IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 25 September 2023, accepted 23 October 2023, date of publication 27 October 2023,
date of current version 13 November 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3328207

RESEARCH ARTICLE

Dynamics of Greenhouse Gas Emissions From Cement Industries in Saudi Arabia–Challenges and Opportunities

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ABSTRACT This paper presents the challenges and options for reducing GHG emissions in the cement sector in the Kingdom of Saudi Arabia (KSA) and analyses short- and long-run causal relationships between emissions from cement production and their key factors through developing a Vector Error Correction Model (VECM). The cement industry in the KSA has been expanding rapidly due to the annual rise in the number of tourists, the development of residential and commercial sectors, and the government's strong drive towards economic diversification under Vision 2030. With this growth of the sector, however, arises an increase in Greenhouse Gas (GHG) emissions. The growing population coupled with an objective to grow economically subsequently demands further jobs and infrastructure. The local production of cement depends on many factors including demography, urbanization, tourism, GDP and interactions. The unit root test results prove no variables have unit roots "at first differences". Equilibrium relationship results displays cement emissions are positively correlated with population, number of tourists, GDP, energy consumption and negatively correlated with urban population. Causality test results demonstrates cement production have a long-run causal relationship with population, urbanization, GDP, and energy consumption and negative causal relationship with urban population. Therefore, GDP and energy consumption must be clean, and policymakers must accelerate the transition to low- or zero-carbon economies and energy sources to cut cement industry emissions. Future population growth must be accommodated in metropolitan areas to limit cement emissions. The results also show a unidirectional causal relationship between tourists and emissions. Therefore, public and private sectors should offer services with low carbon footprints and support initiatives to reduce tourist-induced emissions. A set of recommendations were also provided to mitigate GHG emissions in cement industries.

INDEX TERMS Climate change mitigation, cement industry, greenhouse gas emission, granger causality analysis, vision 2030.

I. INTRODUCTION

The global increase and indiscriminate use of natural resources have led to increase in Greenhouse Gases (GHG) emissions, transgressing planetary thresholds and fast-tracking anthropogenic climate disruptions [1], [2], [3]. The contributory factors to all these earthly dynamics are the global economic growth and increased production and consumption of resources, which put enormous strains on the environment. The high-level solution to the identified

The associate editor coordinating the review of this manuscript and approving it for publication was Liandong Zhu.

situations above is as stated in the Sustainable Development Goal number 8 (SDG8), "promote sustained, inclusive and sustainable economic growth…" While there is an agreement on the veracity of the SDG8 recommendations, there are sharp contrasts on the feasible and required strategies in handling the relationships between economic growth and environmental sustainability. Many experts have argued the impossibility of simultaneously assuaging the imperativeness for an economic growth based on current Gross Domestic Product (GDP) model and urgent need to cut down carbon emissions [4]. Some others have argued that economic growth has no direct bearings on climatic problems, but the absence of appropriately designed public policies to help reduce GHG do. With all the policies to control the impacts in place, the disquiets for environmental sustainability will percolate all the decision-making process in all organizations, be it private or governmental [5].

Several promising strategies are being investigated to reduce Carbon Dioxide (CO_2) emissions from the global cement industry and get it closer to the zero-emissions goal. Development of low-carbon cement, such as activated alkaline binders, belite-rich cement, sulfaluminate cement, magnesia cement, and geopolymer cement, etc., has proved to be one of the most effective means of lowering CO_2 emissions. Solidia, a calcium silicate cement with a lower lime content and no hydraulic additives, has been shown to cut CO_2 emissions by 70% [6]. The emphasis in the development of low-carbon cement technologies has shifted from a focus on the final outcome to a focus on the origin and procedure. This shift is seen in the exploration of hydrogen and solar energies as alternative sources. Furthermore, it is anticipated that additional innovative and transformative technologies will be produced in this field. Various technologies, including energy efficiency, alternative fuel percentage, low carbon cement production, and carbon capture, use, and storage (CCUS), exhibit distinct features and encounter specific challenges across diverse locations and countries [7]. In a study, the major three criteria that could lead to regulatory restrictions being placed on cement manufacturing were outlined as the quantity of CO_2 that is released into the atmosphere, the amount of iron used in building, and the use of energy [8].

