the Myanmar cement industry create a huge opportunity for the production and use of RDF in cement kilns (Karstensen and Saha 2017). As such, fuel substitution scenario in this study will focus on the use of RDF. However, data about the production, transport and combustion of RDF in the Myanmar cement industry are currently unavailable. Thus, life cycle inventory (LCI) data about the pre-treatment, transport and combustion of RDF (Appendix 3) were adopted from Garcia-Gusano et al. (2015) and a 20% thermal substitution rate was considered as suggested by Rahman et al. (2015). Due to technological limitation about combustion process modification, fuel substitution option was considered only for dry process cement plants, i.e., plants C, D, E, F, G and H. Changes in fuel composition used in different cement plants for thermal energy are described in Appendix 4.

3.3.4 Energy recovery from exhaust streams (S_4)

Energy recovery from exhaust streams during the manufacturing process is a potential option to reduce CO_2 emissions. In heating and cooling parts of the pyro-processing stage, thermal heat losses are caused by flue gas and hot air streams. The waste heat can be used for electricity generation by steam turbines. It can also be used to dry raw meals (Benhelal et al. 2013). About 10 to 30% of the electricity required for the cement manufacturing process can be produced by applying a waste heat recovery option in a regular cement plant (Mikulcic et al. 2016). Energy recovery from waste heat can save up to 20% of the fuel consumed for electricity generation and as a result reduce CO_2 emissions by 8% (Benhelal et al. 2013).

Among the 8 cement plants investigated, only plants C and D have already installed WHR system operating based on a conventional water steam cycle. The electricity generated by each WHR system enables saving up to 25% of the electricity consumed in plant C and about 35% in Plant D. To the best of our knowledge, there has not been any published work on the installation of WHR systems in wet process plants. Therefore, this scenario was considered only for dry process plants, i.e., plants E, F, G and H. Emissions to air from the electricity generated through a WHR system were estimated based on the data collected from the WHR system of Plant C (Appendix 5), assuming 25% of the electricity was recovered for the manufacturing process.

3.3.5 Ideal scenario (S_5)

With the purpose of enhancing the environmental performance of the Myanmar cement industry, this scenario aims to integrate all possible mitigation measures/scenarios in each of the 8 cement plants investigated. In general, this scenario is a kind of combination of all the scenarios described above. For Plants A and B, which are operating with a wet process, all four scenarios have been employed to achieve optimized environmental benefits. However, for dry process plants, not all scenarios were to be considered. The ideal scenario considered in each of the 8 cements plants is as detailed in Table 3.

Table 3. Description of the ideal scenarios

No.	Cement Plant	Current process description	Ideal scenario description
1.	Plant A	Wet process	$S_1+S_2+S_3+S_4$
2.	Plant B	Wet process	$S_1+S_2+S_3+S_4$
3.	Plant C	Dry process with preheater, precalciner and WHR	S_2+S_3
4.	Plant D	Dry process with preheater, precalciner and WHR	S_2+S_3
5.	Plant E	Dry process with preheater and precalciner	$S_2+S_3+S_4$
6.	Plant F	Dry process with preheater and precalciner	$S_2+S_3+S_4$
7.	Plant G	Dry process with preheater and precalciner	$S_2+S_3+S_4$
8.	Plant H	Dry process with preheater and precalciner	$S_2+S_3+S_4$

4. Results

Compared with the emissions data presented in Appendix 1, it was found that emissions from the 2 wet-process plants (plants A and B), including, CO_2, CH_4, N_2O, NO_x, CO, NMVOC, $PM_{2.5}$ and NH_3, were higher than those from the dry-process plants as a result of larger consumption of fuel, i.e., coal, diesel and gasoline. Also, plant D was found to contribute larger emissions of NO_x than any other dry-process plants as well as higher emissions of SO_2 and heavy metals than any other plants because of its coal-fired power plant. As illustrated in Figure 2, the emissions from all the cement plants were averaged in order to investigate the contribution of cement manufacturing steps to those emissions. Figure 2 shows that clinker production is the main contributor to air pollutant emissions apart from dust emissions (TSP and PM_{10}) which are mostly contributed by raw material quarrying.

Life cycle inventory results show that CO_2 is the air pollutant mostly emitted from the cement industry, accounting for about 99% of all considered emissions. On average, the production of one tonne of portland cement by wet-process and dry-process plants leads to emissions of 1,272 kg CO_2 and 1,006 kg CO_2, respectively which corresponds to 1,072 kg CO_2 for the entire cement industry in Myanmar. These emissions are comparable to those estimated in other related studies which are in the range 0.56-1.10 tonne CO_2 emissions per tonne of cement (Feiz et al. 2015; Li et al. 2015; Chen et al. 2014; Moya et al. 2010; Marceau et al. 2006; and Josa et al. 2004). CO_2 is mainly released through decarbonation of limestone in the clinker kiln, combustion of fuel during clinker production and the energy used throughout the whole cement manufacturing process. Of all the steps contributing to CO_2 emissions, clinker production is the main one responsible for approximately 96% of the total CO_2 emissions.

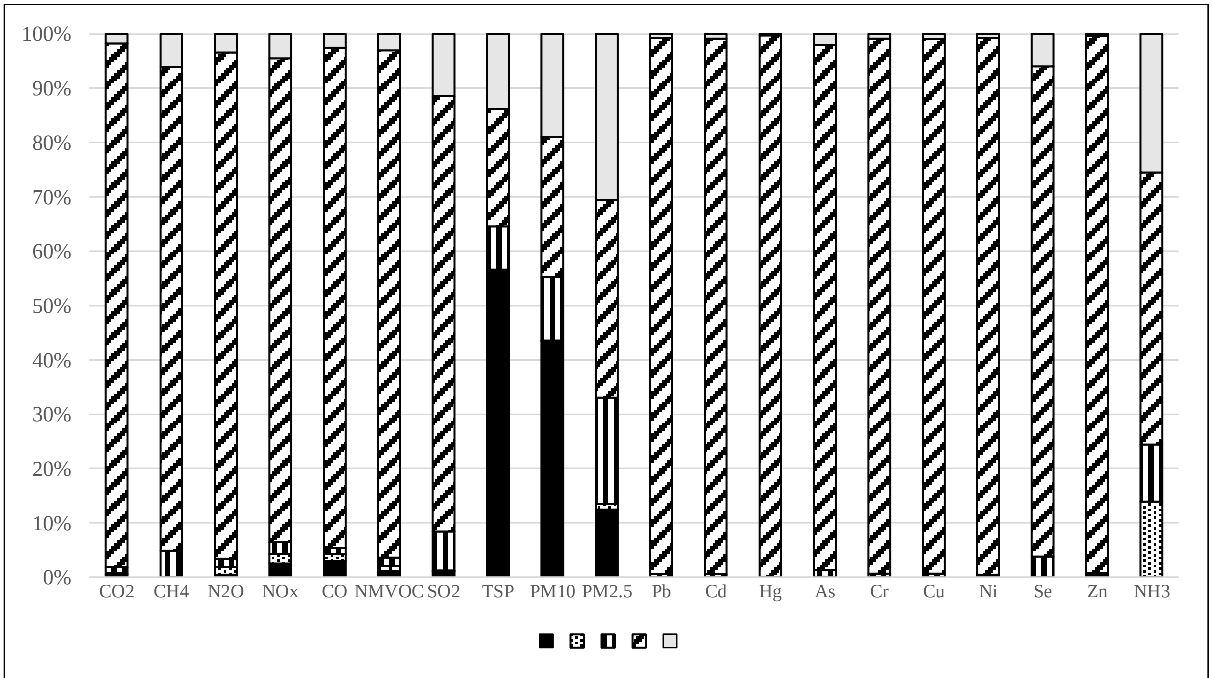

Figure 2. Contribution analysis of portland cement manufacturing steps to air emissions

