Decomposition analytics of carbon emissions by cement manufacturing – a way forward towards carbon neutrality in a developing country

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Abstract
Carbon emissions have emerged as an alarming and complex issue causing a long-lasting debate over climate change in the construction, building, and industrial sectors. There is tremendous growth in the construction and building industry, especially in low-middle-income developing countries, that involves rising production and consumption of cement and energy. As such, a growing amount of carbon emissions is becoming a serious challenge for developing economies. This study has assessed the driving factors that influence the critical levels of carbon emissions by employing Kaya identity and logarithmic mean Divisia index (LMDI) decomposition models in the growing cement manufacturing sector of a low-medium developing country, Pakistan, from 2005 to 2020. The results portrayed a typical trend of carbon emissions which are summarized as follows: (a) From 2006 to 2010, a slight increase is shown; (b) a slight decrease in the trend during 2011–2013; (c) from 2014 to 2018, there is a rapid rebound in the trend; and (d) a slight decline in 2019–2020. While the resultant mean values regarding the growth of the cement sector (6.34%), labor productivity (12.03%), energy structure (0.06%), energy intensity (−0.63%), and carbon intensity (−0.87%) have deliberated that these are the driving factors for carbon emissions by the cement industry in a developing economy. This study will provide an insight to the policymakers of developing nations so that they can efficiently monitor their carbon emissions and design and implement effective mitigation strategies. Ultimately, they would be able to shift to carbon–neutral technologies and renewable-alternative energy sources to achieve sustainable economic growth and a cleaner environment.

Keywords Climate change · Carbon–neutral building · GHG emissions · Eco-construction · Sustainable development · Sustainability

Introduction
Climate change is arguably the most profound challenge that has drawn the attention of academic researchers and policymakers. The current generation is the first to experience the consequence of human-induced climate change on the natural system (Loarie et al. 2009). Despite knowing their negative impacts on human health and the global system, countries deliberately emit greenhouse gas emissions to boost their economic expansion and enhance human welfare (Mahasenan et al. 2003; Rasheed et al. 2020). The greenhouse gases concentration has increased rapidly to 386 ppm since the start of this century, compelling that 90% of these emissions are attributable to human activities (Rodrigues and Joekes 2011; Devi et al. 2017).

The threats of adverse consequences of climate change are evident. This interest received the attention of international efforts that started at the United Nations Conference on Environment and Development (UNCED), 1972, and reached a milestone of the Paris Climate Agreement. Under this, the nations agreed to reduce the global greenhouse emissions and limit the global temperature increase to 1.5 °C (Glanemann et al. 2020). The construction and building sectors are the major contributors to the carbon emissions. Among these, the most energy-intensive sector and major
emitter of greenhouse gasses is the cement industry (Zeb et al. 2018). It accounts for around 7% of the global carbon emissions, where each ton of Portland cement releases 1 ton of carbon dioxide (Bakhtyar 2017). The cement production releases CO₂ emissions directly and indirectly. Direct CO₂ emissions are emitted during clinker production, and indirect CO₂ emissions are released from the burning of fossil fuels and higher electricity consumption (Attari et al. 2016; Shahzad et al. 2017).

Mostly, Portland cement is manufactured and utilized all around the world (Dunuweera and Rajapakse 2018). The cement manufacturing process employs three basic steps: raw mix, clinker production, and pure cement. The raw materials consisting of a combination of limestone, cement rock, shale, clay, sand, and iron ore are converted to small pieces of 0.39 inches in diameter by crushing, blasting, and drilling machines. These small pieces are grounded and blended with cement proportions (homogenized) (Habert 2013). In this step, electricity consumption is the source of carbon emissions. In the next step, the raw mix is heated at 1500 °C in a kiln, producing a clinker which is rapidly cooled (Gao et al. 2016). It is the basic material required for making cement composed of rounded nodules in size range of 1–25 mm. The breakdown of calcium carbonate and consumption of fossil fuel and electricity generates greenhouse gas emissions (Ali et al. 2011). Finally, gypsum is added to the clinker, and both are grounded to form a pure blended cement. The fuel products are dispatched in bulk or bags to the consumer. The fuel emissions and electricity consumption are the main sources of carbon emissions in the final step (Mikulčić et al. 2016; Abdul-Wahab et al. 2016).