The natural environment is essential to the economic activities of any nation. There is a complex relationship between economic growth and the environment in which various factors, such as the scale and composition of the economy and technological advancements, have the potential to reduce environmental impacts on consumption and production. In achieving sustainable economic growth, there needs to be an absolute decoupling of cement production from its impacts on the environment. In other words, sustainable consumption of environmental resources is either through efficient consumption of resources or adoption of new production techniques. The need for absolute decoupling is revealed in the existing commitment to avoid climate change in order to reduce GHG. To reduce the GHG especially in the face of global economy expansion, there is need for an absolute decoupling where the relevant environmental variables are decreasing or stable with a growing economy.

Ordinary Portland Cement is one of the most produced substances worldwide. Cement, being a key ingredient of concrete, has shaped the built-environment and has an enormous carbon footprint. It is the third largest source of human-caused carbon dioxide emissions, after fossil fuels and land use change [9]. The duo of climate change and global warming due to CO_2 emissions are two of the most important issues at the fore around the world [10]. The global industry for cement production remains one of the major industrial sectors that emit CO_2. Despite global call to reduce CO_2 emission, little has been done to change the raw materials used and reduce the high temperature (∼1500°C) from carbonates decomposition such as limestone and coal burning in the production of cement [11] and power generation [12].

Majorly in cement production processes, the CO_2 emission comes from two main sources: the raw materials and the coal burning to power the raw material decomposition. These production processes are responsible for 5-7% of the total CO_2 emitted globally [11] and it was reported to be 8% in other work [13]. These staggering numbers have motivated researchers to find answers to the queries of how to reduce cement production's CO_2 emissions and production energy costs [12], [14], [15]. The unsustainable production of cement is a major contributor to global CO_2 emissions. 96% of the carbon footprint of concrete and 85 % of the embodied energy is contributed by OPC alone [16].

It has been reported that for every ton of OPC produced, between 0.73 and 0.85 tons of CO2 are emitted [17], [18]. The World Business Council for Sustainable Development (WBCSD) Cement Sustainability Initiative's (CSI) global cement database reported that that burning limestone produces 500 kg CO2 per ton of clinker and 300 kg CO2 per tons of clinker, for a total of 840 kg CO2 per ton of clinker [18]. CO2 emissions from clinker manufacture are approximately 0.5 kg per kg, depending on the clinker-to-cement ratio between 0.5 and 0.95.

The demand for cement was driven up by the rise in global population and changing urbanization trends leading to increased infrastructure developmental needs [19]. Global cement production has been estimated to grow by 12-23% and the associated CO_2 emission to increase by 4% by 2050 (from 12% increase in global cement production) more than the level in 2018. To accomplish the sustainable transition of 2 degrees Celsius, it is recommended that global CO2 emissions be reduced by 24% relative to business as usual by 2050. Given the quantity of global anthropogenic CO2 emissions from the cement industry, it is a crucial sector for CO2 emission mitigation. The Kingdom of Saudi Arabia (KSA) scenario of GHG emissions from cement industry has been following the trend of many developing countries.

As the sixth largest contributor to the gross domestic product (GDP) of Saudi Arabia, the dynamics of GHG emissions from the construction industry must be studied to comprehend the various factors that influence GHG emissions and the mitigation strategies that can be implemented to reduce emissions. Furthermore, the industry sits conveniently at this position as a result of the favorable cost-structure due to inexpensive fuel prices and abundance in available raw materials.

