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Meeting international standards of cleaner production in developing countries: Challenges and financial realities facing the Indonesian cement industry

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ABSTRACT

A key challenge for heavy industry in emerging economies is how to meet international greenhouse gas (GHG) emission standards since they are often based on the conditions and capacities of manufacturing in advanced countries. Firms in developing nations are typically cost-driven and reliant on older, less efficient technology: very few have achieved the relevant targets. Cement making underscores the point: no study to date has specifically quantified, in technical and financial terms, the gap between existing firm performance and global GHG emission standards. We examine Indonesia's largest cement manufacturing facility to investigate what needs to be done to overcome the discrepancy. The article starts by reviewing key contextual issues such as the facility's location, scale, organisational configuration, available materials, energy use, and technological capacities. The plant's direct emission intensity is 0.69 t CO_2e/t cement, higher than the global target for 2030 (0.55 t CO_2e/t). Analysis reveals six potential emissions reduction activities: (1) utilizing fly ash as a clinker substitute; (2) employing limestone as a clinker substitute; (3) using biomass from rice husks as an alternative fuel; (4) adding pre-heating stages in kilns; (5) waste heat recovery for power generation; and (6) using refused-derived fuel from municipal solid waste as an alternative fuel. These measures, if adopted in full, could reduce GHGs at the facility by up to 33%, or a total of 34,145,190 t CO_2e over a 10-year timeframe (2020–2030). This abatement action would leave the facility's direct emissions intensity to 0.48 t CO_2e/t cement. In present values, assuming a 10% discount rate, they would result in savings of US$415 million for a US$94 million outlay. Despite the apparent technical and financial advantages, all measures together are unlikely to be adopted, since the plant studied is well advanced in its lifecycle and the parent company is experiencing financial constraints common to those in developing nations.

1. Introduction

In engineering today, standard-setting is indispensable to safety and replication of process outcomes. It provides specifications, guidelines, and reference points against which measures and processes can be calibrated to ensure the consistency and reliability of products, services, and systems. These provisions create a level and accessible playing field, overseen by globally recognized bodies. The impetus for cleaner production in manufacturing owes much to the transportation industries (EPA, 2021) as exemplified in the London smog outbreaks of 1873 and 1952 which caused many fatalities. Whereas procedures in mechanical and structural engineering were formalized earlier in the 20th century, chemical engineering standards for factory wastes were frequently overlooked. Across entire economies, air and water pollution have claimed increasing attention, necessitating public and private sector oversight to manage emissions. In 1976, the United States National Academies of Science reported the damaging effect on the earth's ozone layer of chlorofluorocarbons (CFCs) (ACS, 2017). By the late 1980s, this concern had expanded to GHGs as they affect global warming (Weart, 2008). The United Nations Inter-governmental Panel on Climate Change (IPCC), in its first Assessment Report (1990), recognized the effect of GHGs: in its second (1995), raised the concept of mitigation; and, in the third (2001), advocated climate change adaptation. Quantitative standards were subsequently established for the release of emissions into the atmosphere from particular sources over certain periods (Farzin, 2003;

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Abbreviations

AF	Alternative Fuel
CCS	Carbon Capture and Storage
CKD	Cement kiln dust
GAR	Gross as Received
^{N}CV	Net Calorific Value
RDF	Refused-Derived Fuel
WHRPG	Waste Heat Recovery Power Generator

Rootzén and Johnsson, 2013).

Presently, industry-related emissions form more than 30% of the global GHG output from all sources. Nearly half the secondary sector's emissions come from cement and steel making (van Ruijven et al., 2016; Pee et al., 2018). They generate bulk carbon dioxide (CO_2) both from large-scale energy consumption and inherent chemical processes. Cement production alone accounts for 8% of total world emissions, greater than the contributions of the leading individual nations, save China and the United States (Andrew, 2018; Timperley, 2018). Four of the world's six largest cement-producing countries are regarded as emerging economies.[1]

The achievement of cleaner production depends on many factors. Those relevant to cement making have been discussed in respect of: fuel sources and energy usage (Madlool et al., 2013; Brunke and Blesl, 2014); component technology and cleaner production (Benhelal et al., 2013; Morrow III et al., 2014); and emissions management (Kajaste and Hurme, 2016; Panjaitan et al., 2020). The focus of these works is invariably upon developed countries (Benhelal et al., 2013; Madlool et al., 2013). They do not canvass contextual issues of technology and production dynamics, as can confront onshore manufacturers in developing countries when addressing worldwide standards (Dicken, 2003; Hasanbeigi, Menke and Therdyothin, 2010; Rootzén and Johnsson, 2013; Kajaste and Hurme, 2016). There, production, market, and regulatory realities, along with possible environmental constraints, render the notion of "best practice" an aspiration, rather than as a fact, as might be implicit in advanced nations. Emerging economies cannot necessarily provide extensive resources to curb emissions since, being labour-rich but capital-constrained, their initial concerns must be about *competitive* and *sustainable* operations.

This triad – competitive, leading to sustainable and, then, cleaner production – forms our initial theoretical standpoint. In a country lacking a competitive sector, there is no domestic manufacturing to study: probably, its market would instead be served by importing. 'Competitive production' segues into two senses of sustainability: first, manufacturing should evolve durably over time and, second, it should reflect the logic of 'reuse, recycle, reduce' around which eco-industrial complexes in developed societies function. Thus, competitive and sustainable processes become pre-requisites of cleaner production. In the global South, the last could pose cost burdens which could impact financial returns or, alternatively, create outcomes judged sub-optimal compared with other investment opportunities.

Given this background, a major gap in knowledge emerges around the challenges faced by cement producers in the global South to meet the international standards which underpin cleaner production. The need for deeper inquiry exists in that foregoing studies have overlooked the important nexus of constraints and capabilities (Table 1). They have taken only the initial step, with less than full financial accounting, to appraise emissions. None has discussed the use of marginal abatement cost analysis beyond its immediate contribution to GHG reduction: pursued further, it can specify *the means* to meet international emission targets. Admittedly, some of the research pre-dated the inception of current standards. In developed countries, writers might have surmised that global climate targets would be inevitably or easily met. Alternatively, the relation of industrial performance to key concerns such as a social licence to operate and corporate reputation (as a 'clean' or 'dirty' industry) might have been under-appreciated. Such rationalisations, however, fail to acknowledge the reality today of international requirements for sustainable development. The contribution of the current investigation will be novel and significant in answering the focal research question: how can cement manufacturers in emerging economies meet global cleaner production accords given their plant technology and market opportunities?

An approach to this query must set out the terms of reference which link cement production with emission levels. For clarity in this article, *inputs* are read (in consistent order) as materials and energy. The *outputs* of primary interest are final products: simply, cement, and gaseous emissions.

Apropos emissions, the 2015 Paris Agreement, a legally binding international agreement on climate change, aims to limit global warming to below 2 °C, preferably to 1.5 °C, compared with pre-industrial levels. The United Nations Framework Convention on Climate Change (UNFCCC) has responded with a global direct emission intensity standard (i.e. an *output*) for cement making (Dietz, 2017; IEA, 2018b). Cognizant of the IPCC guidelines, the World Business Council for Sustainable Development (WBCSD) and the International Energy Agency (IEA) have established four *input* efficiency targets for sustainable operations by 2030. Explaining them from the top of Table 2: (1) the clinker factor specifies the ratio of clinker (as an intermediate product from the calcination process) per tonne of cement; (2) alternative fuel (AF) utilization represents the percentage level of thermal energy requirements obtained from alternative, lower carbon fuels; (3) the thermal energy index indicates the thermal energy required for calcination in the kiln to produce one tonne of clinker; (4) the electricity index relays the electricity consumption needed to produce one tonne of cement; and (5) the direct emission intensity shows the tonnage of direct emissions released in producing one tonne of cement. The first four standards should contribute to both competitive and sustainable operations. They are necessary to achieve the fifth condition concerning the direct emission output of a plant, as a measure of its 'cleaner production'.