LCIA was performed for each of the 8 cement plants investigated. The results of midpoint environmental impacts are described in Appendix 6. From the results, it was found that plant G contributes the lowest environmental impacts for most of the categories covered except for climate change, ozone depletion, water consumption and fossil resource scarcity. This is due to the lower environmental load related to transportation and mineral resource consumption compared with other plants. With regard to climate change, ozone depletion and fossil resource scarcity, plants C and D were found to contribute the least impacts due to lower coal consumption resulting in lower GHG emissions from coal burning for clinker making. However, plant D was characterized by the highest impacts concerning fine particulate matter formation, terrestrial acidification and toxicity as a result of the on-site coal-fired power plant used to generate electricity. Because of the large amount of coal consumed for thermal energy in the clinker production step and large usage of energy for transportation, plant A and plant B (wet-process plants) were found to contribute the highest impacts with regard to global warming, ozone depletion, photochemical oxidant formation (that damages to both human health and ecosystem quality) and fossil resource scarcity. For most impact categories, plants E, F and H (dry process plants) were observed to have moderate contributions. Plants C, E, F and H showed higher impacts regarding mineral resource scarcity as a result of larger consumption of resources to produce clinker.

4.1 Identifying major environmental impacts and key factors

Specific impact categories of different cement plants were assigned to relative damage categories. They were then normalized with the application of normalization factors from the ReCiPe (2016) endpoint method to investigate and compare the magnitude of environmental impacts from the Myanmar cement industry. Normalized results are illustrated in Figure 3, showing that major environmental impacts include climate change, fine particulate matter formation, ecosystem damage due to photochemical oxidant formation, terrestrial acidification, and fossil resource scarcity.

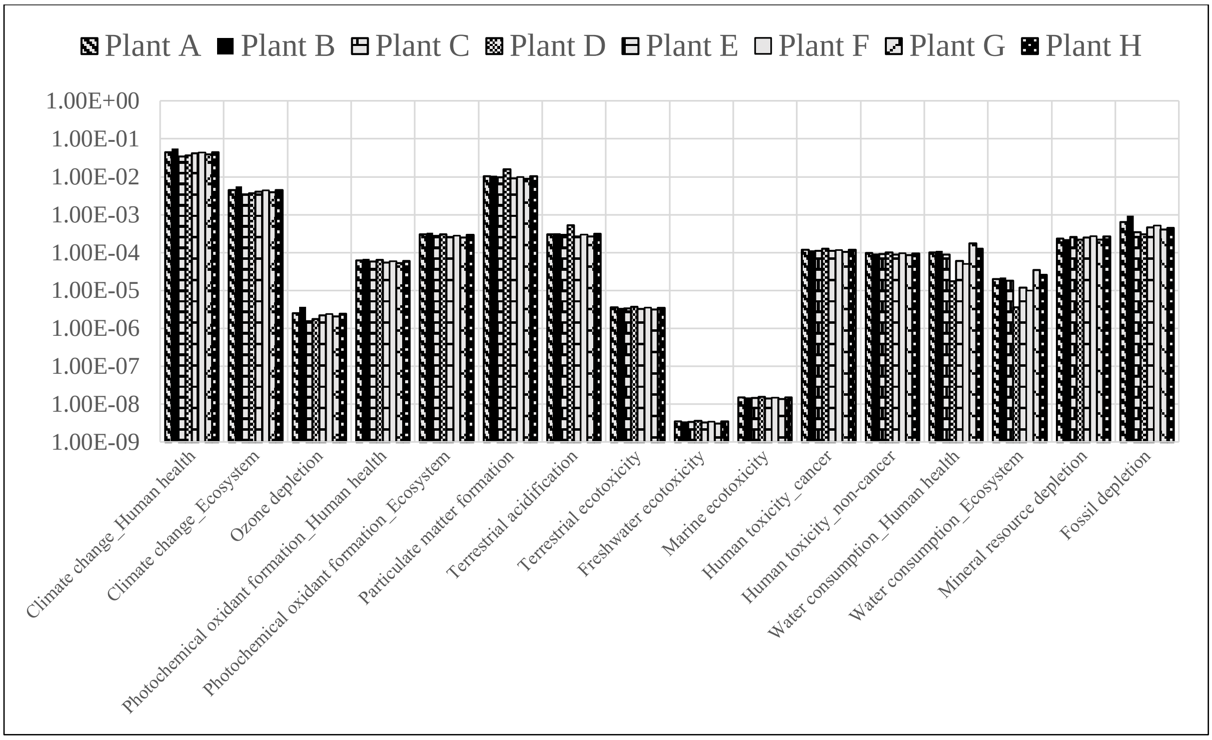

Figure 3. Normalized results (per impact category) of cement plants in Myanmar

In order to identify the key factors responsible for these major environmental impacts, a contribution analysis was performed as shown in Figure 4. For all the cement plants, fossil resource scarcity was found to be contributed by fuels (crude oil, natural gas and coal) that are used as main sources of energy in the cement manufacturing process (not presented in Figure 4). Concerning impacts such as ecosystem damage due to photochemical oxidant formation, fine particulate formation and terrestrial acidification, major contributors were identified to include NO_x, SO_2, and $PM_{2.5}$. Tracing back to the inventory data, NO_x was found to be mainly released during the activities for clinker production, with 76% from coal combustion and about 8% from transporting coal to the plant. Similarly, around 70% of SO_2 was found to be emitted as a result of coal combustion and approximately 9% from electricity in the clinker production stage. With regard to $PM_{2.5}$, emissions occur throughout the cement manufacturing process, but major contributing sources include the clinker production stage (about 28%), the cement making step (about 28%) and the raw meal preparation step (nearly 19%).

CO_2 emissions are mostly from coal combustion, representing 48% of all CO_2 emissions, and limestone decarbonation, contributing 46% of all CO_2 emissions, during the clinker production step. These emissions combined constitute the largest impact to the climate change impact. Based on the contribution analyses (Figure 2 and Figure 4) and the above-mentioned results, it is observed that direct emissions from coal burning and decarbonation, and fossil resource consumption for energy conversion i.e., electricity and transportation, are major contributors to environmental impacts from the Myanmar cement industry. This finding is compatible with the study by Chen et al. (2014) which indicates that key contributing factors to major environmental impact categories are direct emissions from coal and limestone consumption, and energy use.