KSA's topographical features and sub-tropical high-pressure system contribute greatly to the vast variations in its climatic conditions. The interior and coastal regions have the greatest variability across seasons. Winters are chilly in the interior parts and moderate in the coastal areas, and summers are dry and hot in the interior regions and humid in the coastal areas. Seasonally, the inland regions' temperatures range from 8°C to 20°C in the winter to 27°C to 45°C in the summer. Temperature variations in the coastal regions are 27°C - 38°C during summers while higher temperatures are recorded (19°C - 29°C) during winters relative to the interior region of the country [20]. KSA becomes one of the most sensitive countries to the effects of climate change as a result of the country's harsh and extreme weather conditions. Climate models have predicted severe impacts on water resources, coastal and marine ecosystems, desertification and agriculture in KSA due to the decrease in rainfall and increase in average temperature across all regions of the Kingdom [21]. An increase in average temperature across the Kingdom will result in extreme stress on the already limited renewable water resources, posing severe implications on the natural resources and consequently, the economy of the country.

In the 1990s, huge concerns were raised regarding unemployment situations of the Saudi youth, which coincided with the slow economic growth. Through education and training, the National Industrial Development and Logistics Programme and Human Capital Development Programme of Vision 2030 seek to increase the employability of Saudi youth while making the Kingdom a leader in the four industries of industry, mining, energy, and logistics [22], [23]. With majority of the population in the Kingdom belonging to the age groups below 35, it has been noted that the Saudi government considers employment to be one of its top goals especially with regards to meeting its Vision 2030 objectives. Subsequently, statistics now reveal that the total number of employees is highest in the age group 30-34 which concurs with the objectives of the government [24] Furthermore, it is vital to mention that relative to previous years, employment has improved in the government sector by 8% in 2018 compared to 2017 [24] and further opportunities are opening across the private and public sectors.

This research study aims to examine the various problems and potential strategies for mitigating greenhouse gas (GHG) emissions within the cement industry of KSA. Additionally, it seeks to analyze the causal linkages, both in the short and long term, between emissions resulting from cement production and the important factors influencing them. Through the development of a Vector Error Correction Model (VECM), this work finds and examines the causal linkages between cement emissions and their components in the short- and long-term. In addition, relationships among the factors of cements emissions are also identified and investigated using VECM based Granger Causality tests. An overview of the framework of this study is presented in Fig. 1. The elements of the framework are explained in the methodology section.

The rest of the paper is organized as follows. Section II includes the methodology adopted for this study. Here we discuss the data used, identify and investigate the variables influencing cement industry greenhouse gas emissions and present the development steps of a Vector Error Correction Model (VECM) model. A time-series analysis is carried out in the in this section to monitor the temporal trends of various components and emissions. The correlation analysis after the first difference was performed to determine the inherent relationships of the factors with the emissions. In section III, results and discussions are presented. It includes simulation results of VECM model for unit root testing, co-integration testing and causality testing are discussed. It also provides mitigation opportunities to reduce GHG emissions from cement industry. Finally, section IV gives conclusion of this study.

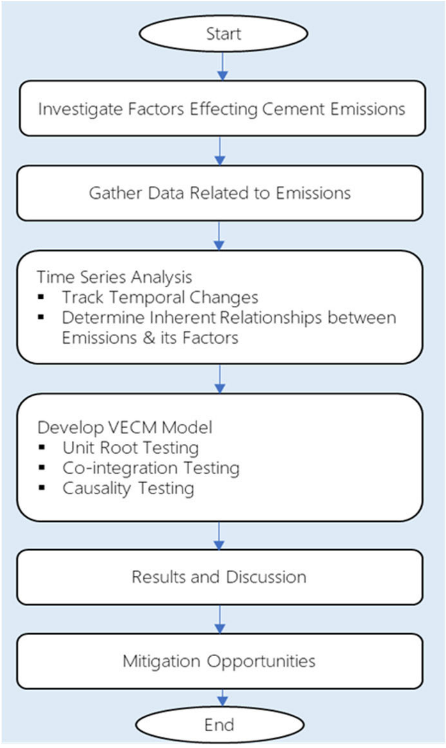

FIGURE 1. Framework of this study.

II. METHODOLOGY

A. DATA

Population (Pop), urban population (U), number of tourists (T), gross domestic product (GDP), and energy consumption (E) are the elements influencing emissions from

TABLE 1. Data used in this study.

