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Life-cycle environmental impact analysis of a typical cement production chain ☆

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HIGHLIGHTS

- The lifetime environmental impacts of a cement production chain were evaluated.
- A comparison of best available technologies was conducted by setting scenarios.
- Calcination and grinding processes are the largest environmental emitters.

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ABSTRACT

Cement is one of the three main construction materials, which provides support for other related industries and fuels the economic growth. However, cement production is also a high-polluting sector. In this study, a life-cycle environmental assessment was performed for a typical new suspension preheater dry process (NSP) cement production in China. A comparison of the life cycle environmental impact of best available technologies was also conducted by setting a series of scenarios so as to find the most promising alternative in reducing environmental impacts. The results suggest that although direct calcination is the largest contributor of environmental emissions in the cement production system, indirect sections, particularly the downstream grinding section, play an important role in terms of environmental impact, which should be considered as the control point in achieving energy saving and emission reduction goal. Comparing the environmental performance of raw material and fuel substitution alternatives and best available technologies, the results of scenario analysis reveals that environmental benefits of carbide slag and the mixture of carbide slag and limestone slag as raw material substitutions is not prominent as it induces extra environmental costs that offset the environmental benefits from reduced limestone usage. Corn straw as coal substitution and heat recovery and cogeneration are found to be promising ways to achieve environmental mitigation with a notable environmental benefit for cement production. The prevailing NSP kiln technology is more environmental beneficial compared with shaft kiln technology.

1. Introduction

Cement industry provides an irreplaceable support for the operation of various downstream industries of Chinese economy. The production of cement industry in China increased from 597 million tons in 2000 to 2.18 billion tons in 2012 due to growing demand. Cement produced by China's industry accounted for 58% of global cement output in 2012 [1,2]. Moreover, this status will continue in the next decade, which may exert great pressure on the environment. The total coal and electricity consumptions of the Chinese cement industry in 2012 amounted to 208 million tons and 168 billion kWh, which result in the atmospheric emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulates at 1.09 million, 1.98 million and 0.67 million tons, respectively [3,4]. In addition, CO_2 emissions of Chinese cement industry accounts for 5–8% of global anthropogenic emissions [5]. Due to the extensive resource consumption and inevitably environmental discharge in the production process, cement production has attracted growing

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concern in exploring its emission reduction potential [6,7]. Different from other industries, cement production emits pollutions not only via direct fossil fuel use, but also through the production procedure as indirect emission [8]. Therefore the whole process emission must be considered when assessing the environmental impacts of cement industry.

Life cycle assessment (LCA) is a valuable tool for improving our understanding of the environmental hazards posed by a product's life stages. Using LCA, many existing studies have been conducted to evaluate the environmental impacts of cement production chains [7,9–14]. However, in light of the expanding cement production in China, it is crucial to not only probe into environmental impacts of traditional production lines, but also to find possible improvements of Chinese cement production through technological changes in the context of environmental impacts alleviation. Currently, research on environmental impacts of fuel substitutions [15,16], raw materials substitutions [17–21], and best available technologies [3,12,22–26] for cement production have already been conducted. In China, although new suspension preheater dry process cement production constitutes more than 90% of total cement production in 2012, technological improvements that contribute to energy saving and environmental emission reduction should be explored to meet the more and more strict environmental protection goals.

This paper aims to undertake a lifetime environmental assessment of a typical 2500 t/d new suspension preheater dry process (NSP) cement production line in China, and compare its environmental impacts with those of best available technologies and raw material and fuel substitutions in calcination. The purposes of this paper include: to find the environmental emission-intensive sections in the cement production chain, and to shed light on future technology selection of cement production based on a life-cycle examination of the pro and cons of best available technologies in cement production. The rest of this paper is organized as below: In Section 2, the steps how LCA is conducted in cement production are introduced in detail. The environmental impact assessment results of a typical Chinese NSP cement production chain are presented in Section 3. Scenario analysis of best available technologies is conducted in Section 4. Finally, based on the LCA of the cement production line, conclusions are drawn to shed light on the selection of cement production technological pathways.