As a consequence, the complex energy flows make it complicated to investigate the carbon inventory of the cement industry. Therefore, during the last two decades, efforts have been made to establish guidelines. In view of this, IPCC developed carbon accounting guidelines for countries (IPCC 2006). Similarly, “The Cement and Energy Protocol,” released in 2011, provided a carbon accounting method for cement production (CSI 2011). Cement has a direct relation to economic growth. The world production of cement was 4.1 billion metric tons in 2020. Pakistan has a well-developed cement industry, ranking among the top 5 exporters and the 14th largest cement producer (Memon et al. 2012). According to statistics, 5.21 million tons of cement has been produced in 2020. The average economic growth has increased by 22% since 2019. During the Paris Climate Summit, Pakistan’s Nationally Determined Contribution (NDC) has committed to reduce 20% emissions by 2030 and the share of renewable energy has increased with a total electricity output of 31.4% in 2015 (Raza et al. 2019).

Several studies and literature are available for the assessment of carbon accounting in the cement industry in different countries (Cai et al. 2016; Zhang et al. 2017; Markewitz et al. 2019). Wang et al. (2013) identified the driving factors for carbon emissions and presented a carbon emission inventory for the Chinese cement industry. Oral and Saygin (2019) examined the Turkish cement industry’s carbon emissions and applied simulation techniques for future energy consumption. Similarly, Mikulčić et al. (2013) applied the simulation methods for reducing CO₂ emissions from the cement industry in Croatia. Liu et al. (2007) examined the emissions from 36 industrial units from 1998–2005 based on decomposition analysis (LMDC). Apart from these studies, a lot of attention is required for the less developing nations like Pakistan. With air pollution becoming the biggest concern in Pakistan, the cement industry as one of the primary sources of emission requires attention in terms of environmental sustainability. Some studies have employed the index decomposition analysis (IDA) – Logarithmic Divisia Index Model (LDIM) for analyzing the CO₂ emissions in various sectors (Dai and Gao 2016; Olanrewaju 2018; Fatima et al. 2019; Wang et al. 2011). It is a well-organized method for analyzing the relative impacts of changes in industrial emissions and energy consumption. It is widely used because of its perfect imposition, ability to handle zero values, and consistency in aggregation (Zhao et al. 2017).

While against this backdrop, to the best of our knowledge, no research studies are available on the emissions analytics of the cement industry of Pakistan. Therefore, the current study is a novel investigation aimed to holistically analyze the carbon emissions of the cement industry of a low-middle-income developing country. This study will fill the relevant research gaps by provision of an account of carbon emissions from cement production in developing countries like Pakistan. That would be highly assistive for future trend analysis and environmental management. The specific objectives of the current study are;

i. investigation and identification of driving factors associated with carbon emissions by the cement industry of Pakistan using the Kaya identity (KI) method.
ii. quantification and analysis of energy structure effect, energy intensity effect, labor productivity, and carbon intensity effect based on logarithmic mean Divisia index (LMDI) to determine the varying levels of carbon emissions.

Considering the importance of the cement industry towards sustainable building and development for tomorrow, the potential outcomes of this research will persuade policy efforts in developing countries to reduce their CO₂ emissions and contribute toward unified global efforts to achieve carbon neutrality and sustainability.
Methodology

Figure 1 has summarized the overall methodology employed for this study which is further illustrated in the following sections.

Narrative of Pakistan’s cement industry

Pakistan’s cement industry is considered as a flourishing industry fulfilling the local market needs and exporting cement to neighboring states (e.g., Iraq, Sri Lanka, Afghanistan, India, and UAE). The cement industrial units are owned by the government and private sectors. Government has 5 plants, whereas the private sector has 24 plants, reflecting that huge investment is carried out in the private sector. This initiative has changed the perspective and broaden the horizon of the cement industry. Among these, 24 industrial units are operational (Ali et al. 2015; Hijazi and Bin Tariq 2006). Figure 2 has portrayed the cement production plants in Pakistan. Table 1 has further illustrated that Lucky Cement Limited is the largest producer and exporter of quality cement in Pakistan, followed by Bestway Cement Limited, D.G Khan Cement Limited, and Maple Leaf Cement Factory. The cement sector production has been recorded as approximately 65 million tons in the

Fig. 1 Overview of the methodology adopted for the study

Fig. 2 Operational cement production plants in Pakistan
fiscal year 2020. The cement sector has witnessed some major developments, such as the installation of a waste heat recovery system. The major players are interested in expanding cement production capacities. The projected expansion would enhance the total cement production in Pakistan to approximately 81 billion tons in the upcoming years.