Data	Definition	Time period	Unit	Source
Greenhouse gas emissions (GHGs)	Emissions from the production of cements in Saudi Arabia	1980-2018	CO2	Estimated by the authors
Population (Pop)	Total annual population of Saudi Arabia	1980-2018	Individual	The World Bank (2022) [28]
Urban Population (U)	Total annual number of people living in urban areas of Saudi Arabia	1980-2018	Individual	The World Bank (2022) [28]
Number of tourists (T)	Total number of tourists visiting Saudi Arabia each year	1980-2018	Individual	[36], [37]
Gross Domestic Product (GDP)	The monetary value of all final services and goods produced in Saudi Arabia in a year	1980-2018	United States Dollar (US$)	The World Bank (2022) [28]
Energy Consumption (E)	Total amount of energy consumed in a year in Saudi Arabia	1980-2018	Million Barrels	The World Bank (2022) [28]

cement industries. Details of the factors of cement emissions that are used for time series analysis and VECM development are provided in Table 1.

B. FACTORS AFFECTING CEMENT PRODUCTION

Sustainable cement production is related to myriad of factors, among which are resources efficiency, demography and population and reduction in energy waste [25].

1) DEMOGRAPHY

With a higher-than-average growth rate of 2.5% [26], KSA has a total population of about 34.2 million, of which 19.7 million are men and 14.5 million are women. Around 3.7 million people in Saudi Arabia are in the 35 to 39 age bracket, making up the majority of the country's population. With only 172,838 individuals between the ages of 75 and 79 [24], it is evident that the majority of government policies and economic development plans are geared towards creating more employment opportunities for Saudis. In addition, meeting the needs of a growing population while ensuring the sustainability of natural resources and attaining the goals outlined in its National Determined Contributions (NDCs) and ambitious Vision 2030 plans are essential. In 1974, 1992, 2004, and 2010 censuses were conducted, and the ensuing recorded populations were 7 million, 16.9 million, 22.7 million, and 27.1 million, respectively [27]. The start of Kingdom's fifth general population census was announced in the first quarter of 2020; however, the kingdom's population has been projected to be approximately 35 million in 2020 according to worldometers.info, a resource website that offers counters and current data on a range of subjects. The demography of the KSA comprises Saudis and non-Saudis, with the non-Saudis contributing 37.84% to the total population. The Saudi population is divided into 31.65% Males and 30.5% females whereas the non-Saudi population is divided into 25.93% males and 11.91% females. Additionally, it has been noted that the largest cities, such Makkah and Riyadh, which have populations of about 9.03 and 8.66 million each, respectively, are the most densely populated [24].

With large deposits of limestone that companies rented for a small fee and low gasoline price used by huge cement kilns positioned KSA ideally for cement production [29]. As per GlobalPetrolPrices.com, the average prices of gasoline places Saudi Arabia among the top 20 nations with the cheapest gasoline prices globally. Around May 2019, there was a steady increase in cement sales and production percentages, however, the build up to Covid-19 lockdown periods, the cement industry hit a decline [29]. Some months after lockdown ease in November 2020 according to reports [30], Saudi cement makers' overall sales volume increased by 15% to 4.9 million tons from 4.3 million during the same period last year.

2) URBANIZATION

Significant urbanization has occurred in the Kingdom of Saudi Arabia [31], which according to the World Urbanization Prospects: 2018 Revision has increased steadily from 2009 to 2019. In 2019, the share of urban population was 84.07% which has been increasing from a low of 21% in 1950 and is expected to reach 86% by 2030 and 90% by 2050 [32]. Additionally, the number of cities has also increased within the Kingdom from 58 in 1936 to 285 in 2015. Cities such as the capital Riyadh, Jeddah, Dammam, and the two Holy Cities of Makkah and Madinah have extremely dense populations. According to long-term estimates of the Kingdom, Saudi Arabia's population growth is projected to increase by an average of 2.5% per year. As a result, other smaller cities outside of these larger cities are also experiencing development [33].

