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Eco innovation strategies for promoting cleaner cement manufacturing

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Carbon dioxide (CO_2) emissions in cement plants are generated by the decarbonation of raw materials and fuel combustion in the cement kiln during the cement clinker production process and account for 8% of global emissions. This paper presents a mixed integer linear programming (MILP) by considering various mitigation measures, such as co-processing of fuels, kiln improvements and carbon capture and storage (CCS) yields, that can have substantial benefits. The benefits include cleaner cement production with minimum production costs, while satisfying the quality standard, carbon reduction target, and fuels substitution rate. The developed model is applied to a case study in order to demonstrate the applicability of the model. For the base case, the optimal cost for clinker production is USD 90.21/t clinker while CO_2 emissions generated from both calcination of raw materials and fuels combustion is 531.68 kg CO_2/t clinker and 325.00 kg CO_2/t clinker. It was found that the highest possible CO_2 emissions reduction that can be achieved by a combination of co-processing, kiln improvements and CCS technology is 79%, with an increment cost of USD 136.46/t clinker.

1. Introduction

Cement is an important component of concrete as it is considered to be a binder that holds concrete mixture together and gives it strength. Despite the fact that it is an energy and emission intensive industry, the cement industry is essential for the economic development of a country. The manufacturing process for the cement industry consists of 3 major steps: raw material preparation, clinker production, and cement production. In raw material preparation, quarrying is done first, then followed by pre-homogenization and grinding of raw materials. During clinker production, burning of fuels to provide heat and chemical reaction occurs in a cement kiln. A chemical reaction between pre-homogenized raw materials and fuels' ash in the cement kiln produces clinker that is then stored in clinker silos. During cement production, blending of clinker with grinding aids for final adjustment occurs, followed by storage, then shipment. Fig. 1 shows the general dry and wet manufacturing process.

The decarbonation reaction of raw materials - normally limestone (conversion of limestone to lime) or calcium carbonates ($CaCO_3$) rich materials in cement kiln - contributes to about 50% of the total carbon dioxide (CO_2) emissions of a cement plant while the combustion of fuels in the cement kiln leads to 40% of the total CO_2 emissions (Benhelal et al., 2013). According to Tsakalakis and Stamboltzis (2008), roughly two thirds of the total electrical energy consumption for cement production are used for particle size reduction (grinding) and about 2% of the electricity produced globally is used during the grinding process of raw materials (Katsioti et al., 2009). Cement industry is a significant contributor of greenhouse gas (GHG) emission. It was found that reducing the emission may lead to substantial reduction of overall GHG emission (Valderrama et al., 2012). Improving thermal efficiency would create a high potential for reducing CO_2 emissions from cement plants.

An optimisation model towards emission mitigation in cement plants has been discussed by numerous researchers. The most relevant study was published by Kookos et al. (2011). The author developed a mixed integer linear programming (MILP) optimisation model to minimise cement manufacturing costs by co-processing. Carpio et al. (2008) used mathematical modelling to

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Nomenclature

Sets

a	Alkalis
fg	Flue gases
h	Heavy metals
j	Raw materials
k	Fossil fuels
l	Non fossil fuels
o	Oxides
p	Clinker phases
s	Sulfurs

Parameters

A	Availability in kg/t clinker
Bogue	Bogue value
C	Unit cost in \$/kg
CEF	Carbon emission factor in kg CO_2/kg
CO_{2GHG}	Current CO_2 emission without mitigation method in kg CO_2/t clinker
FCI	Capital investment in \$ M
M	Big M constant
MB	Amount of *p*th clinker phases in clinker product in %.
mw	Molecular weight in kg/kmol
n_c	Effects when oxy-fuel capture is selected
NCV	Net calorific value in GJ/kg
Ø	Effects when fuels are selected
OC	Operating cost in \$ M/y
St	Stoichiometric for O_2 required for fuel combustion in kg O_2/kg
TED	Thermal energy demand in GJ/t clinker
TED*r*	Thermal energy reduction in %
TSR	Thermal substitution rate in %
ε	Carbon capture and storage efficiency in %
ω	Mass fraction in wt%

Binary variables

X	Technology selections

Continuous variables

m	Mass in kg/t clinker
V	Volumetric gas flow in Nm^3/t clinker under normal condition
$\alpha, \beta, \gamma, \theta$	Linearization variables for *mX*

Abbreviations and nomenclature

ASU	Air separation unit
BP	Back propagation
C	Carbon content in fuels
C_2S	Dicalcium silicate
C_3A	Tricalcium aluminate
C_3S	Tricalcium silicate
C_4AF	Tetracalcium aluminoferrite
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CCS	Carbon capture and storage
CL	Carbon looping
CO_2	Carbon dioxide
GA	Genetic algorithm
GAMS	General Algebraic Modelling System
HDP	Heuristic dynamic programming
LCA	Life cycle assessment
MBM	Meat bone meal
MEA	Monoethanolamine
MgO	Magnesium oxide
MILP	Mixed integer linear programming
MLD	Mixed logic dynamic
NCV	Net calorific value
N_2	Nitrogen
O&M	Operating and maintenance
O_2	Oxygen
OPC	Ordinary Portland cement
PC	Petroleum coke
PS	Pattern search
PSO	Particle swarm optimisation
RDF	Refuse derived fuel
S	Sulfur content in fuels
SO_3	Sulfur trioxide
SS	Sewage sludge
TED	Thermal energy demand
TSR	Thermal substitution rate
TDF	Tire derived fuel

calculate whether the substitution levels of the primary fuels by alternative fuels is possible. Similarly, Oyepata and Obodeh (2015) used Particle Swarm Optimisation (PSO) to find the whether optimal cost for cement production is bounded by environment constraint and cement quality. The results shows that the optimal cost with the use of alternative fuel can be reduced by 30–70% without compromising the product. The studies, however, only considered co-processing in mitigating CO_2 emission from cement plants.

The integration of various methods using MILP optimisation has been discussed by several studies. Adebiy et al. (2015) discussed the implementation of several energy efficient technologies in the cement plant. Ba-Shammakh et al. (2008) considered three mitigation options: efficiency improvement, switching to less carbon content fuel and applying a post combustion capture system. Ogbeide (2010) also considered several energy efficient technologies, fuel switching and a post combustion capture system. The models that considered economic and environmental factors, however, did not consider how the selected technologies will affect the quality and chemistry of the product and the effects of CO_2 reduction on the raw materials and fuels consumption. Moya et al. (2010) studied a cost effective combination of retrofitting of rotary kilns, energy efficient grinding technology (substitution of ball mills to vertical roller mills), co-generation (waste heat recovery), and a post combustion capture system to improve energy efficiency and mitigate CO_2 emissions up to 2030. The study proposed an economical optimisation model with no consideration of quality and chemistry of the product; the environmental aspect of the study is driven by the economic value of the savings.

As a whole, few studies have implemented systematic and comprehensive modelling to evaluate the economic and environmental impact from various mitigation methods on cement quality and production. There is also a lack of optimisation studies that consider the potential of an oxy-fuel combustion system as one of the options for capture technologies. This study integrates various CO_2 mitigation in cement plants while satisfying cement quality