In that these standards apply universally, producers in the South should reflect upon their origins and local applicability. The WBCSD comprises leaders of around 200 global/multinational business organizations, more than 80% of whom come from developed countries.[2] In its sub-group fostering sustainable processes in the cement industry, membership consists of 24 of the world's foremost producers operating in 100 nations, but is again dominated by capital domiciled in the advanced world (WBCSD, 2009). The IEA is a Paris-based, global energy authority which helps members coordinate collective responses to supply disruptions. It includes 30 countries, all ('rich nation') participants within the Organisation for Economic Co-operation and Development (OECD).[3] In sum, the standards set out in Table 2 did not emerge from the developing world and might not take full account of the situation of its domestically-invested cement manufacturers.

In tackling the challenges of cleaner (cement) production in an emerging nation, we need to: (1) select a suitable country and manufacturing complex for study; (2) develop appropriate methods to analyze production and emission dynamics; and (3) propose a research plan oriented to the overarching international standards. Such a plan can provide new dimensions in identifying the opportunities for innovation in green strategy and compliance. The agenda requires an in-depth investigation which considers relevant investment costs and

[1] https://www.statista.com/statistics/267364/world-cement-production-by-country/.

[2] https://www.wbcsd.org/Overview/Our-members.

[3] https://www.iea.org/about/membership.

Table 1
Mitigation measures, emission reduction and associated costs in cement making for different locations/countries.

Study	Location	Aim	Method	Finding	Statement
Benhelal et al. (2013)	Global	Developing global strategies and potential for emissions reduction	Identifying barriers to adopting abatement measures	Alternative materials utilization, energy-saving, and carbon capture and storage (CCS) are key strategies of emission abatement	Economical and technical challenges still pose critical barriers in adopting the latter two key strategies to reduce emissions.
Hasanbeigi, Menke, & Price (2010)	Thailand	Assesses emission reductions and abatement costs	Marginal Abatement Cost (MAC)	41 abatement technologies and measures	MAC results could vary, depending on variables which could post different values from one country to another.
Hasanbeigi et al. (2013)	China	Reviews energy efficiency opportunities	MAC	23 energy efficient technologies and measures	Energy savings and energy efficiency costs will vary. Efficiency gaps occur because requisite measures cannot be adopted.
Brunke & Blesl (2014)	Germany	Determines cost-effective energy-saving potential	MAC	21 measures	Efficient usage could compensate for the high electricity price.
Kajaste & Hurme (2016)	Global	Managing emissions in cement making	MAC	Clinker substitutes, technology, energy sources and geographic location are the key to the emissions balance	Abatement costs vary, depending on the technology, geographical location and initial level of emissions.
Zuberi & Patel (2017)	Switzerland	Insights, indicators, energy-efficiency and cost measurement	MAC	Reduce the energy consumption and emissions by 14% and 13% respectively from the 2014 figure.	The adoption of best practice runs into techno-economic constraints, and the savings from cost-effective measures are low due to low final energy and CO_2 prices.

Table 2
Key elements of the 2030 global sustainable development scenario for cleaner production in the cement industry (IEA, 2018b).

	Indicator	Ratio measure
Input:	1. Clinker factor (CF)	clinker/cement
	2. Alternative fuels (AFs) utilization	% of total thermal energy required
	3. Thermal energy index	GJ/t clinker
	4. Electricity index	MWh/t cement
Output:	5. Direct emission intensity of cement	t CO_2/t cement

other variables (e.g. raw materials and AF prices along with their location and availability, discount rates, and emission factors) to quantify the link of abatement costs with emission reductions unexplored in previous enquiry (Nauclér and Enkvist, 2009; Benhelal et al., 2013; Kajaste and Hurme, 2016). The work must also interrogate cleaner production measures against a broad economic and environmental backcloth and propose a staged approach to low-carbon operations. This process should highlight the challenges in meeting global standards with, effectively, sub-optimal manufacturing infrastructure compared with that of advanced nations.

The first decision, regarding the selection of a candidate country, can be quickly resolved. As one of the world's largest cement producers, Indonesia offers an ideal study setting. In 2018, the said industry accounted for around 20% of its GHGs in manufacturing, equivalent to 7% of all the nation's emissions from energy use (Panjaitan et al., 2018). Cement-making has become a focus of domestic climate change policies. In 2018, 11 firms were undertaking onshore production, with some additionally importing. Most plants are located in Java which boasts up to 80% of the archipelago's production capacity. Four-fifths of the market is dominated by two cement groups (Indocement, 2018), one of which is selected for detailed analysis in the current project.

Quantitative elements essential to project deliverables include: (1) re-application of the marginal abatement cost (MAC) approach, not only because it has been absent in academic/industry studies in Indonesia (Nauclér and Enkvist, 2009; Benhelal et al., 2013; Kajaste and Hurme, 2016), but also as the key to understanding investment decisions to realize emission reductions and (2) detailed in-company information. Without hard data derived from accounting investigations at the firm level, management priorities and attitudes to carbon reduction remain clouded. Needed also is a sound engineering appreciation of plant fit-out, operations and opportunity, consonant with professional experience of market and economic realities in a developing country. Evidence-based assessment (i.e. a MAC audit) provides the most logical route to build a theoretical base which, initially, must be inductively-constructed and pay close attention to local conditions. As to Indonesian cement production, two core issues emerge:

1. Which appropriate and potential mitigation actions are achievable, given site-specific plant conditions and the developing country context?
2. What are the costs from successive mitigation actions, taking into account the plant's location and condition compared with those of other emerging and developed countries?

To address these queries, the necessary tasks involve a statement of project methods including those of data collection, assessment techniques, an explanation of MAC accounting, and a description of the case study setting. Emergent results must be subject to in-depth analysis and discussion, leading to the development of a new theoretical approach to finalize the research agenda. It can be used as a blueprint by industrial sectors in different locations or economic settings to address shortfalls in clean production and to help achieve international emission standards.

2. Method and data sources

2.1. Data collection

Manufacturing data were collected first-hand from the leading cement operation in Indonesia for the timespan January to December 2017. They cover operational hours, types of equipment, age, volume of raw materials, energy usage and prices, production output, and emission reduction measures undertaken. Data were fact-checked with company management to guarantee their validity. The information gathered is necessary and sufficient to (1) assess the direct and indirect emission intensity for each tonne of clinker or cement produced; (2) determine sources of emissions which should become a priority for reductions; (3) provide expense estimates for the potential abatement methods identified as operationally feasible; and (4) interrelate the emission gains with their respective costs in the case of a mid-life, technologically sub-optimal plant in an emerging nation. The results obtained from calculations using these original and detailed data will furnish a set of local performance benchmarks but could obviously require calibration for competitor cement companies at different stages of engineering development in Indonesia and comparable nations.

2.2. Assessing resources, production technology and emissions

On the input ledger, resource usage of both materials and energy can be recorded by charting consumption data over an accounting period. Materials usage is calculated as a unit of weight (tonnes) and volume (kiloliter). Common identifiers of energy are power capacity (MW), consumption (MWh, GJ) and the ratio of energy used for producing one unit of output (GJ/t and/or MWh/t product).

On the output side, the WBSCD requires cement manufacturers to report their direct (Scope One) intensity. Such emissions emanate from activities owned or fully controlled by a company; for example, burning fossil fuels, calcination, and on-site transportation. Indirect emissions are counted in Scopes Two and Three. The former tracks external electricity inputs purchased in company-administered operations. Scope Three is an optional reporting category to cover production-related outputs from sources not controlled by a company (WBCSD, 2011). Their calculation involves multiplying energy or materials consumption by given emission factors (WBCSD, 2011; Williams et al., 2012).