With eight out of every ten residents living in urban areas, one of the world's most urbanized nations is Saudi Arabia. Urbanization can act as a progressive factor if well-planned and controlled, which can be leveraged for the sustainable and equitable growth of cities in Saudi Arabia. Over the past three decades, rapid urbanization, the growth of infrastructure and the modernization of Saudi society have improved the quality of life of Saudi people. Nonetheless, urbanization faces many challenges in Saudi Arabia due to its much reliance on oil. In order to address these and other urbanization challenges, the KSA government in 2013 developed and implemented an initiative called, "Future of Saudi Cities", in conjunction with the Ministry of Municipal and Rural Affairs and UN-Habitat, which is fully in line with the KSA vision 2030 and in response to global call on urban development [34]. There is an overwhelming demand for cement in Saudi Arabia due to increase in urbanization, infrastructural growth and increase in demand for commercial and residential construction. The cement market is expected to grow exponentially, driven by increased government spending to support infrastructure growth and rapid urbanization, especially in the KSA's central region. Due to the economic downturn of decrease oil sales, a gradual decline in the rate of megaprojects after years of immense growth, demand for cement decreased. In a 2019 US-Saudi Arabian Business Council report [35], it was revealed that cement production decreased from 57.2 million tons to 42.2 million tons in 2014 to 2018 respectively, resulting in a production decline of 26 percent. Clinker production also fell from 57.4 million to 48.3 million tons in the same period, resulting in a 16 percent production decline [35].

Despite the COVID-19 pandemic shock, the Saudi Arabia cement industry was expected to be extremely hit the pandemic and lower oil prices, however, the industry remained relatively healthy, and the housing sector continued to drive demand of almost 45 % of the total. In addition, the implementation of megaprojects across the kingdom became a game-changing catalyst for the industry. Although, demand for cement for infrastructure projects is expected to decrease in the short term as government reduces project investment, a decision that would affect the cement consumption adversely by the first half of 2021. The demand for cement is not expected to return to growth until the fiscal year of 2022 [36].

3) TOURISM INDUSTRY

As far as the tourism industry in the kingdom is concerned, it emphasizes the goals of economic diversification in accordance with Vision 2030 while also having a contemporary vision for successful and sustainable growth. Because of its ability to generate numerous job opportunities, the tourist industry is strongly supported, and as a result, it experiences consistent expansion. In 2011, 22.5 million local visitors made up most of the the country's overall 17.5 million foreign visitors [37]. In just seven years, these numbers have increased to roughly 61.8 million domestic tourists and 23.7 million foreign tourists [24]. The total expenditure of domestic tourists was 62.8 billion SAR while incoming international tourists incurred an expenditure of 128.3 billion SAR. There are 552,556 jobs created directly as a result of the tourism industry, and the Kingdom just received the 69th-best ranking on the World Economic Forum's Tourism Competitiveness Index [37]. The holy sites of Makkah and Madinah have historically served as the industry's cornerstone, but more recently, brand-new cities, festivals, and heritage sites have begun drawing domestic tourists and boosting the country's economy by encouraging investment in the sector and generating jobs for Saudi youth. The old city of Jeddah, which is listed as a UNESCO World Heritage Site, AlUla, the location of Hegra, another UNESCO World Heritage site [38], Abha, and others are incredibly appealing places to visit since they feature diverse landscapes, lovely seasons, and oasis.