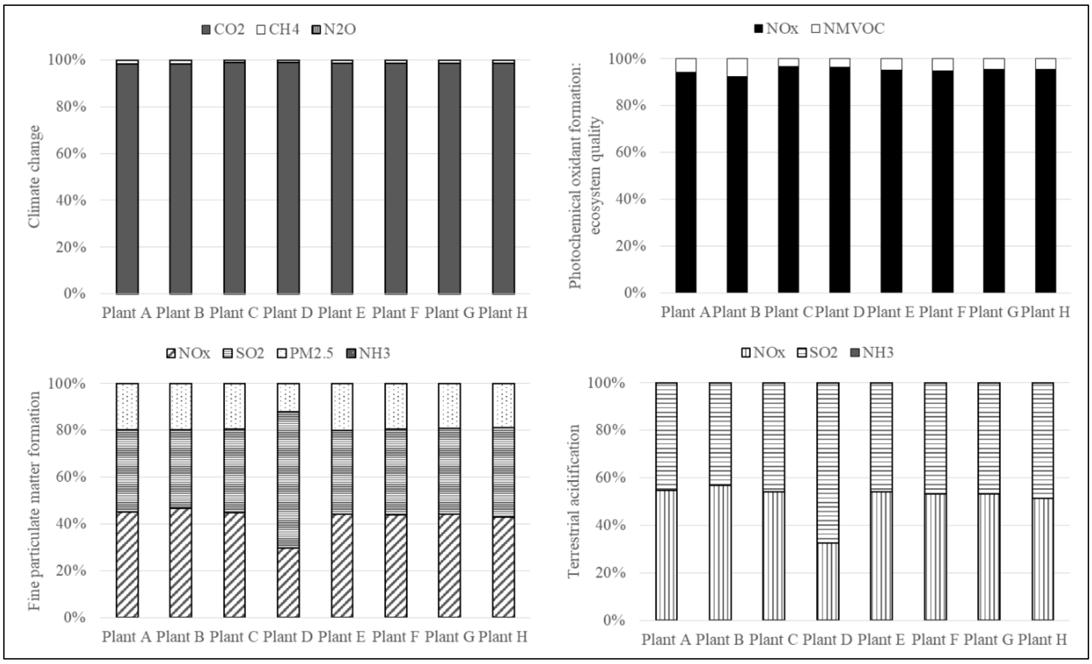

Figure 4. Contribution of substances to major environmental impacts from the Myanmar cement industry

5. Discussion

This section discusses scenario results in each cement plant, focusing on key factors, including, CO_2, NO_x, SO_2 and $PM_{2.5}$ emissions, and major environmental impacts, namely, climate change, photochemical oxidant formation: ecosystem quality, particulate matter formation, terrestrial acidification and fossil resource scarcity (fossil depletion). Figures 5, 6, 7 and 8 represent emissions to air and Figures 9 to 13 depict major environmental impacts from cement manufacturing in different cement plants under various scenarios.

For wet process Plants A and B, shifting to a dry process with precalciner (S_1) was found to noticeably reduce CO_2 emissions in the range 25-40% (Figure 5). This decrease was found to be attributed to thermal energy saving. The result of CO_2 reduction agrees with Benhelal et al. (2013) which discussed that shifting from a wet to a dry process with precalciner contributed to reduce CO_2 emissions from cement manufacturing by about 20%. NO_x, SO_2 and $PM_{2.5}$ emissions were simultaneously lowered within the range 5.0-13.3%, 2.7-3.0% and 3.9-10.1% respectively (Figures 6-8). Consequently, major environmental impacts from cement manufacturing were also found to be reduced in the range 25.0-40.5% for climate change, 7.2-16.9% for photochemical oxidant formation: ecosystem damage, 4.0-9.2% for particulate matter formation, 4.0-8.9% for terrestrial acidification and 41.8-60.5% for fossil resource depletion (Figures 9-13). It was observed that fuel saving (coal) for thermal energy in the process modification scenario (S_1) substantially decreased the impacts on climate change and fossil resource depletion (Figures 9 and 13) compared to the base scenario (S_0).

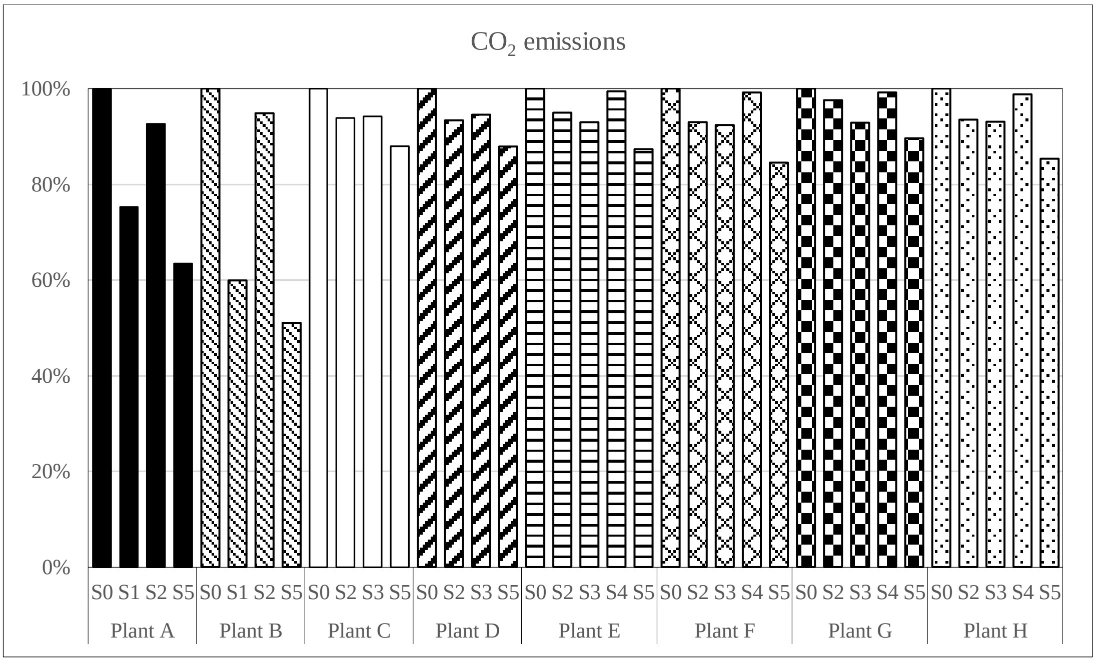

Figure 5. Contribution to CO_2 by different cement plants under various scenarios

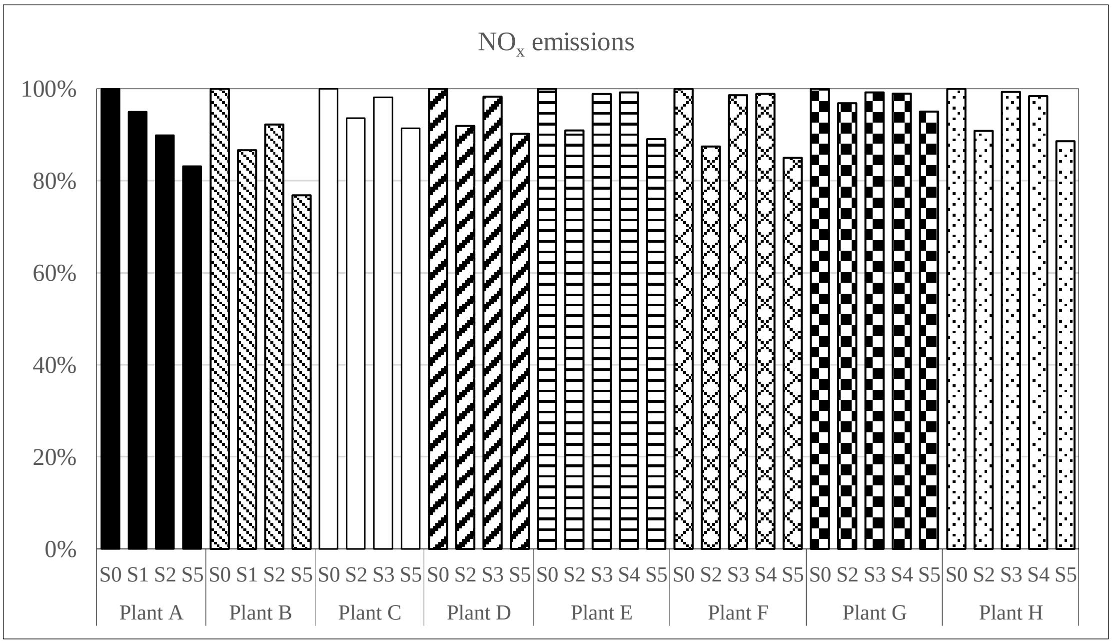

Figure 6. Contribution to NO_x by different cement plants under various scenarios