The UNFCCC has also publicized project boundaries for emission sources related to the use of low-carbon fossil or AFs from outside facilities (Table 3). Its work forms a basis for assessing potential emission reductions due to the replacement of fossil fuels with lower carbon or carbon-neutral fuels, such as biomass and refused-derived fuel (RDF).

From Table 3, we can derive equations for measuring the annual emission reductions from AF utilization as follows:

$$ER_{AF} = (BE_{FF} + BE_{CH4,\ AF}) - ((EC_{PJ} \times EF_{grid}) + ((\sum AF_T/TL) \times AVD \times EF_{km,\ CO2})) \quad (1)$$

Where:

ER_{AF} = Emission reductions from AF utilization (t CO_2e/year)
BE_{FF} = Baseline emission from fossil fuels displaced by AF or less carbon-intensive fuel (t CO_2)
$BE_{CH4,\ AF}$ = Baseline emissions from methane due to AF dumped and left to rot or burn uncontrollably (t CO_2e/year)

Table 3
Project boundary for emission sources in cement production using AFs (UNFCCC, 2011).

	Emission Source	Emission	Description
Baseline	Reduction of fossil fuels at the plant due to alternative/low carbon fuels utilization (t CO_2e)	Carbon dioxide (CO_2)	Major source/ included
		Nitrous oxide (N_2O), Methane (CH_4)	Not significant/ neglected
	Reduction of methane due to no disposal or burning of AFs (e.g. biomass and RDF) (t CO_2e)	CO_2	Not significant/ neglected
		CH_4	Included (assumed no leakage)
		N_2O	Not significant/ neglected
Project activity	Alternative/less carbon fuels utilization (t CO_2e)	CO_2	Major source/ included
		CH_4, N_2O	Not significant/ neglected
	Energy consumptions such as electricity and fossil fuel to support the project (t CO_2e)	CO_2	Potential to be a significant source
		N_2O, CH_4	Not significant/ neglected
	Fuel consumption for transportation of AFs to the plant (t CO_2e)	CO_2	Can be a significant source
		N_2O, CH_4	Not significant/ neglected
	Biomass cultivation on land specifically provided (t CO_2e)	CO_2, N_2O, CH_4	Potential to be a significant source

EC_{PJ} = Electricity consumption for the project (MWh/year)
EF_{grid} = Emission factor for the local grid (t CO_2e/MWh)
$\sum AF_T$ = Amount of AF transported to the plant (t/year)
TL = Vehicle carrying capacity (t)
AVD = Average distance from AF location to the plant (km)
$EF_{km,\ CO2}$ = Emission factor for vehicles (t CO_2e/km)

2.3. Marginal abatement cost (MAC)

MAC analysis offers an accessible way to identify those actions most technically and financially effective in reducing one unit of CO_2e created during a study period (Ibrahim and Kennedy, 2016). The net financial results of abatement measures are derived from the equation below (Greensense, 2014; Ibrahim and Kennedy, 2016):

$$NFR = \left(C - \sum_{t=0}^{L} \boldsymbol{B}\right) \Big/ ER \quad (2)$$

Where:

NFR = Net financial operating results of reducing emissions carried out during the implementation of an abatement measure (US\$/$\sum$ t CO_2e reduction)
C = Capital cost arising from adopting abatement measures (US\$)
B = Revenue stream generated by application of abatement measures over the project duration (US\$)
L = Length of the project (years)
ER = Emission reductions during the measured period (t CO_2e).

This equation follows the discounted cash flow technique developed as part of the capital asset pricing model in finance theory. It involves the present value of initial capital (C) outlaid for technical measures designed to reduce plant emissions. Over the project duration, the measures create a reversionary flow of income (B), negative or positive, which can also be read as a present value in the same 'time value of money' metric as the original capital outlay. Management decision-making involves an appraisal of the measures' capital cost, net revenue stream, and technical efficiency towards the objective of emission reductions (to meet international standards).

2.4. Case study setting

The project now considers the premier site of the subject cement firm. The *company* claims around 50% of total national production capacity and has significant stakeholdings across the archipelago (Indocement, 2018). The case study *complex* consists of an operating *plant* employing four integrated cement *lines*, and on-site quarries for limestone and clay (Fig. 1). Raw material mining is carried out by third parties so that their emissions are included in Scope Three. Three of the production lines were constructed in the 1990s but, even then, were not state-of-the-art. They engaged horizontal grinding, though a vertical option was available, which would have lowered (bought-in) electricity costs and, hence, indirect emissions. The kilns lacked the pre-calcining equipment then common in developed-country cement making. The fourth line was added in 2012, around which time the other three were upgraded to the improved standard, thereby featuring vertical grinding and kilns equipped with pre-calcining and four-stage pre-heating. When all the necessary works were completed, the plant's lines were effectively equal in terms of technology and capacity, while differentiated by age (which affects facility management). Yet, as regards system componentry, the upgrades are not fully integrated. The process equipment is now considered elderly and has undergone about half of its design life (Moya et al., 2011). These drawbacks paint a realistic picture of the limitations of manufacturing technology in an emerging economy.

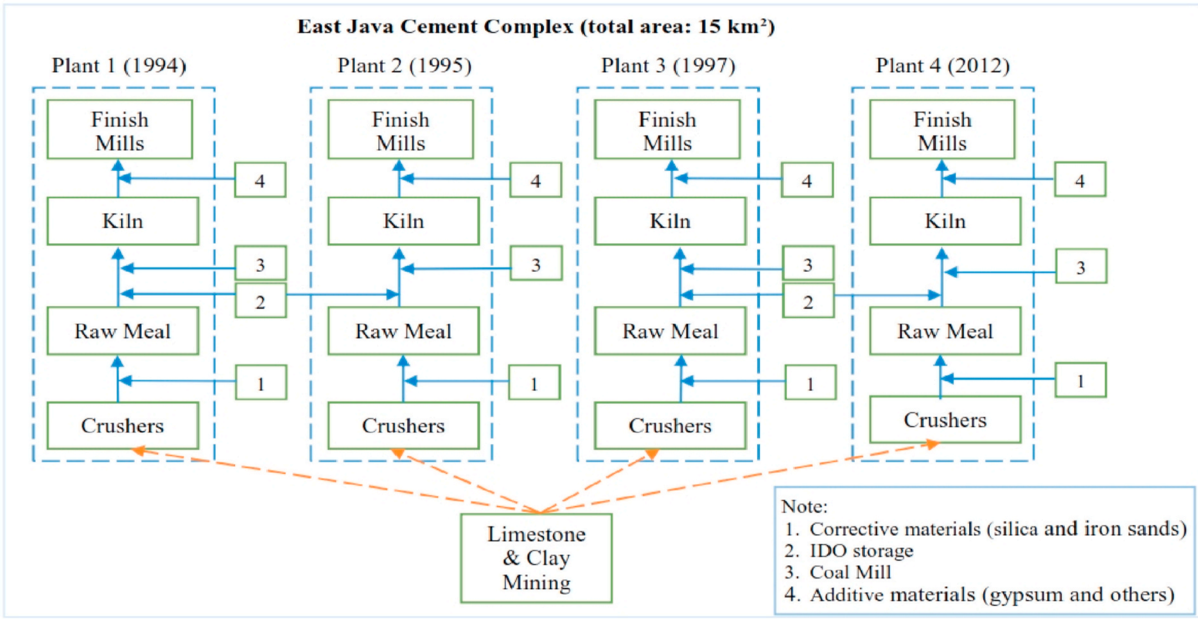

Fig. 1. Block diagram of the production process in the cement plant studied.

3. Results

3.1. Materials and energy (inputs)

In 2017, the plant used 14,232,807 tonnes of on-site limestone and 3,587,798 tonnes of local clay to produce 10,445,084 tonnes of clinker and a further 89,301 tonnes of cement kiln dust (CKD). Lines 1–4 contributed 26%, 24%, 24%, and 26% of the total clinkers. The clinker produced 13,165,745 tonnes of cement.