The KSA tourism industry, like several other industries was badly impacted by the COVID-19 pandemic and the associated lockdown restrictions. As of March 2020, when the lockdown against the spread of the pandemic was in full force, it was difficult to gauge the impact of the pandemic on the Saudi Arabia's tourism industry. Nonetheless, it was very clear the COVID-19 pandemic will significantly affect the tourism numbers in the first and second quarters of 2020 particularly in the kingdom and around the globe. Looking beyond 2020, the future of the industry locally looked bright when there was relaxation on visa restrictions, opening KSA's many unseen and undiscovered landscapes, history and cultures to the world. Comparing tourism with other industries, it has the highest growth opportunities in the Kingdom. With the pace of work in setting up tourism infrastructure and huge investment from the Public Investment Fund (PIF), a sovereign wealth fund of KSA, prospects abound for firms across the hospitality value chain, most especially the construction sector. Public sector investment to the tune of 75 % of all the new capital injections in the KSA tourism industry is expected in the coming decades [39]. The Saudi government's prioritization of numerous megaprojects demonstrates its dedication to offering a wide range of tourist locations to draw both domestic and international visitors. Significant foreign direct investment is anticipated to flow into larger megaprojects like Neom and Red Sea projects, which are anticipated to be finished between 2025 and 2031 as part of destination marketing to draw tourists, and to generate tens of thousands of jobs for Saudis in a variety of industries, including tourism, entertainment, and construction. There will undoubtedly be a need for cement as a result of new projects like the development of new hotels and an international airport in Tabuk (the Amaala project), entertainment city (the Red Sea project), the world's tallest building (the Jeddah Tower), etc. [40].

4) NATURAL RESOURCES

The Kingdom of Saudi Arabia (KSA), one of the major oil exporters and a member of Organization of Petroleum Exporting Countries (OPEC), is the owner of around 22% of the world's proven oil reserves [23]. At the end of 2020, Saudi Aramco, the state's oil company discovered four new oil and gas fields near Dhahran, Al-Ahsa and the northern borders region at the Tuwaiq mountain formation [41], which hints on the country's expanding oil reserves. The country's single-source economy through its dependence on oil is now under transformation with its underlying economic diversification objectives laid out in the NDCs and Vision 2030. The country possesses 267 billion barrels of crude oil reserves, which can persist for more than 80 years at the current extraction rate of 9.81 million barrels/day. As far as natural gas is concerned, KSA extracts 7.5 billion cubic feet every day with proven reserves at around 330,000 billion standard cubic feet [42].

In the Middle East, KSA possesses the largest mineral deposits. The country's western region, known as the Arabian Shield, is made up of Precambrian crystalline and metamorphic rocks that have been unevenly uplifted by volcanic lava flows from the Tertiary and Quaternary Epochs [43]. This holds valuable mineral resources such as gold, copper, zinc, silver, manganese, tin, lead, tungsten, aluminum, iron, and chromium. The east of the country has extensive reserves of industrial minerals such as sulfur, salt, mica, feldspar, and gypsum. When explored further, the country is also home to a quarter of the world's highly prized rare element tantalum and niobium [44]. The Kingdom has lately identified 54 mineral-mining sites covering an area of around 4000 km^2, with the minerals detected including gold, copper, silver, zinc, iron, quartz, lead, and tin. The Kingdom is actively involved in expanding the mining industry [45]. The Ministry of Industry and Mineral Resources aims to develop the KSA mining sector to attract domestic and foreign investment as it proposes a huge market opportunity for the private sector to diversify its economy, increase GDP and create jobs for the Saudis [46]. Since the quality of the minerals is exceptional and rich [47], and prices of minerals on the world market have been increasing, this creates an opportunity for the kingdom to move forth with its expansion plans within the mining sector. The focus is towards attracting the private sector to become the backbone of the sectors' expansion to increase the government's return on investment and ensure future returns.