2. Methodology

LCA is a tool to assess the potential environmental impacts and resources used throughout a product's lifetime, i.e., from raw material acquisition, via production and use phases, to waste management [27]. Based on ISO 14040 standard, there are four major steps of an LCA of cement production, i.e., (1) define the assessment goal and system boundary; (2) compile the life-cycle inventory; (3) conduct the life-cycle impact assessment of the product/technology; and (4) interpret, summarize, analyze and communicate the results. In this section, the LCA method of cement production is elaborated based on the steps aforementioned.

2.1. Goal and scope definition

The goal of this study is to appraise the environmental performances of a typical NSP cement production chain as well as its technological alternatives. The considered functional unit is 1 t Portland cement production. In terms of system boundary, LCA is in principle a cradle to grave exercise. However, in some cases cradle to gate, gate to gate, gate to cradle or, more recently, cradle to cradle approaches are possible. In the case of cement the approach can only be cradle to gate as it can have many different applications later. Therefore, the whole cradle to gate process within system boundary include mining, transportation of raw materials, crushing, preblending, grinding, homogenization, preheating decomposition, clinker calcining, grinding, packaging, and waste treatment. To simplify the whole production chain, we merge the whole chain into 8 processes, i.e., mining, transportation, raw material preparation, calcination, waste gas treatment, grinding, packaging and others (see Fig. 1). The emission discharge is emphasized at these stages.

2.2. Life cycle inventory analysis

The materials and energy consumed in this system embrace: (1) limestone, sandstone, flyash, sulfuric-acid residue, gypsum and mixtures; (2) energy input from external systems such as coal and electricity. The system outputs include P.O 42.5 Portland cement (0.455 million tonnes) and P.F 42.5 Portland cement (0.578 million tonnes). The specification of P.O 42.5 and P.F 42.5 Portland cement is shown in Table 1. The data was collected from a typical enterprise in north China with a production capacity of 77.5E + 04 tons per year. The data cover all the consumed raw materials and energy in the production chain.

2.2.1. Mining

The required limestone is 0.92 million tonnes per year for cement production. The recoverable source of the mine nearby the concerned cement plant is 70.02 million tonnes, which is affluent for limestone extraction. In the mining process, the environmental impacts of electricity consumption by extraction machines used are taken into account.

2.2.2. Transportation

The cement production plant concerned in this study has a convenient transportation network. Motor transportation is used for raw material and products delivery, starting from the manufacturer nearby and arriving at each specific site for production. In this case, heavy diesel truck with the carrying capacity of 30 t was used for transportation. The quantity and distance transported is shown in Table 2.

2.2.3. Raw material preparation

The raw material preparation stage includes processes of crushing, preblending of sandstone, raw material grinding, fuel preblending and grinding. In this stage, electricity is used to drive equipment of crusher, belt conveyor, stacker–reclaimer, vertical mill system and ball pulverizer. The electricity consumed in this stage is 19.6 GW h.

2.2.4. Calcination

The prepared raw material is then heated in a pre-calciner to initiate the decomposition of $CaCO_3$ to calcium oxide (CaO) and CO_2. It is then burned in a rotary kiln to continue the reaction between CaO and other elements to form calcium silicates and aluminates. The output mixture, i.e., clinker, is delivered for cooling afterwards. The capacity of the calcination system is 2500 t/d, with the heat rate of 3178 kJ/kg. In this stage, direct environmental emissions from $CaCO_3$ decomposition and raw coal combustion and indirect emissions from electricity consumption are considered.

2.2.5. Waste gas treatment

The dust generated from raw material grinding and calcination is collected and delivered to a bag filter, and emitted out via dust-discharging fan. In this stage, electricity of 0.2 GW h is used for the operation of bag filter and dust-discharging fan.

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