Meanwhile, increasing the share of clinker substitute (S_2) in the 8 cement plants contributed to reduce emissions of CO_2 by 2.4-7.4%, NO_x by 3.1-12.5%, SO_2 by 3.7-13.3% and $PM_{2.5}$ by 4.3-13.8% compared to the base scenario (S_0) (Figures 5-8). The application of clinker substitute directly resulted in CO_2 emissions reduction from the decarbonation of limestone and indirectly decreased the emissions to air related to the extraction and transportation of the raw materials consumed to produce clinker. The proportion of clinker substitute, i.e., fly ash, and the distance for transporting fly ash to the cement plants influenced the magnitude of emissions reduction. Thus, Plant A, using the greatest portion of fly ash, and Plant F, having the shortest fly ash transportation distance, showed the largest reduction in emissions among all the plants studied (Appendix 2, Figures 5-8). As a result of the emissions abated by this scenario (S_2), major environmental impacts, such as climate change, photochemical oxidant formation: ecosystem quality, particulate matter formation and terrestrial acidification, were found to be decreased by 2.4-7.2%, 3.0-11.9%, 3.8-12.6% and 3.7-12.3%, respectively (Figure 9-12). The results are comparable to the study results by Garcia-Gusano et al. (2015) which found that the use of alternative materials to produce cement contributed to reduce environmental impacts including climate change and acidification potential in the range 10-13% compared to traditional cement production systems. However, the consumption of fuel, i.e., diesel, for transporting fly ash from its source to the cement plants contributed to increase the impact on fossil resource depletion (2.7% on average) as presented in Figure 13.

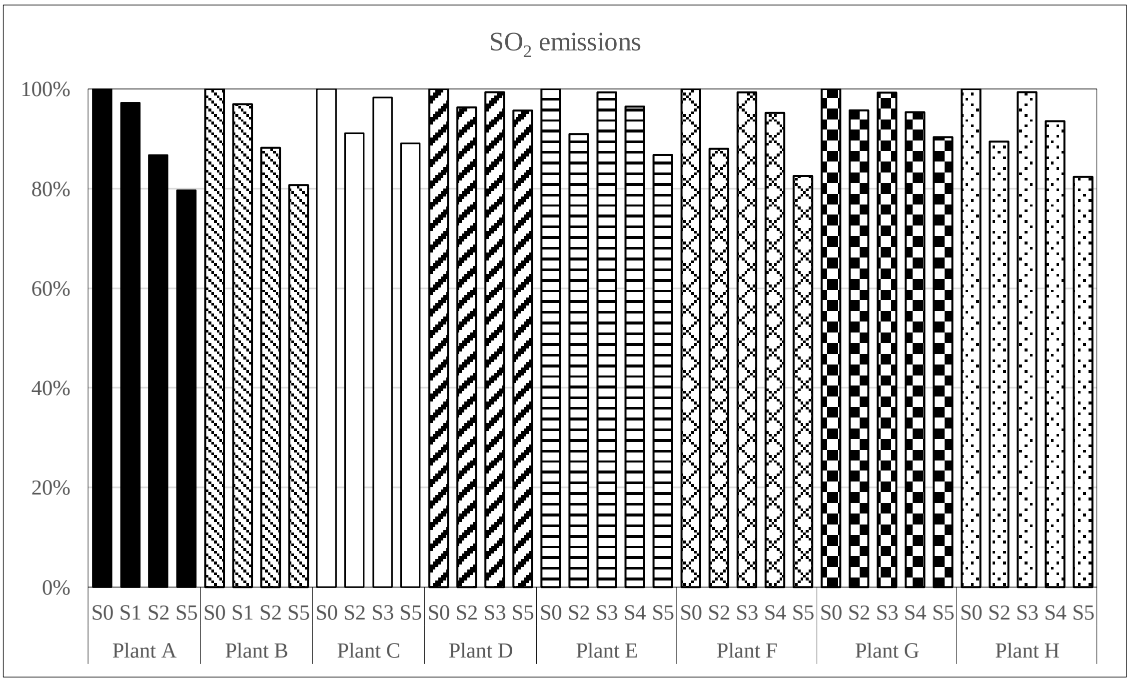

Figure 7. Contribution to SO_2 by different cement plants under various scenarios

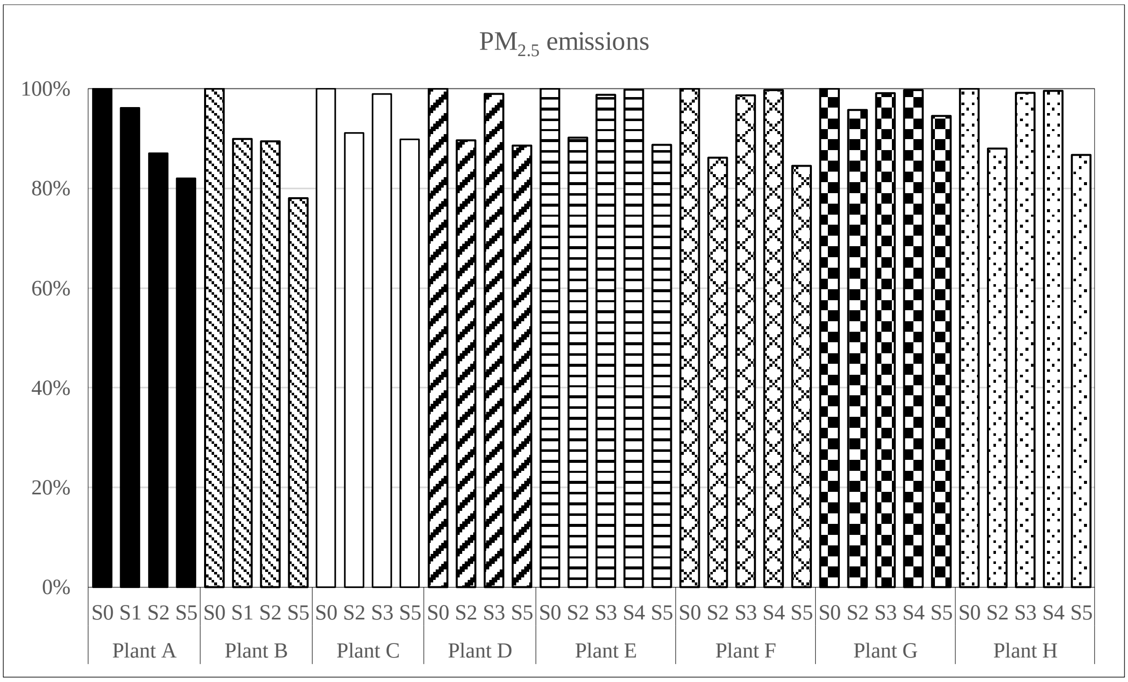

Figure 8. Contribution to $PM_{2.5}$ by different cement plants under various scenarios