The primary energy sources are: lignite coal which requires industrial diesel oil (IDO) for pre-ignition; electricity; diesel fuel; and petrol. The last two are used only in secondary plant activities as fuels for vehicles (Table 4). The specific energy consumption (of coal and IDO) for combustion in kilns is around 3.35 GJ/t clinker. Lignite is a low-calorie resource (≤17.58 GJ/t (GAR)) equal to 14.8 GJ/t (NCV) with a price of around US$58/t[4] (Damayanti and Khaerunissa, 2018; Indonesia, 2018a). Its usage per tonne of clinker approximates 0.22t. Most cement industries outside Indonesia use bituminous and anthracite coal which has a higher calorific value (≥21.35 GJ/t) and can accordingly offer a lower usage index (≤0.15 t/t clinker) (CCAP, 2008).

AFs in overall Indonesian cement operations meet less than 2% of energy requirements (Indonesia, 2018a). The company has tried to feed in biomass from rice husk and RDF from municipal solid waste. These AFs are low-carbon compared with fossil fuels such as coal, but can represent renewable energy sources (Perea-Moreno et al., 2019; Yasar et al., 2019). The availability of rice husk within 200 km of the complex amounts to 867,625 t/year. Of that quantity, at least 563,957 t can be accessed less than 75 km distant, at a price around US$4.30/t[5] (UNFCCC, 2011).

In Indonesia, the government's energy subsidy is continuing to decrease, thus spurring companies to raise the efficiency of their electricity consumption. The plant's average electricity index in 2017 was 0.093 MWh/t cement.

Table 4
Energy sources.

Source	Unit	Total line usage/year			
		Line 1	Line 2	Line 3	Line 4
Production equipment:					
Lignite coal	tonnes (t)	624,565	561,770	569,521	608,221
IDO	kiloliter (kl)	515	434	592	519
Electricity	megawatt-hour (MWh)	392,511	296,983	275,345	268,818
Supporting ancillary equipment (e.g. transportation and offices):		**Total plant usage/year**			
Electricity	MWh	37,325			
Petrol	kl	111			
Diesel fuel	kl	1,096			

3.2. Scale and technology

The cement lines' lifespan can reach 50 years, with modernisation typically undertaken after 20 or 30 seasons to maintain market positioning. Retrofitting or revamping requires significant investment yet can be attractive if supported by a rising market, or if equipment has become outdated in the face of sustained demand (Moya et al., 2011; Schneider et al., 2017). Though not always possible in developing countries, the aspiration is best practice technology, which considers scale, system design integration and cost to achieve competitive, sustainable and cleaner production.

Specific energy consumption in clinker production (GJ/t clinker) is the primary determinant of efficiency. It can be increased by adding preheating stages in the kiln and pre-calcining (Hasanbeigi, Price, et al., 2010; Madlool et al., 2013). The global state-of-the-art is six pre-heater stages. In 2010, the case study company increased production capability

[4] https://industri.kontan.co.id/news/inilah-hitungan-batasan-harga-jual-batubara-lokal.

[5] *US$1 = IDR 14,000.*

and updated technology. The retrofit increased individual kiln capacity to 8,000–9,000 tpd. Upgrades include vertical coal mills, separate feed pre-heaters, and new: induced draft fans; burners; kiln drives; and retrofit coolers. The initiative relied upon the increasing national demand for cement and, at that time, a relative lack of competition. The plant had previously undertaken several other developments, such as advanced mechanical transportation, or conveyor belts, instead of pneumatic means, vertical roller mills (currently state-of-the-art in grinding technology for limestone, clay and other additives), kilns with four stage pre-heaters and pre-calciners, electrostatic precipitators, variable frequency drives, and process control systems. These modifications represent energy-efficient technology consistent with emerging country capability (Hasanbeigi et al., 2012; Schneider et al., 2017). They remain some way behind the world-best technical practice which, differentially, would feature five to six pre-heater stages kilns and move toward carbon capture storage (CCS).

As to AF utilization, there is already a RDF manufacturing facility 100 km from the complex, with production capacity of up to 130 t/day, but its contribution has been hampered by operational disruptions (Indonesia, 2018a). Needed is additional investment of IDR 60 billion (US$4.3 million) to adopt appropriate RDF processing technology, which will entail annual running costs of IDR 3 billion (US$214,000) (Syaifudin, 2016; Hidayat, 2017). For biomass utilization, appropriate infrastructure has been installed in two of the four lines. Each requires investment of IDR 22 billion (US$1.57 million) and involves electricity input of 607 MWh/year (UNFCCC, 2011).

From a technical angle, therefore, the cement complex experiences sub-optimality in its quest for competitive, sustainable, and cleaner production. Of primary importance is its kiln status and capacity. Next is the issue of the coal used, understood as inferior from the standpoints of its energy content and emission factor compared with other fractions such as sub-bituminous and anthracite. In Indonesia, however, lignite is abundant, and better quality coal is mainly destined for export to support the nation's current account.

3.3. Emissions (outputs)

The cleaner production performance of the plant was measured in terms of Scopes One and Two emission intensity for each tonne of clinker or cement manufactured, with the objective to determine direct sources which could be prioritized for reduction. The local (i.e. country and plant-specific) emission factors were used for more detailed calculations. They are consonant with the IPCC guidelines (UNFCCC, 2011; WBCSD, 2011; Perindustrian, 2014; ESDM, 2017; JCM, 2017; Damayanti and Khaerunissa, 2018). That is, any differences in using local or IPCC emission factors are negligible.

From Table 5 and Fig. 2, the plant's total GHGs in 2017 amounted to 10,486,304 t CO_2e, consisting of direct emissions (Scope One) of 9,390,718 t CO_2e and indirect ones (Scope Two) of 1,095,586 t CO_2e. The prime source is calcination at 53.7%, followed by coal-burning for kilns (35.7%) and off-site electricity generation (10.5%): the remainder comes from IDO, diesel fuel and petrol consumption. Of direct emissions, calcination contributes 60%, followed by coal combustion at 39%, and the residual from IDO, diesel fuel and petrol usage. The direct emission intensity of the company studied is 0.69 t CO_2e/t cement. The average electricity index, 0.093 MWh/t cement, is equivalent to an indirect emission intensity of 0.08 t CO_2e/t cement.

3.4. Cleaner production techniques

Results presented so far offer a reliable audit of the performance of the cement plant. The next requirement is to calculate the potential for emission reduction, as a result of adjusting inputs to the production process. However, in an emerging country, the leeway around these measures will differ considerably from those relevant to a more advanced setting. Attention should focus not only on physical parameters such as tonnes of CO_2e saved per year but also on financially competitive production, and the scarce rupiahs (dollars) available to achieve GHG reduction. This outlook acknowledges the different impact and implications of capital and operating expenditure in manufacturing. The allied condition of sustainable management looks to any local sources or opportunities which could be applied to contain costs involved in lowering the carbon profile.

3.4.1. Materials: clinker substitutes

The complex's clinker to cement ratio is 0.8, whereas it is technically possible to achieve 0.6 as an effective way to check GHGs. The economical means lies in the use of limestone and fly ash (Yunita, 2017; Notonegoro, 2018). Limestone can replace 10–12% of clinker without decreasing cement or concrete strength (Mohammadi and South, 2016; Scrivener et al., 2018). It also has the potential for higher utilization in mixed cement types (Cancio Díaz et al., 2017). The plant can use limestone as a clinker substitute to the extent of 10% of material inputs, or 1, 044,508 t/year.