The data in Table 2 shows the trend of the cement industry in Pakistan along with cement production, GDP growth rate, energy consumption using fossil fuels, and natural gas for the period of 2005–2016. During the fiscal year 2020, the industry produced 63.63 million tons of cement prior to the COVID-19 crisis. The imports and exports were reported at 47.81 million tons. The proportion of GDP growth has been on a declining trend which matches the economic transitions in the government policies. The energy consumptions of the sector are based on fossil fuel (natural gas and coal) and electricity, whereas CO₂ emissions have increased due to technological advancement and increased labor productivity effect (Jaffar et al. 2014; Raza et al. 2019; Raza and Shah 2020).

### Data sources

For calculating the energy consumption and CO₂ emissions in the cement sector of Pakistan, we acquired the data from Pakistani Economic Survey (2019–2020), Pakistan Statistical yearbook (PBS 2019). The study covers the period for 2005–2020. Total energy consumption data are in million tons of oil equivalent (Mtoe). Carbon dioxide emission data are in metric tons, GDP is in percentage (%), and the population (labor) is in millions. Due to data limitations, the variables are taken in different measurements. However, when the decomposition analysis is applied, all the variables are converted into % for the evaluation. The data (Table 2) was further analyzed using extended Kaya identity (KI) and logarithmic mean Divisia index (LDMI) decomposition models, as illustrated in the following sections.

### Extended KI method

Kaya identity (KI) is a widely employed technique proposed by Kaya and Yokobori (1997). Kaya identity is an extended and improved form of the IPAT model which relates the human impact on the environment (I) to the product of...
population (P), affluence (A), and technology (T). It quantifies the man-made CO2 emissions at all scales using the four driving factors. A number of studies have witnessed the application of the Kaya identity in different fields (Li et al. 2014; Ma et al. 2018). The full description of these parameters is depicted in Table 3. Based on Eq. (i), a relationship as presented in Eq. (ii) has been established.

\[
CE = \frac{E_f}{E_c} \times \frac{E_c}{GDP} \times \frac{GDP}{LP} \times \frac{C}{E_c}
\]

Additive analysis by LDMI decomposition model

After having KI analytics, (LMDI) decomposition additive model is further applied. This decomposition model has a sound theoretical framework and convenience of adaptation for various environmental monitoring aspects (Li et al. 2014; Ma et al. 2018). The full description of these parameters is depicted in Table 3. Based on Eq. (i), a relationship as presented in Eq. (ii) has been established.

\[
CE = ES \times EI \times LP \times CI
\]

\[
\Delta C_{tot} = C^{2005} - C^0
\]

\[
\Delta C_{tot} = \Delta C_{es} + \Delta C_{ei} + \Delta C_{lp} + \Delta C_{ci}
\]

The changes in total carbon emissions are attributed to the driving factors; energy structure effect (\(\Delta C_{es}\)), energy intensity effect (\(\Delta C_{ei}\)), labor productivity effect (\(\Delta C_{lp}\)), and carbon intensity effect (\(\Delta C_{ci}\)).

Table 2 Trend of cement industry in Pakistan from 2005 to 2020: cement production and energy consumption details

| Year | Cement production (million tons) | Percentage growth in cement sector (%) | Fossil fuel consumption (metric tons) | Natural gas (Mm cft) |
|------|---------------------------------|----------------------------------------|--------------------------------------|---------------------|
| 2005 | 17.91                           | 27.10                                  | 3807.2                               | 13,383              |
| 2006 | 20.83                           | 13.50                                  | 3342.8                               | 15,335              |
| 2007 | 30.50                           | 22.49                                  | 4451.2                               | 14,686              |
| 2008 | 37.68                           | 17.64                                  | 6186.9                               | 12,736              |
| 2009 | 42.28                           | 6.09                                   | 5001.8                               | 7305                |
| 2010 | 45.34                           | 10.49                                  | 5007.8                               | 1444                |
| 2011 | 42.37                           | −8.43                                  | 4617.1                               | 1378                |
| 2012 | 44.64                           | 2.93                                   | 4456.9                               | 1266                |
| 2013 | 44.64                           | 5.07                                   | 4129.9                               | 586                 |
| 2014 | 44.64                           | 1.17                                   | 3669.2                               | 522                 |
| 2015 | 45.62                           | 2.44                                   | 5553.8                               | 831                 |
| 2016 | 45.62                           | 10.09                                  | 5845.3                               | 497                 |
| 2017 | 46.39                           | 4.49                                   | 7470.8                               | 583                 |
| 2018 | 66.27                           | 11.14                                  | 9603.3                               | 886                 |
| 2019 | 59.74                           | −5.45                                  | 1500.0                               | 387                 |
| 2020 | 63.63                           | 1.74                                   | 6000 *                               |                     |