Due to technological constraints, the replacement of 20% thermal energy with RDF (S_3) was only considered in dry process plants, i.e., Plants C, D, E, F, G and H. The amount of RDF used to replace coal was different based on the thermal energy requirement and calorific values of the coal consumed in each plant (Appendix 4). The extraction, transportation and combustion of coal, and the amount of RDF replacing the coal fuel were found to be major factors contributing to emissions from cement manufacturing in this scenario (S_3). Generally, a 20% thermal substitution with RDF in the cement kilns contributed to reduce emissions of CO_2 by 5.5-7.6%, NOx by 0.7-1.9%, SO_2 by 0.6-1.7% and $PM_{2.5}$ by 0.8-1.3% compared to the base scenario (S_0) (Figures 5-8). This led to a decrease in major environmental loads by 5.6-7.7% for climate change, 1.4-2.3% for photochemical oxidant formation: ecosystem quality, 0.7-1.7% for particulate matter formation, 0.6-1.8% for terrestrial acidification and 14.0-19.8% for fossil depletion (Figures 9-13). These results are in line with the study of Genon and Brizio (2008) that assessed the reduction in CO_2 and NO_x emissions when using RDF compared to using hard coal, and the study of Güereca et al. (2015) which also showed that co-processing 20% RDF with 80% pet coke in a Mexican cement kiln resulted in lower environmental impacts than the use of 100% pet coke. When the results of this fuel substitution scenario (S_3) were compared to those of the clinker substitute scenario (S_2), better reduction results were obtained for climate change and fossil resource depletion. On the other hand, higher impacts were observed in photochemical oxidant formation: ecosystem quality, particulate matter formation and terrestrial acidification mainly because of the pretreatment, transport and burning of RDF in the cement kilns (Figures 9-13).

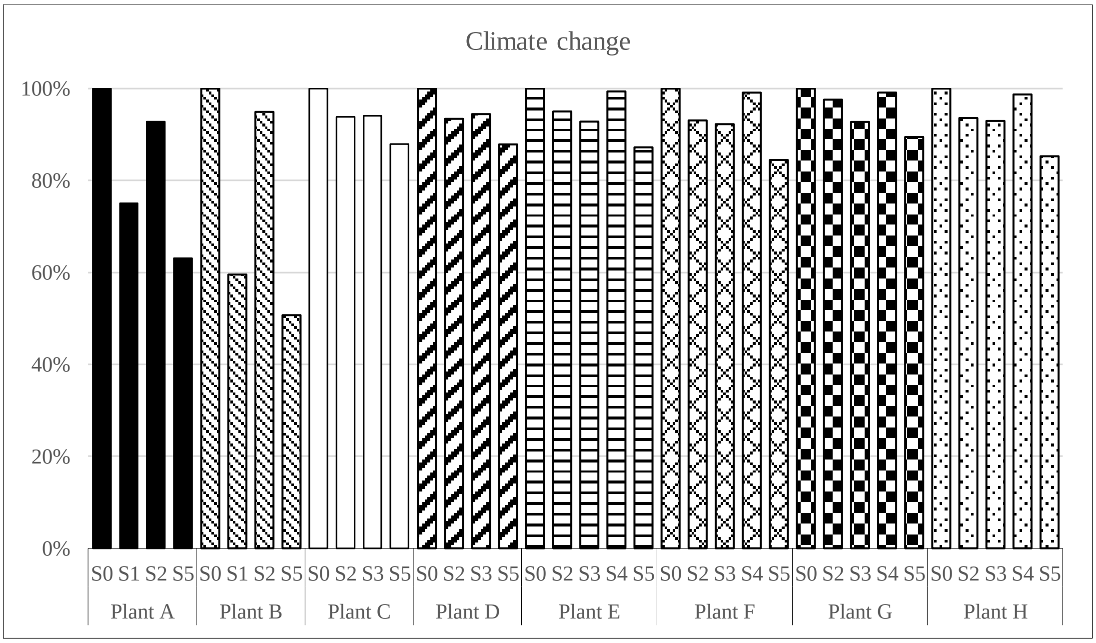

Figure 9. Contribution to climate change by different cement plants under various scenarios

Installing waste heat recovery systems in Plants E, F, G and H (S_4) enabled to substitute 25% of the electricity from the grid required to produce cement. Thus, it was found to contribute to reduce emissions of CO_2 by 0.6-1.2%, NO_x by 0.8-1.6%, SO_2 by 3.5-6.5% and $PM_{2.5}$ by 0.2-0.4% compared to the base scenario (S_0) (Figures 5-8). These reduced emissions result in lower environmental impacts compared to those of the base scenario (S_0), including, 0.6-1.3% reduction in climate change, 0.77-1.57% reduction in photochemical oxidant formation: ecosystem quality, 1.64-3.24% reduction in particulate matter formation and 2.0-4.0% reduction in terrestrial acidification (Figures 9-12). These results are quite different to those from Song et al. (2016) which showed that heat recovery and cogeneration contributed to reduce the environmental impacts related to cement production by 10%, including, eutrophication, abiotic depletion, ozone layer depletion, marine aquatic ecotoxicity and terrestrial ecotoxicity. It was because about 56% of the electricity produced in Myanmar is generated by hydropower and the electricity related emissions of Myanmar were found to be relatively lower than those by Song et al. (2016). The investigations by Müller and Harnisch (2007) also emphasized the importance of electricity on environmental impacts from the cement industry depending on the national grid mix.

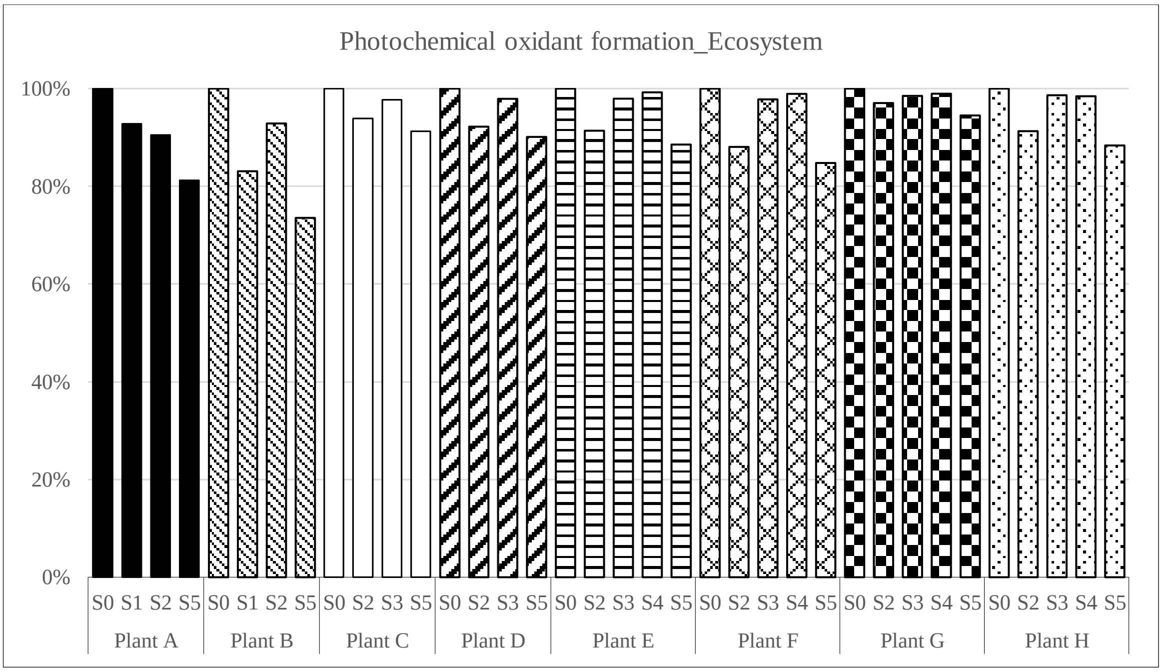

Figure 10. Contribution to photochemical oxidant formation: ecosystem by different cement plants under various scenarios