Readily available throughout Indonesia, fly ash is a by-product of electricity generation. Power stations report average annual consumption of 5,500–6,500 tonnes of coal to create 1 MW of electricity. Around 5.5–7.5% of the total coal used turns into ash, composed of 80–90% fly ash and 10–20% bottoms ash[6] (Jayaranjan et al., 2014; Yunita, 2017; Notonegoro, 2018). The company has cooperated with two generators, one with 700 MW (16 km from its complex) and the other with 3,250 MW located 265 km away (Indonesia, 2018a; Notonegoro, 2018). They can provide fly ash at a rate of 1,072,860 t/year. The introduction of limestone and fly ash could reduce the four cement lines' direct emissions by 1,891,763 t CO_2e/year and indirect outputs by 116,423 t CO_2e/year. By sustainably re-using an otherwise waste commodity, the plant will lower the clinker factor to around 0.6 (Table 6).

3.4.2. Energy: alternative fuels

Given nearby supplies, biomass could offset the plant's coal usage by up to 25% per annum. Based on the material's availability and the currently-installed processing capacity, biomass and RDF could lower total fossil fuel consumption by almost 30%. Via such sustainable production and with reference to Equation (1) above, these by-products will (more cleanly) reduce GHGs by 1,055,175 t CO_2e/year or 11% of direct emissions, equal to 10% of the total emissions (Table 7).

3.4.3. Plant technology: Kiln upgrading and waste heat recovery power generator (WHRPG)

In the plant, the specific energy consumption of the existing kilns is around 3.35 GJ/t clinker. Increasing the number of pre-heating stages would normally limit the thermal energy required. One or two extra pre-heater stages could deliver potential cuts ranging from 224,651 to 449,302 t CO_2e per annum, equivalent to a 2.5–5% fall in direct emissions, or 2–4% in total emissions (Table 8). The addition of one single-stage pre-heater for each of the four lines would entail a capital cost of US$26.5 million, equating to US$2.54/t clinker (Madlool et al., 2011). To achieve full six pre-heater status, the gross bill of US$53 million for a complete renovation of the plant's kilns would include eight units (two x one-stage pre-heaters x four lines). That sum is significant in the manufacturing budget of an enterprise in a developing nation.

The firm has commenced construction of a WHRPG with an installed capacity of 30.6 MW. Total investment is US$60 million, subsidized US $11 million by the Japanese government and the remainder coming from internal funds. The WHRPG will require electricity of 29,668 MWh to operate 24 h/day for 335 days/year. It will shut down for 30 days due

[6] *The heavier portion of coal ash which settles on the bottom of the boiler, a toxic by-product which has pozzolanic properties, is also used sustainably for the manufacture of concrete, lightweight blocks and as a road base component.*

Table 5
Emission sources.

Source	Amount	Energy content (GJ/unit)	Emission factor (t CO_2e/GJ)			Emission factor (t CO_2e/t $_{clinker + CKD}$)			Total emissions (t CO_2e)
			CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	
Direct emissions (Source One) from fuels usage in kiln and non-kiln and calcination									
• Lignite coal (t)	2,364,078	14.80[a]	0.107[a]	–	–	–	–	–	3,743,753
• IDO (kl)	2,060	43.39[b]	0.074[c]	0.003	0.001	–	–	–	6,919
• Petrol (kl)	111	43.97[b]	0.073[c]	0.003	0.001	–	–	–	376
• Diesel fuel (kl)	1,096	44.12[b]	0.074[c]	0.003	0.001	–	–	–	3,773
• Calcination (Clinker + CKD) (t)	10,534,835	–	–	–	–	0.535[d]	–	–	5,635,896
Indirect emissions (Source Two) from electricity usage									
• Electricity (MWh)	1,270,982	3.6[e]	0.2394[e]	–	–	–	–	–	1,095,586

[a] Estimated by Damayanti and Khaerunissa (2018).
[b] Estimated by Irzon (2012).
[c] Estimated by Hidup (2012) and Perindustrian (2014).
[d] Estimated by WBCSD (2011), Perindustrian (2014), and Energy (2017).
[e] Estimated by JCM (2017).

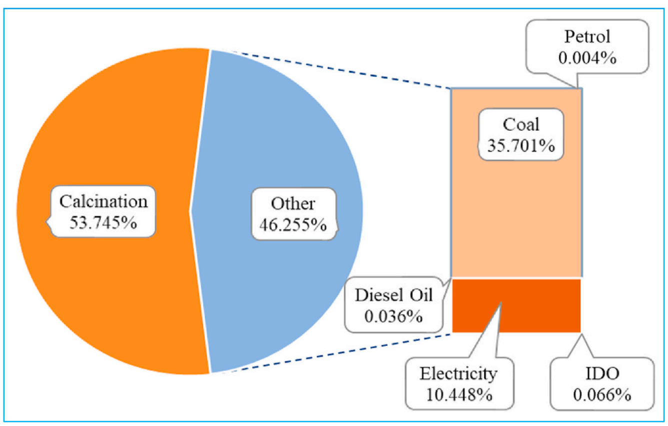

Fig. 2. Emission sources of the subject cement plant.

Table 6
Energy and emission reductions due to the utilization of clinker substitutes.

Parameter		Unit	Substitute materials		Total
			Limestone	Fly ash	
Input:	Amount	(t/year)	1,044,508	1,072,860	2,117,368
	Ratio reduction	–	0.1	0.1	0.2
	Total energy saved	GJ	3,499,103	3,594,081	7,093,184
	Total fuel (coal) saved	(t/year)	236,426	242,843	479,269
	Total electricity saved	(MWh/year)	55,777	79,284	135,061
Output:	Emissions saved from coal usage	(t CO_2e/year)	374,404	384,567	758,971
	Emissions saved from calcination	(t CO_2e/year)	558,812	573,980	1,132,792
	Emissions saved from electricity	(t CO_2e/year)	48,080	68,343	116,423

to kiln maintenance. In the dry season, the generating capacity is around 28 MW, while the rainy months produce only 22 MW because waste heat must be diverted from the kilns to dry raw materials which tend to be wetter or more humid (Indonesia, 2018b).

Based on the specifications obtained, the WHRPG can generate net electricity of 171,332 MWh/year, equal to indirect emission reductions from the complex of up to 13%, or 147,688 t CO_2e/year. In respect of sustainable and cleaner production targets, it will lower the index of electricity from non-renewable sources from 0.093 to 0.082 MWh/t cement, equal to overall plant electricity reductions of 0.011 MWh/t

Table 7
Potential reduction in emissions due to AF utilization.

Parameter		Unit	AFs: Biomass (substituting 25% of coal usage)	AFs: RDF (130 t/day or 2.6% of coal usage)
Input:	Calorie value for AF	GJ/t	12.77[a,b]	21.34[c]
	Calorie value for coal	GJ/t	14.80	14.80
	Fuel saving (t coal)	t	591,019	61,844
	Emission factor for coal	t CO_2e/GJ	0.107	0.107
	Emission factor for CH_4	t CH_4/t AF	0.001971[a]	0.006[c]
	Emission factor for electricity	t CO_2e/MWh	0.862	0.862
	Emission factor for transportation	t CO_2e/km	0.00054[a]	0.00054[a]
Output:	Baseline emissions fossil fuels displaced	t CO_2e/year	936,046	97,948
	Baseline emissions for methane avoided	t CO_2e/year	28,353	5,405
	Project emissions	t CO_2e/year	11,957	618
	Emission reductions	t CO_2e/year	952,441	102,735

[a] Estimated by UNFCCC (2011).
[b] Estimated by Anshar et al. (2016).
[c] Estimated by Ummatin et al. (2017).

Table 8
Emission reductions due to adding pre-heater stage in the kiln.