*No data is available

Table 3 Definition of parameters for the decomposition analysis

| Parameter | Description |
|-----------|-------------|
| CE        | Total CO2 emissions in Pakistan’s cement industry |
| E_f       | Proportion of fossil fuel consumption of cement industry in j province |
| E_c       | Total energy consumption of cement industry in j province |
| GDP_c     | The percentage growth rate of Pakistan’s cement industry in j province |
| LP        | Labor population in the cement sector of j province |
| C         | Carbon emissions of cement enterprises in j province |
| ES        | Energy structure |
| EI        | Energy intensity |
| LP        | Labor productivity |
| CI        | Carbon intensity |
whereas the final resultant (mathematical relationship), as depicted in Eq. (ix), is called the logarithmic mean. 

\[
\Delta C_{es} = \sum_{j,k} w_{j,k} \ln \frac{ES_t}{ES_{2005}}
\]  

\[
\Delta C_{ei} = \sum_{j,k} w_{j,k} \ln \frac{EI_t}{EI_{2005}}
\]  

\[
\Delta C_{lp} = \sum_{j,k} w_{j,k} \ln \frac{LP_t}{LP_{2005}}
\]  

\[
\Delta C_{CI} = \sum_{j,k} w_{j,k} \ln \frac{CI_t}{CI_{2005}}
\]  

The carbon emissions have increased up to 17.22% from 6.70% in 2005. This shows that energy demand in Pakistan has grown the fastest and consumption-induced carbon emissions have increased dramatically. While there is an agreement on the fact that industrialization is directly related to environmental pollution, and the production of Portland cement (clinker) produces the highest carbon emissions during the cement production process due to the high usage of carbon fuels (Gartner 2004). Currently, coal is the primary energy source for consumption in Pakistan’s cement industry (Kurup and Jenkins 2008), considered as a cheap option for utilization. Benhelal et al. (2013) predicted that the recent trend of carbon emission is associated with outdated industrial equipment that emits higher emissions. These figures have deliberated that reducing coal usage and developing a low carbon economy is just a social consensus. The current trend of higher economic growth is also considered as the main driving force (Khan and Majeed 2019).

\[
w_{j,k} = \frac{C_{j,k}^t - C_{j,k}^{2005}}{\ln C_{j,k}^t - \ln C_{j,k}^{2005}}
\]  

**Results and discussion**

This section presents the results and discussion of four decomposed driving factors: (i) energy structure effect, (ii) energy intensity effect, (iii) labor productivity, and (iv) carbon intensity effect so to portray the changes in cumulative carbon emissions.

**Analysis of cumulative carbon emissions**

Figure 3 illustrates the trend of carbon emissions by cement production for the period of 2006–2020. The carbon emissions have considerably grown during the analysis period.

The energy structure effect is the ratio of the proportion of fossil fuels to the total energy consumed in Pakistan’s cement industry. Figure 4 has revealed that there is a fluctuating trend regarding the energy structure effect during the selected study time period. The years 2010–2011 and 2017–2018 have shown much larger fluctuations. By observing the trend, it is quite evident that the energy structure effect has remained significantly negative throughout the time period. As such, the pattern of energy consumption by Pakistan’s cement industry is not changed so far. The energy structure has positive and negative effects, but considering the overall impact of energy structure, it inhibits the
per capita carbon emissions. The results correlate with the study of Yasmeen et al. (2020). Zameer and Wang (2018) highlighted that energy consumption is highly dependent on natural gas and coal for electricity production in the cement industry. Hence, this close association correlates with the proportion of coal consumption. While during 2010–2015, the consumption of coal decreased due to an increase in prices which is also reflected in the trend analysis of energy structure.