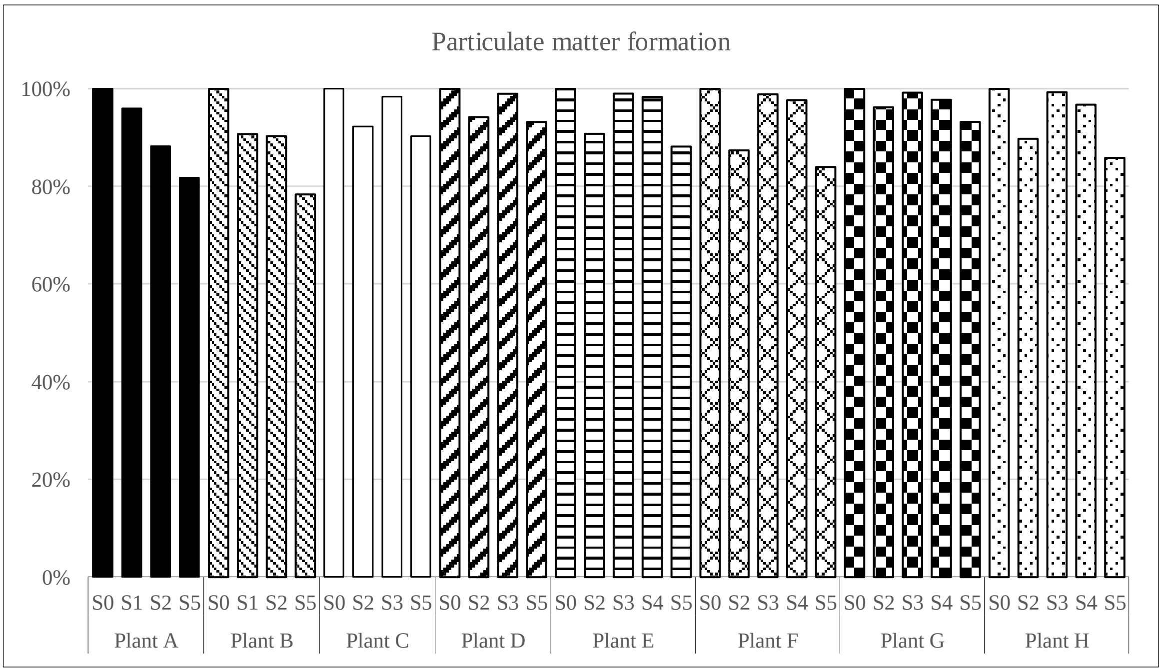

Figure 11. Contribution to particulate matter formation by different cement plants under various scenarios

All possible options related to the above-mentioned scenarios were integrated for each of the 8 cement plants investigated in this study. The results showed that the ideal scenario (S_5) is the best option to mitigate major emissions from the cement plants (Figures 5-8), consequently reducing the major environmental impacts caused by those emissions (Figures 9-12). Regarding fossil resource depletion, the ideal scenario (S_5) showed slightly higher impacts in some plants than the fuel substitution scenario (S_3) due to higher consumption of diesel for transportation of fly ash (Figure 13). However, it was observed that the values of fossil resource depletion related to the ideal scenario (S_5) for all cement plants were much lower than those of the base scenario (S_0).

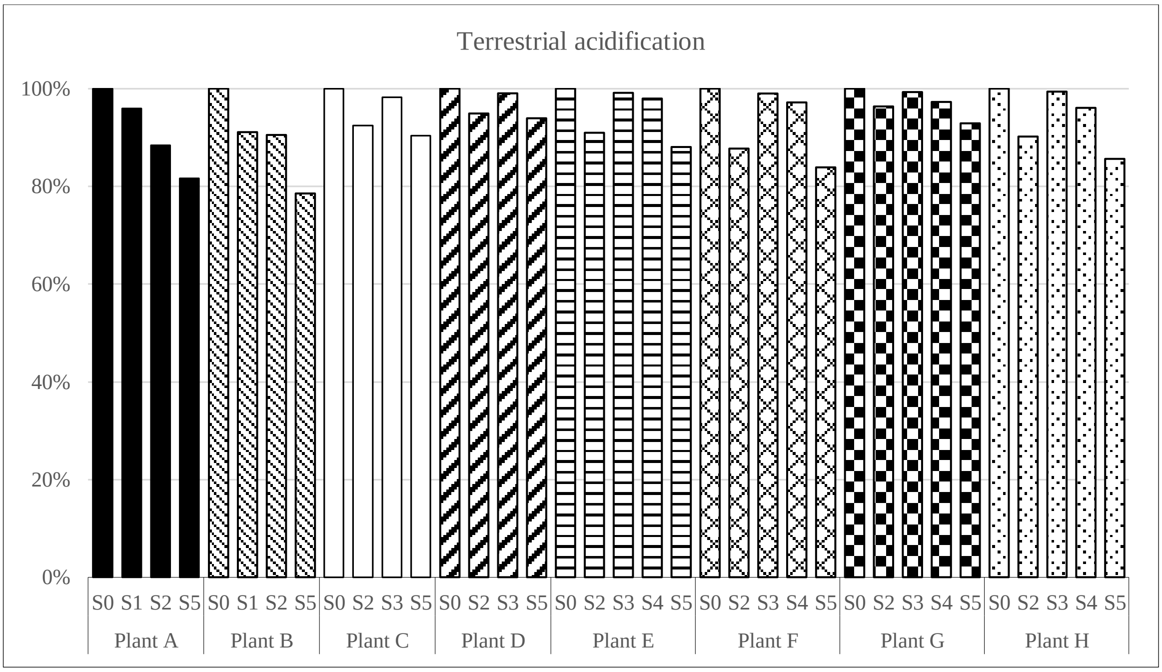

Figure 12. Contribution to terrestrial acidification by different cement plants under various scenarios

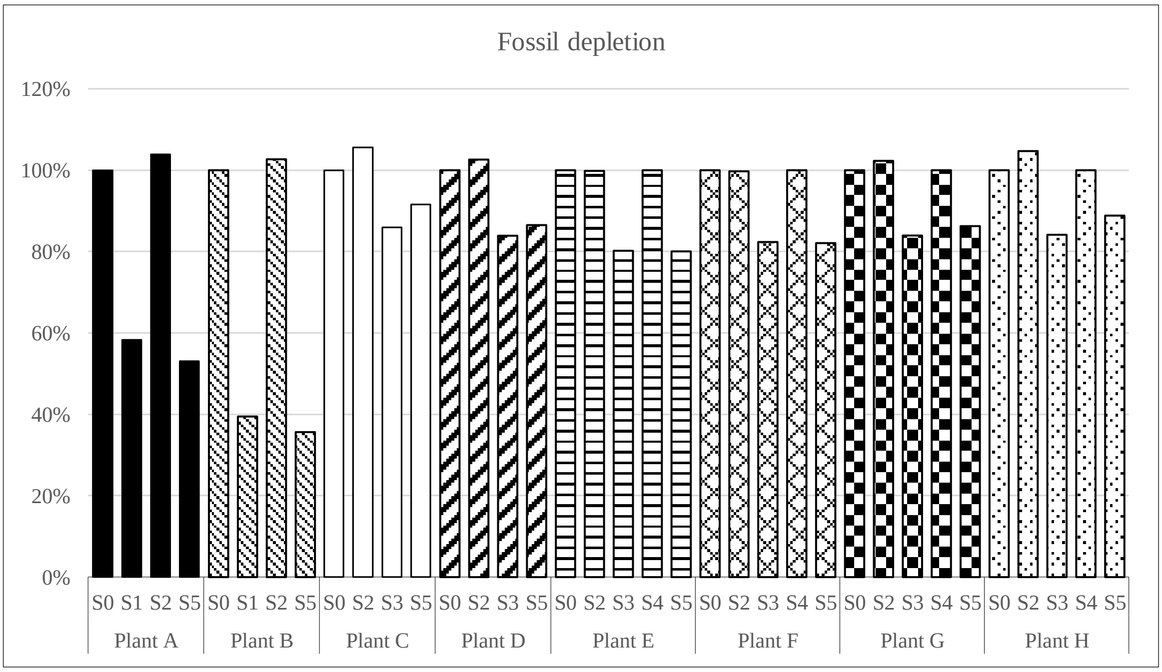

Figure 13. Contribution to fossil resource depletion by different cement plants under various scenarios