Parameter		Unit	Five stages	Six stages
Input:	Heat consumption [a,b]	(GJ/t clinker)	3–3.1	2.9
	Calorific value of coal	(GJ/t coal)	14.80	14.80
	Heat reduction[a]	(GJ/t clinker)	0.2–0.3	0.4–0.5
	Heat reduction	(%)	6–9	12
	Amount of clinker	(t)	10,445,084	10,445,084
	Total fuel reduction	(t coal)	141,845	283,689
Output:	Emission factor	(t CO_2e/GJ)	0.107	0.107
	Emission reductions	(t CO_2e)	224,651	449,302

[a] Estimated by Grydgaard (2006).
[b] Estimated by Hasanbeigi, Price, et al. (2010).

cement. As to enhancing competitive production, it will cut the firm's electricity bill by US$12 million annually.[7]

3.5. The marginal abatement cost curve (MACC)

The MACC technique relates the capital and operating costs/savings of measures taken in a manufacturing plant to reduce a volume of emissions in a given year. Its key inputs include: costs (initial capital and ongoing operational and maintenance) associated with any proposed measure; a selected discount rate (nomenclature = i); the expected project life span in years (= n); current energy prices; and estimated energy reductions. A critical output is the net financial return involved in reducing one tonne of CO_2e derived from any nominated abatement measure, which is obtained from the foregoing Equation (2) (Kesicki and Strachan, 2011). The approach assumes a 10-year scenario, appropriately aligned with the 2030 international targets for emission intensity. The discount rate is set at 10%,[8] a figure used in several studies concerned with Indonesia's energy projects and those overseas (Hasanbeigi, Menke and Price, 2010; UNFCCC, 2011; Lee et al., 2019).

We recall from earlier commentary that the plant's total GHGs of 10,486,304 t CO_2e are composed of direct emissions (Scope One) of 9,390,718 t CO_2e and indirect ones (Scope Two) of 1,095,586 t CO_2e. According to Table 9 and Fig. 3, the most effective among six potential measures, biomass utilization, will offset 10 per cent of direct emissions (936,046 t CO_2e/year) with the largest abatement saving of (-US$17.68/t CO_2e). This saving is derived from the division of the NPV by the total abatement tonnage of emissions during the project period. While RDF has a similar value (-US$15.38), it curbs only a small output (97,948 t CO_2e/year). Bracketing around the diminutive fourth measure (WHRPG), the third and fifth ones (utilizing up to 10% of limestone, and adding fly ash) will inhibit more significant emission volumes; respectively, 981,296 t CO_2e/year (10.5% of Scope 1) and 1,026,890 t CO_2e/year (10.9%) at a saving of per tonne of CO_2e abated of -US$11.07 and -US$9.15. The sixth measure, kiln upgrading, provides modest emission reductions at a relatively moderate cost.

Apart from material and energy substitutes, the company will save money by implementing technological innovations (as per the fourth and sixth measures in Fig. 3). Capital costs will be offset by energy efficiency, coupled with the fall in purchased electricity charges, which will boost competitive production. The WHRPG will cut back 147,688 t CO_2e/year, with savings of US$10.12/t CO_2e abated. Adding a single pre-heater will restrain emissions by 224,651t CO_2e/year, with savings of US$7.44/t CO_2e abated. The illustrated measures, excluding WHRPG, could reduce direct emissions by 3,150,408 t CO_2e/year, equivalent to 34% of current GHGs. Meanwhile, WHRPG and clinker substitutes could lower indirect (Scope Two) emissions by 264,111 t CO_2e/year, equivalent to 24% of such output. In sum, the theoretically-possible annual reductions equal 3,414,519 t CO_2e/year (x-axis, Fig. 3), representing 33% of the plant's total CO_2e discharge in 2017.

4. Discussion and policy implications

4.1. Findings

Emerging countries, including Indonesia, are generally agrarian, with growing populations demanding large quantities of concrete for the necessary infrastructure to transit to industrialisation. In respect of scale and technology, the predominant dry process of cement manufacturing is presently conducted with four-stage kiln pre-heating (Hasanbeigi, Menke and Price, 2010; Hasanbeigi, Price, et al., 2010; Ionita et al., 2013). Results reveal nothing extraordinary in the quantities of materials (limestone and clay) used in the case study plant. More unusual is the choice of energy inputs, dominated by lignite which detracts from operating and emissions efficiency. It is supplemented by imported electricity which, likewise, is mainly generated from fossil fuels. Ancillary inputs include fly ash from coal combustion in external power stations, plant residues and municipal refuse (Ahuja and Tatsutani, 2009; Gupta and Mondal, 2020). In the South, these by-products are usually cheaper and more readily accessible than in advanced economies, providing opportunities for competitive and sustainable manufacturing (Ahuja and Tatsutani, 2009; Mohiuddin et al., 2016; BPS, 2018).

Exploration of emission reduction in cement manufacturing has suggested six possible abatement measures, then subjected to MAC analysis. The most effective alternatives, biomass deputizing for lignite, and limestone substituting in clinker production, offer the greatest emission reductions with the largest financial returns per tonne of CO_2e re. Greater use of fly ash could substantially contribute to moderate saving, whereas similarly-priced WHRPG alterations could only remove a small component of GHG outputs. The choice of remedial technology in a manufacturing trajectory must complement sunk investment in prior plant to avoid extra works which can increase capital and operating costs and so impact competitive production. For example, one might imagine that installation of pre-heaters in an existing kiln would be more economical than building a new facility with more pre-heaters. Yet, adding a stage can create costs by delaying production scheduling, escalating complexity and amplifying risk. It will not be considered for aging cement lines. Instead, market conditions permitting, the feasibility of an entirely new facility would be appraised within capital constraints.

4.2. Abatement targets

We next analyze the discrepancy between the global standards and the achievements, as outlined, of the lines under review (Fig. 4). From the cleaner production standpoint, the critical target concerns outputs, namely, direct and indirect emission intensity (Scopes One and Two). The international targets for 2030 are 0.55 t CO_2e/t and 0.07 t CO_2e/t cement, respectively (IEA, 2018a). The plant has achieved an intensity of 0.69 *vis-à-vis* Scope One and of 0.08 regarding Scope Two (Fig. 4). Thus, the cleaner production objective should be to reduce the direct emissions by at least 20%, or 1,878,144 t CO_2e and indirect emissions by 12.5% (136,948 t CO_2e). Our task is to determine what would be required, technically and financially, to match up these two sets of figures.

Table 10 amplifies information in Table 2 by quantifying, as ratios, the indicators constituting the global targets (Column A). To illustrate, in Column (B), the target ratio of clinker to cement is 0.64. The subject plant is running at a ratio of 0.8 (Column C), producing an absolute discrepancy of 0.16 ratio points (Column D), equivalent to a 20% reduction needed for compliance (Column E). The remedial measures include the substitution of limestone and fly ash (Column F). The difference reduction (Column G) shows each measure's contribution in reducing the clinker to cement ratio, that being 0.1 ratio points apiece, to achieve 0.60 in aggregate. The annual emissions reductions are 981,296 t CO_2e and 1,026,890 respectively (Column H). Based on MAC analysis, Column I portrays the value of savings per tonne CO_2e abated from each measure as US$11.07 (limestone) and US$9.15 (fly ash). Finally, Column J displays the annual remedy savings, obtained from multiplying Column H (unit value of abatement saving) by Column I, annual emission reduction: the results are US$10.8 million and US$ 9.39 million respectively.

As shown before in Column B of Table 9, the complex would require aggregate (present value) capital expenditure of around US$94 million to adopt all six measures to meet the global targets, not including the use of limestone and fly ash as clinker substitutes which do not require expenditure. That outlay offers a handsome potential return on investment, reaching US$415 million in present value terms as the reversion at

[7] https://web.pln.co.id/statics/uploads/2020/03/TA-April-Juni-2020.jpg.

[8] *The company uses a discount rate taken from commercial bank loan interest rates on its emission reduction projects (OJK, 2019).*

Table 9
Abatement measures for the complex.