### Energy intensity effect

This factor is analyzed in terms of contribution toward the reduction of carbon emissions by the cement production sector of middle-income countries like Pakistan. The total fuel mix of Pakistan consists of oil, coal, and gas, while industrial sectors also heavily rely on these sources with fractional use of renewables. The negative trend is associated with higher energy prices, interest rates, less allocation in projects, and competitiveness with market players. It is clearly evident by Fig. 4 that energy intensity has depicted a rapid decline after 2009 and later by the period of 2010–2020, the energy intensity, i.e., associated with the carbon emissions, becomes further negative. Such decline in emissions is due to the fact that during this period, a number of renewable projects (including solar power) have been installed under the China-Pakistan Economic Corridor (CPEC) joint project which are contributing to a positive change. Energy efficiency is a restraining factor, and the carbon emissions would be significantly reduced if energy intensity is improved in the cement production sector (Ghulam and Jaffry 2015).

Similarly, the revolution of renewable-alternative energy projects and coal-power plants under CPEC will directly affect economic growth positively. While if conventional coal-based power generation will be deployed that will impact the carbon emissions negatively (Lin and Raza 2019; Mirza and Kanwal 2017).

### Carbon intensity effect

Pakistan’s cement industry has experienced a steady and reasonable growth rate since its inception. While this growth factor also caused an increased trend in terms of carbon dioxide emissions due to the reliance of industry on conventional fossil fuels for its energy needs. The relative impacts of carbon intensity are depicted in Fig. 4. The carbon intensity proportion shows that since 2006 to 2014, a negative trend is followed, being favorable in reducing emissions. The comparative analytics presents a notable increase in the emissions by approximately 3% for the period of 2015–2018. Whereas a gradual decline in the carbon intensity has been recorded during 2019–2020 and the COVID-19 restrictions imposed in Pakistan led to a significant decrease in the emissions, imposing a positive change in the natural environment. It is clearly portrayed that the carbon intensity of any fuel being employed is a major driver towards raising CO₂ emissions. As such, the higher carbon-intensive fuels, per capita GDP, increase the per capita carbon emissions. Mirza and Kanwal (2017) also described similar facts and figures regarding economic growth.
and carbon emissions. They concluded that economic growth is a critical factor for the enhanced amount of carbon emissions.

**Labor productivity effect**

The labor productivity (population) has been in a state of modest increase. It has a positive contribution to carbon emissions. Figure 5 illustrates that the labor productivity factor has accounted for up to 16.98% by the end of 2020. This is directly correlated with the increased productivity of cement, i.e., 63.63 million tons in 2020. The trend has been increasing gradually, but a slight decrease is also evident during 2020 due to the COVID-19 lockdown restrictions imposed on various sectors, the decline in the GDP economic growth, and the percent growth rate. While during 2019–2020, the flow of funds by the private sector has been halted due to economic recession because of COVID-19 restrictions, stoppage of developments in the building and housing sector due to tax reforms, and limitations imposed on high rise building and construction.

**Conclusion and policy implications**

In middle-income developing states like Pakistan, consistent economic growth and rapid urbanization have triggered the profligate development of the construction and building industry. Likewise, the GHG-carbon emissions from cement production are also mounting and want immediate attention. This study has attempted to assess the carbon emissions of the cement industry by employing extended Kaya identity and LDMI decomposition models for the 2006–2020 period. The research outcomes of the study indicate that Pakistan’s cumulative carbon emissions are being continued to increase with a slight decrease during 2011–2012. The energy intensity is a major driving force and carbon intensity being the second critical factor. The following policy implications will be greatly assistive for decreasing cumulative carbon emissions and stepping forward towards sustained industrialization in developing countries like Pakistan.

- Improvement and optimization of cement production and energizing this major industrial sector via renewable-alternative fuels so as to make an effective and smooth transition towards a carbon–neutral economic development.
- Relevant industries who will invest in renewables, cleaner production systems, science, technology, and innovation may be given special tax incentives like tax holidays and duty drawbacks by the government for importing and installing such sustainable, cleaner systems.
- Stringent technical legislation, i.e., standards for carbon emission and market-based regulations like permit licensing and emission-pollution charges, should be established for significant reduction of emissions by the sector.
- Lastly, there should be a system of strict pursuance and cancelation of licenses of the violators, and they must be fined and/or banned from future production, sales, and/or trading.
Author contribution Rizwan Rasheed: conceptualization, visualization, methodology, and supervision.
Fizza Tahir: methodology, data curation, writing, and formal analysis.
Muhammad Afzaal: data review.
Sajid Rashid Ahmed: supervision.

Data availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

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Competing interests The authors declare no competing interests.

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