6. Conclusion

This study performed LCA of the cement industry in Myanmar and addressed possible options (scenarios) that may be appropriate for the Myanmar cement industry to mitigate environmental burdens from manufacturing cement while improving its environmental performance. Generally, the improvement measures identified are concerned with energy requirement in clinker kilns and fuel consumption. Among the five alternative scenarios developed, the ideal scenarios combining all the possible mitigation measures/ scenarios for optimizing the environmental performance of the investigated cement plants showed the best results. Emission reduction levels were assessed to reach 10-50% for CO_2, 5-23% for NO_x, 4-20% for SO_2 and 6-22% for $PM_{2.5}$, thus reducing major environmental impacts, by 10-50% for climate change, 6-27% for photochemical oxidant formation: ecosystem quality, 7-22% for particulate matter formation, 6-22% for terrestrial acidification and 8-64% for fossil depletion. Myanmar has already published its Sustainable Development Plan (2018-2030) including an action plan to increase the productivity and competitiveness of industrial systems through disaster-and-climate resilience, and low-carbon and green characteristics. As such, the results of this study can assist policy makers in selecting environment-friendly and best available technologies appropriate for the Myanmar cement industry and in developing the related policy for the country's sustainable development. These results can also help industrial design engineers to get a more comprehensive idea about emissions reduction potentials from various options. Sustainability of the Myanmar cement industry requires well-educated and well-trained employees along the value chain of the cement manufacturing. This calls for strong capacity building of the existing employees, i.e., transfer of skills and knowledge regarding emissions reduction in the cement industry and employing dedicated specialists for spreading the best practices in the existing and new plants. Intensive training programmes should be conducted that address the efforts to reduce the consumption of energy and raw materials while complying with environmental regulations and standards for cement quality and cost requirement of the market. Promoting awareness and applied research and development programme would also contribute to enhance the sustainability of this industry sector.

7. Acknowledgements

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Appendices

Appendix 1. Life cycle inventories of cement production by different cement plants in myanmar (per tonne of portland cement)

	Wet Process		Dry Process with pre-calciner					
	Plant A	Plant B	Plant C	Plant D	Plant E	Plant F	Plant G	Plant H
Resource inputs								
Limestone (t)	1.302	1.334	1.368	1.264	1.303	1.502	1.285	1.458
Clay (t)	0.132	0.022	0.098	0.027	-	0.107	0.025	0.059
Mudstone (t)	-	-	-	-	0.157	-	-	-
Sandstone (t)	-	-	0.092	0.038	-	0.034	-	0.119
Bauxite (t)	0.059	-	-	0.107	-	-	-	0.068
Iron ore (t)	-	0.007	0.055	-	-	-	0.032	-
Laterite (t)	-	-	-	-	0.059	0.054	-	-
Dolomite (t)	-	-	-	-	0.032	-	-	-
Gypsum (t)	0.033	0.051	0.055	0.055	0.065	0.053	0.036	0.051
Fly ash (t)	-	-	0.031	0.02	0.027	-	0.11	-
Water (t)	1.068	1.18	0.95	0.19	0.635	0.532	1.865	1.364
Energy inputs								
Explosives (kg)	1.92	2.67	1.16	1.05	1.52	1.70	1.34	1.48
Diesel (kg)	12.49	18.70	8.61	7.28	8.56	9.65	8.48	9.44
Gasoline (kg)	0.05	0.08	0.03	0.02	0.04	0.04	0.03	0.04
Propane (kg)	0.02	0.04	0.01	0.01	0.02	0.02	0.02	0.02
Fuel oil (kg)	0.002	0.003	0.003	0.003	0.004	0.003	0.002	0.003
Natural gas (m^3)	0.041	0.063	0.068	0.068	0.080	0.065	0.044	0.063
Coal (t)	0.35	0.52	0.17	0.15	0.26	0.29	0.22	0.24
Electricity (kWh)	141	127	123	96	101	155	135	230
Emissions to air								
CO_2 (kg)	1.13E+03	1.41E+03	8.62E+02	9.13E+02	1.03E+03	1.11E+03	9.84E+02	1.13E+03
CH_4 (kg)	3.66E-01	5.43E-01	2.25E-01	2.19E-01	3.25E-01	3.78E-01	3.01E-01	3.67E-01
N_2O (kg)	1.02E-	1.52E-	6.19E-	7.05E-	8.95E-	9.71E-	8.54E-	9.86E-

	02	02	03	03	03	03	03	03
NO_x (kg)	1.57E+00	1.70E+00	1.48E+00	1.62E+00	1.37E+00	1.49E+00	1.34E+00	1.54E+00
CO (kg)	1.69E+00	1.81E+00	1.60E+00	1.59E+00	1.59E+00	1.70E+00	1.52E+00	1.71E+00
NMVOC (kg)	3.21E-01	4.70E-01	1.79E-01	2.05E-01	2.49E-01	2.79E-01	2.18E-01	2.44E-01
SO_2 (kg)	4.57E-01	4.49E-01	4.50E-01	1.22E+00	4.18E-01	4.73E-01	4.24E-01	5.21E-01
TSP (kg)	2.80E-01	2.82E-01	2.75E-01	2.71E-01	2.75E-01	2.97E-01	2.43E-01	2.94E-01
PM_{10} (kg)	1.81E-01	1.82E-01	1.78E-01	1.78E-01	1.76E-01	1.90E-01	1.59E-01	1.89E-01
$PM_{2.5}$ (kg)	7.57E-02	7.92E-02	7.05E-02	7.22E-02	6.86E-02	7.35E-02	6.49E-02	7.40E-02
Pb (kg)	9.61E-05	9.43E-05	9.02E-05	9.78E-05	8.91E-05	9.45E-05	8.45E-05	9.50E-05
Cd (kg)	7.85E-06	7.68E-06	7.36E-06	8.28E-06	7.27E-06	7.71E-06	6.90E-06	7.76E-06
Hg (kg)	4.77E-05	4.67E-05	4.48E-05	4.65E-05	4.43E-05	4.68E-05	4.19E-05	4.69E-05
As (kg)	2.64E-05	2.58E-05	2.47E-05	3.16E-05	2.44E-05	2.60E-05	2.33E-05	2.64E-05
Cr (kg)	4.02E-05	3.94E-05	3.77E-05	4.23E-05	3.73E-05	3.95E-05	3.54E-05	3.98E-05
Cu (kg)	6.36E-05	6.22E-05	6.11E-05	6.88E-05	5.91E-05	6.28E-05	5.63E-05	6.34E-05
Ni (kg)	4.80E-05	4.70E-05	4.68E-05	5.17E-05	4.47E-05	4.74E-05	4.26E-05	4.79E-05
Se (kg)	2.68E-05	2.60E-05	2.47E-05	4.65E-05	2.44E-05	2.65E-05	2.37E-05	2.77E-05
Zn (kg)	4.17E-04	4.09E-04	3.92E-04	4.14E-04	3.87E-04	4.09E-04	3.66E-04	4.10E-04
NH_3 (kg)	8.87E-05	1.45E-04	4.71E-05	3.05E-05	5.72E-05	6.78E-05	6.29E-05	7.65E-05