Abatement measures (listed in US $ savings order) (A)	Capital cost, year 0 (US$ million) (B)	Cash flow (US$ million/year) (C)	NPV of reversion (i = 0.1, n = 10) (US$ million) (D)	Abatement ($t\ CO_2e$/year)			Abatement saving (US $/t CO_2e) (H)=(-D/(Gx10))
				Direct (E)	Indirect (F)	Total (G)=(E + F)	
Biomass (substitute for 25% of coal)	3.143[a]	27,448	165.511	936,046	–	936,046	−17.68
RDF	4,.286[b]	3.149	15.061	97,948	–	97,948	−15.38
Limestone (clinker substitute by 10%)	–	17.684	108.659	933,216	48,080	981,296	−11.07
WHRPG	60.000[c]	12.198	14.952	–	147,688	147,688	−10.12
Fly ash	–	15.287	93.933	958,547	68,343	1,026,890	−9.15
Add one pre-heater stage in kiln	26.530[d]	7.037	16.710	224,651	–	224,651	−7.44
TOTAL	93.959	82.803	414.826	3,150,408	264,111	3.414.519	−70.84

[a] Estimated by UNFCCC (2011). See also subsection 5.2.
[b] Estimated by Hidayat (2017). See also subsection 5.2.
[c] Estimated by Indonesia (2018b). See also subsection 5.4.4.
[d] Estimated by Madlool et al. (2011). See also subsection 5.4.3.

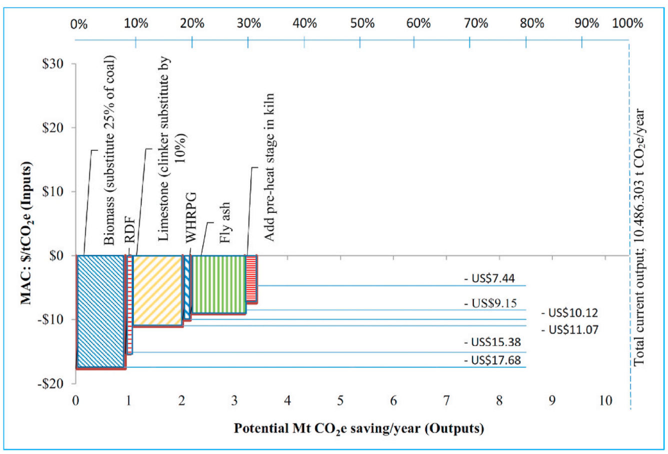

Fig. 3. The MACC for mitigation measures developed.

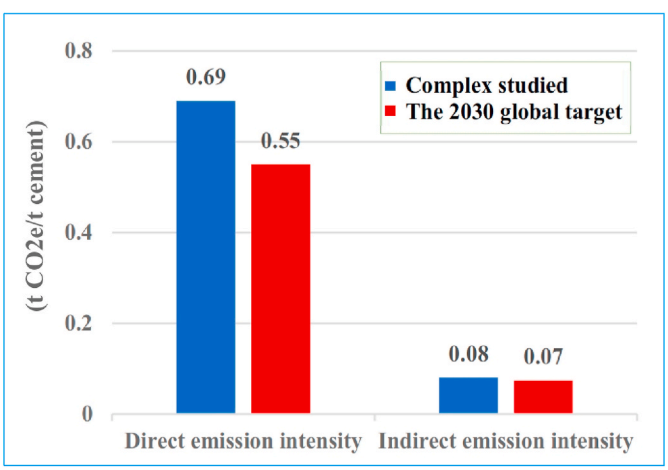

Fig. 4. Global 2030 targets and the current emission intensity profile of the subject cement complex.

10% occurs over 10 years. What, then, would stop the company from immediately investing since, in 2020, the cement group owning the complex achieved revenue of US$2.5 billion with a profit of US$404 million, equivalent to an operating margin on sales of 16.1%?.[9] In reality, expenditure of US$94 million on one of its *six* Indonesian production complexes is a substantial impost, especially when sub-optimal or aging machinery is involved. More than the capital cost is involved, since operating losses caused by plant downtime must be factored in to the total budget. Company sources recall that the 2010 three-line upgrade necessitated output reductions of up to one-third over one semester. Viewed more positively, were such investment to proceed, the necessary capital could be obtained from several sources: internal funds, government subventions to the state-owned company, capital raising by means of full or partial privatization through an initial public offering, and multilateral supports.

Apart from examining the discrepancies and costs to achieve aspired manufacturing performance standards, international comparisons of project indicators deserve attention. From Table 11, our Indonesian study suggests that the potential savings of certain abatement measures would be greater in emerging than in developed countries. For example, clinker substitutes are not necessarily cost-saving in Germany (McKinsey and Company, 2007; Brunke and Blesl, 2014). Other global evidence indicates that AFs from waste do offer cost savings (-US$8/t CO_2e), but, generally, the use of biomass is relegated due to its expected abatement cost price (US$2.4/t CO_2e). Given these conditions, an opportunity exists for emerging countries to achieve specific emission reductions at lower costs, or even higher savings than in developed countries.

For all this, cement facilities in advanced nations have far better operational indicators than those of emerging countries like Indonesia, and even today they surpass the 2030 global targets[10]. In referring to evidence in Table 12, 'optimal' entries should be understood chiefly as an inductive estimate, based on the authors' in-plant observations and selected references.

It is further possible to construct a surface (radar) chart to suggest the ease or otherwise of meeting global 2030 cleaner production standards given differing production technology and market conditions (Fig. 5). The potential for four main types of integrated cement plants (ICPs) is portrayed. ICPs in developed countries, which have implemented state-of-the-art kiln facilities (five to six-stage pre-heating with pre-calcination) should easily match, or exceed, the global targets set out

[9] https://www.marketscreener.com/quote/stock/PT-SEMEN-INDONESIA-PERSE-9058802/financials/.
[10] https://gccassociation.org/gnr/.
[11] Ease level in meeting the 2030 global target is based on authors' assessment.

Table 10
Discrepancy and remedy cost of production efficiency indicators to meet the 2030 international emissions intensity targets.

Input indicator ratio (A)	Global target[a] (B)	Plant result (C)	Discrepancy		Medium (F)	Discrepancy reduced[b] (G)	MAC (cost to remedy)		
			Absolute (D) = C–B	% (E)= (D/B)			Emissions abated (t CO_2e/year)[c] (H)	Unit abatement saving (US$/t CO_2e)[d] (I)	Annual net revenue (US$ million/year) (J)=(HxI)
Clinker to cement ratio	0.64	0.8	0.16	20	- Limestone (clinker substitute by 10%)	−0.1	981,296	−11.07	−10.86
					- Fly ash	−0.1	1,026,890	−9.15	−9.39
Alternative fuels (%)	17.5	1.2	−15.3	87	- Biomass (substitute 25% of coal)	25	936,046	−17.68	−16.55
					- RDF	2.6	97,948	−15.38	−1.51
Thermal energy intensity (GJ/t clinker)	3.3	3.4	0.1	3	Add a pre-heater stage	−0.2	224,651	−7.44	−1.67
Electricity index (MWh/t cement)	0.087	0.093	0.006	6	WHRPG technology	−0.011	147,688	−10.12	−1.49

[a] Estimated by Schneider et al. (2017) and IEA (2018b).
[b] Data derived from Tables 6–8, and Sec. 5.4.4.
[c] Data derived from Column G in Table 9.
[d] Data derived from Column H in Table 9.

Table 11
Abatement cost in several countries.

Country	Abatement measure and cost (US$/t CO_2e)				Reference
	Clinker substitutes	Alternative fuels	Waste heat recovery	Add a pre-heater stage	
Indonesia	−11.07 to −9.15	−17.68 to −15.38	−10.12	−7.44	–
Thailand	−14.38	−19.32	–	−1.37	Hasanbeigi, Menke, & Price (2010)
China	−16.78	−10.32	−45	–	Xu et al. (2016)
Brazil	−40 to −20	−5.00	–	–	McKinsey (2008)
Germany	−17 to −4.7	35 to 174	–	3.00	(McKinsey&Company, 2007; Brunke and Blesl, 2014)
Switzerland	−9.9	71	–	–	Zuberi & Patel (2017)
Sweden	–	56	–	–	McKinsey (2008)
World	−41 to −23	−8 to 2.4	3.5	–	Nauclér & Enkvist (2009)

Table 12
International comparisons of production indicators.