Appendix 2. Raw material constituents for manufacturing one tonne of portland-composite cement

Plant Name	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**Comment**
Process Type	**Wet process**		**Dry process with precalciner**						
Raw materials (tonne)									
Limestone	1.07	1.12	1.20	1.10	1.16	1.26	1.21	1.23	Raw materials to make clinker needed to produce one tonne of cement
Clay	0.11	0.02	0.09	0.02	-	0.09	0.02	0.05	
Mudstone	-	-	-	-	0.14	-	-	-	
Sandstone	-	-	0.08	0.03	-	0.03	-	0.10	
Bauxite	0.05	-	-	0.09	-	-	-	0.06	
Iron ore	-	0.01	0.05	-	-	-	0.03	-	
Laterite	-	-	-	-	0.05	0.05	-	-	
Dolomite	-	-	-	-	0.03	-	-	-	
Total raw materials	1.23	1.15	1.42	1.25	1.38	1.43	1.26	1.43	
Additives in cement making (tonne)									
Gypsum	0.03	0.05	0.06	0.06	0.07	0.05	0.04	0.05	
Fly Ash	0.17	0.15	0.15	0.15	0.14	0.15	0.16	0.15	
Total additives	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	
Distance for transporting fly ash (km)	406	405	410	402	81	78	402	418	

N.B. Some data may not add up to the total values reported because of independent rounding.

Appendix 3. LCI of the pre-treatment, transport, and combustion of 1 kg RDF in cement kiln

	Unit	Amount
Input	**kg**	**1**
LHV	MJ/kg	17.13
Transport, lorry >28t	tkm	0.05
Electricity, medium voltage	kWh	0.092
Heat from incineration plant	MJ/kg	0.23
Emissions to air (kg/kg RDF)		
CO_2	kg	4.74E-01
CH_4	kg	2.53E-06
N_2O	kg	1.32E-05
NO_x	kg	9.94E-05
CO	kg	8.82E-05
SO_x as SO_2	kg	4.46E-06
Pb	kg	1.13E-08
Cd	kg	6.37E-10
Hg	kg	4.07E-14
As	kg	6.38E-15
Cr	kg	4.10E-12
Cu	kg	4.88E-09
Ni	kg	2.35E-12
Se	kg	1.16E-15
Zn	kg	1.61E-08
NH_3	kg	2.48E-06

Note: Pretreatment includes emissions from the production of RDF but does not include the transportation of waste.

Appendix 4. Fuel composition in different cement plants (per tonne of cement)

	Base scenario (S_0)		**20% Thermal substitution with RDF (S_3)**			
	Coal (tonne)	**Coal (MJ)**	**Coal (tonne)**	**Coal (MJ)**	**RDF (tonne)**	**RDF (MJ)**
Plant C	0.17	3556	0.14	2845	0.04	711
Plant D	0.15	3264	0.12	2611	0.04	653
Plant E	0.26	5439	0.20	4351	0.06	1088
Plant F	0.29	5763	0.23	4612	0.07	1153
Plant G	0.22	5063	0.18	4050	0.06	1013
Plant H	0.24	5824	0.19	4659	0.07	1165

Appendix 5. Emissions to air from the generation of electricity through a WHR system

Parameters	**Amount (kg/kWh)**	**Parameters**	**Amount (kg/kWh)**
CO_2	2.8E-03	Pb	8.2E-11
CH_4	5.0E-06	Cd	7.9E-12
N_2O	1.6E-08	Hg	1.8E-11
NO_x	5.0E-06	As	6.1E-11
CO	2.1E-06	Cr	4.1E-11
NMVOC	6.6E-07	Cu	7.4E-11
SO_x as SO_2	6.9E-06	Ni	4.2E-11
TSP	1.6E-07	Se	1.8E-10
PM_{10}	1.2E-07	Zn	1.9E-10
$PM_{2.5}$	6.7E-08	NH_3	1.0E-09

Appendix 6. Midpoint environmental impacts from cement plants in Myanmar

Impact category	Unit	Plant A	Plant B	Plant C	Plant D	Plant E	Plant F	Plant G	Plant H
Climate change	kg CO_2 eq.	1.15 E+03	1.43 E+03	8.72 E+02	9.23 E+02	1.05 E+03	1.13 E+03	9.97 E+02	1.15 E+03
Ozone depletion	kg CFC11 eq.	1.12 E-04	1.67 E-04	6.81 E-05	7.75 E-05	9.84 E-05	1.07 E-04	9.39 E-05	1.08 E-04
Photochemical oxidant formation: human health	kg NO_x eq.	1.63 E+00	1.78 E+00	1.51 E+00	1.66 E+00	1.41 E+00	1.54 E+00	1.38 E+00	1.58 E+00
Photochemical oxidant formation: ecosystem quality	kg NO_x eq.	1.65 E+00	1.84 E+00	1.53 E+00	1.68 E+00	1.44 E+00	1.57 E+00	1.41 E+00	1.61 E+00
Fine particulate matter formation	kg $PM_{2.5}$ eq.	3.80 E-01	3.96 E-01	3.64 E-01	6.03 E-01	3.41 E-01	3.74 E-01	3.36 E-01	3.94 E-01
Terrestrial acidification	kg SO_2 eq.	1.02 E+00	1.06 E+00	9.82 E-01	1.80 E+00	9.12 E-01	1.01 E+00	9.08 E-01	1.07 E+00
Terrestrial ecotoxicity	kg 1,4-DCB eq. emitted to industrial soil	2.22 E+02	2.18 E+02	2.11 E+02	2.29 E+02	2.06 E+02	2.19 E+02	1.96 E+02	2.20 E+02
Freshwater ecotoxicity	kg 1,4-DCB eq. emitted to freshwater	3.65 E-03	3.58 E-03	3.45 E-03	3.73 E-03	3.39 E-03	3.59 E-03	3.21 E-03	3.61 E-03
Marine ecotoxicity	kg 1,4-DCB eq. emitted to seawater	1.04 E-01	1.02 E-01	9.90 E-02	1.08 E-01	9.68 E-02	1.03 E-01	9.19 E-02	1.03 E-01
Human toxicity: cancer	kg 1,4-DCB eq. emitted to	8.49 E-01	8.31 E-01	7.97 E-01	8.97 E-01	7.87 E-01	8.34 E-01	7.46 E-01	8.40 E-01

	urban air								
Human toxicity: non-cancer	kg 1,4-DCB eq. emitted to urban air	1.01 E+01	9.86 E+00	9.45 E+00	1.06 E+01	9.33 E+00	9.89 E+00	8.85 E+00	9.96 E+00
Water consumption	m^3 water consumed	1.07 E+00	1.18 E+00	9.50 E-01	1.90 E-01	6.35 E-01	5.32 E-01	1.87 E+00	1.36 E+00
Mineral resource scarcity	kg Cu-eq.	2.80 E+01	2.74 E+01	3.11 E+01	2.70 E+01	2.98 E+01	3.30 E+01	2.68 E+01	3.23 E+01
Fossil resource scarcity	kg oil-eq.	1.60 E+02	2.37 E+02	8.01 E+01	7.04 E+01	1.18 E+02	1.32 E+02	1.01 E+02	1.10 E+02