Indicator	Global target by 2030	Optimal in emerging economies[a]	Existing plants in developed countries
Clinker to cement ratio	0.64	0.7	0.6–0.7
Alternative fuels substitution rate (%)	17.5	25	45–60
Thermal energy intensity of clinker (GJ/t clinker)	3.3	3.4	3–3.5
Electricity intensity of cement (MWh/t cement)	0.087	0.08	0.074
Direct emission intensity (t CO_2e/t cement)	0.55	0.5–0.6	0.45–0.55

[a] Estimated by Panjaitan et al. (2020).

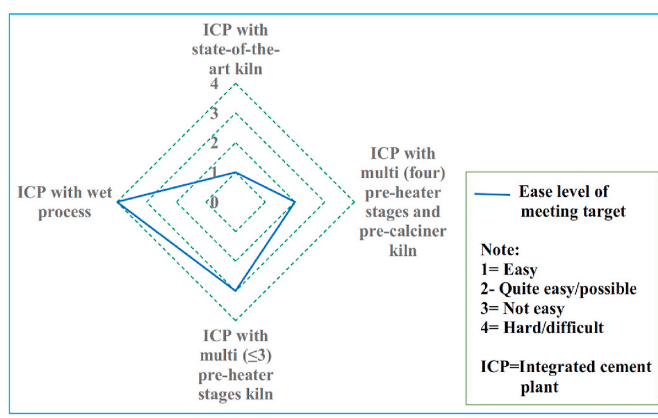

Fig. 5. Assumed ease of different production techniques in meeting the 2030 global cement production targets[11].

in Table 12. Sub-optimal production technology renders the task somewhat-to-considerably harder, with wet-processing cement manufacture the method most challenged.

As opposed to the measures analyzed here, the IEA classifies CCS as the only means of mitigation capable of decarbonizing heavy industries such as cement making (Irlam, 2017). The estimated cost of CO_2 captured will also vary, depending upon the type of process, the separation technology, CO_2 transportation techniques, and the storage location (Hasanbeigi et al., 2012; Budinis et al., 2018). CCS is still at an early stage. Its adoption in emerging countries would reportedly be "too expensive", and would create issues in integrating capture units with production processes which have bespoke designs, shortcomings in systems integration and a variety of emission sources (Irlam, 2017; Budinis et al., 2018). For the time being, these more sophisticated options appear out of reach.

4.3. Challenges to cleaner production

From the information assembled, we can advance a general snapshot of cement making in an emerging economy. The plant will likely be mid-life to elderly and often disjointed. Production is essentially of a low-technology character, with the main barriers to domestic entry relating to the capital costs of establishing an operation of minimum economic scale (MES). Yet, there are other realities in the Indonesian context and surely elsewhere. Two examples suffice. We have noted that the nation's cement market is highly contested, competitive production being a condition of survival. Domestic manufacturing must vie with regional importing, undertaken by several new participants (Citradi, 2020). There are regular allegations of dumping or 'predatory pricing', usually intended to reinforce a niche position or discourage additional would-be entrants. This situation affords limited opportunities for innovation in green strategy or engineering capacity (Table 13). The net effect is that, owing to probable deficiencies in their scale or technology, companies must stress efficiency and work to tight margins. This situation pressures management and ensures that any move into GHG abatement will be vigorously debated unless it can demonstrate clear aggregate savings or revenue enhancement. Cheaper operating measures delivering perhaps modest emission reductions are likely to be seen as more feasible and timely and less risky than wholesale capital investment.

The various constraints illustrated might only be overcome through external demands on national governments to meet their 2030 pledges under the Paris agreement by enforcing binding industry emission regulations. As another reality, it should be noted that such enforceable legislation is currently, for the most part, absent in relevant jurisdictions. Cement and other heavy processors in developing economies do not generally work with social and civic environmental consciousness and lack private incentives and/or government restraints. It is not unusual for different ministries to be sending different signals to producers. Given market exigencies and this official backdrop, it is unsurprising that manufacturers' first orientation is to maintain competitive production before considering the more elevated ideals raised in this article.

Table 13
Analysis of technical engineering criteria and challenges to their implementation in emerging economies.

Criteria	Challenges	Sources
Raw materials (e.g. as clinker substitutes)	- Unsupportive regulations - Deficient quality - Lack of flexibility in expanding supplies - Lack of infrastructures	(Alby et al., 2012; Bouzarovski and Petrova, 2015; Neraca, 2015; Panjaitan et al., 2020)
Alternative fuels (e.g. RDF and biomass)	- Lack of infrastructures and capital - Quality of sources which may vary - Lack of supports and incentives	(Syaifudin, 2016; Schneider et al., 2017; Rosana, 2020)
Technology/ equipment	- Less energy-efficient technology - Less flexible operational development/limited capital - Lack of incentives	(Iizuka, 2015; Nabernegg et al., 2017; Schneider et al., 2017)

5. Conclusion

This study identified a wide and significant research gap in the cleaner production literature which, hitherto, has concentrated on the secondary sector of developed countries. Oriented to the emissions-intensive cement industry, it adopted a novel theoretical approach employing the concepts of competitive and sustainable operations as necessary conditions to overcome shortfalls in cleaner production and so meet international industry emission standards. The relevant equations and techniques advanced offer a template which can be used in industries in both transitional and advanced economies.

Within the largest complex of Indonesia's leading cement company, six techniques were investigated as abatement options. Based on cost-indicative implementation over the scenario period, the annual opportunity for the firm equates to a saving of 3.415 Mt CO_2e, or 33% of its current total discharge. Five measures, fully implemented, can reduce direct emission intensity by 34%, although only a 20% pull-back is needed to meet the relevant 2030 global target of 0.55 t CO_2e/t cement. The sixth medium, WHRPG, together with the use of clinker substitutes, will lower the indirect emission intensity to 0.06 t CO_2e/t cement, again sufficient to satisfy the operative 2030 level. These measures could foster cleaner production in the Indonesian cement industry and that of other emerging countries since substitute materials are often available at low prices. These nations have another advantage, namely, assistance from developed countries in adopting mitigation techniques following the latters' commitment to support global climate action.

This innovative application of the well-proven MAC technique can foster further scholarly progress. An initial avenue of development is to recognize that results in investment studies depend critically on the established discount rate which represents the cost of capital. As regards the current study, were that rate to fall from 10% to 7.5% or 5%, the respective returns in present value terms against the US$94 million expenditure on all six means of emission mitigation would rise to US $474 million and US$545 million respectively. Sensitivity analysis is important in major capital expenditure (CAPEX) decisions for plant upgrading and renewal: worldwide, low interest rate and inflationary environments can thus assist cleaner production aspirations. Cognizant now of the challenges and financial realities which apply when sub-optimal manufacturing attempts to address global standards, a second avenue would be to 'bench test' the present results in appropriate low to middle-income economies. The influence of commercial attitudes to emission mitigation and the actual performance of different company formations and market structures could be firmly established. To meet global emission accords given the pre-requisites of competitive and sustainable production, the need arises to clarify how mitigation decisions are actually made by manufacturing management in a developing country. The authors propose a sequel, conducted first-hand within Indonesian cement-making, to specify what executives see as the drivers and barriers to abatement action. Supporting our theoretical positioning, market conditions and government influence will be a focus of early hypothesisation in the ongoing quest to develop a robust theory of cleaner production in emerging economies. Hopefully, other research teams will join this field of enquiry.

CRediT authorship contribution statement

Togar W.S. Panjaitan: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft. **Paul Dargusch:** Conceptualization, Methodology, Supervision, Writing – review & editing. **David Wadley:** Visualization, Supervision, Data curation, Writing – review & editing. **Ammar A. Aziz:** Supervision, Writing – review & editing.

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.

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