Limestone composed largely of mineral calcite is widely distributed in various parts of the Kingdom in quantities large enough to serve the ever-growing demands. The kingdom is also home to huge deposits of limestone, which constitutes between 70 and 80 percent of the manufactured cement, however, the high purity type in manufacturing white cement is rare. The Sulaiy and Tuwaiq areas situated in the central region, host large deposits of cement-grade limestone, a sedimentary rock about 50% of which is calcium carbonate (CaCO3). The Sulaiy limestone formation have a thickness of about 170 m and 30 km in width while limestone in Khuff formation around Qassim is approximately 20 – 25 m thick [48], [49]. For the sulfate-resistant cement, it raw material (fine-grained limestone) can be found in the Marrat formation [50]. Most of the limestone in the western region are the uplift coral reefs along the coastal areas of the red sea. As for Eastern Province, its limestone formations are not pure enough because it contains carbonates that are rich in magnesia, however, limestone deposits suitable for cement in this region can be found in Hofuf and Dammam. The limestone formation found in the South is the Jurassic formation while in the North, the limestone formation is the low-grade albeit but some good for manufacture limestone formations can be found near Al Jawf and Ar'ar. Aside limestone, dolomite, sand, gypsum and iron ore are the other cement raw materials that made up 30 % of the raw materials required to manufacture cement. All but iron is largely and naturally available Saudi Arabia. Most cement manufacturers procure their iron ore from SABIC, a local petrochemical and minerals producer [51].

C. GHG EMISSIONS FROM CEMENT PRODUCTION

This report's part focuses on a statistical analysis of the data collected to investigate the factors affecting GHG emissions from cement industries.

The first step of this section is to compute GHG emissions from the cement industries. To determine GHG emissions from the cement industries, the following method was employed:

1) Data was collected from publicly available sources such as the General Authority of Statistics and Saudi Central Bank (SCB) relating to the amount of cement produced within the KSA from 1970-2018.
2) According to the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories [52], To estimate the carbon dioxide emissions, it is advised to use clinker data rather than cement data, primarily because CO2 is released during the process's clinker production phase rather than its cement production phase. Therefore, due to the unavailability of clinker production data, the default conversion value for the 95% by weight clinker fraction in cement available in the Emissions Factor Database (EFDB) according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories was utilized to calculate clinker fraction within the cement produced. It is also assumed that cement produced cannot be disaggregated by type and it is known that all cement produced within the Kingdom of Saudi Arabia is Portland Cement which validates the utilization of the clinker fraction value.
3) Once the amount of clinker produced was calculated, default IPCC emissions factor of $0.5071\left(\frac{ton\ of\ CO_2\ emitted}{ton\ of\ clinker\ produced}\right)$ was utilized and input into the following Tier 1 GHG emissions estimation formula to determine the total CO2 emissions from clinker production:

$$\begin{aligned} &CO_2\ emissions\ from\ clinker\ production\ (tons)\\ &\quad = Amount\ of\ clinker\ produced\ (to)\\ &\qquad * Emissions\ factor\left(\frac{ton\ CO_2\ emitted}{ton\ of\ clinker\ produced}\right) \end{aligned}$$

D. VECM DEVELOPMENT

This study demands the creation of a VECM in order to evaluate the short- and long-run causal links among cement emissions and their causes (including the causal interactions among factors). EViews 12 was utilized in this study to create a VECM. and followings are the steps for developing a VECM.

1) MODEL SPECIFICATION

Emissions from the cement industry is the dependent variable for this study while independent or explanatory variables include population (Pop), urban population (U), tourist number (T), GDP, and energy consumption (E). The relationship between the factors that are dependent and those that are not dependent is shown in (1).

$$GHGst = \delta + \beta 1\ Popt + \beta 2\ Ut + \beta 3\ Tt + \beta 4\ GDPt + \beta 5\ Et + \varepsilon t \tag{1}$$

where, δ symbolizes intercept; t symbolizes year; εt symbolizes constant error term; $\beta 1$ to $\beta 5$ symbolize coefficients for Pop, U, T, GDP, E, respectively. Following the previous studies [53], we assumed that the given error term is normalized at zero mean value and constant variance.

Now, for developing the VECM, the examination of stationarity of each variable (both dependent and independent variables) is required, and this requires the logarithmic form of (1) which is denoted as (2).

$$Ln(GHGst) = Ln(\delta) + \beta 1\ Ln(Popt) + \beta 2\ Ln(Ut) + \beta 3\ Ln(Tt) + \beta 4\ Ln(GDPt) + \beta 5\ Ln(Et) + \varepsilon t \tag{2}$$

Based on the logarithmic form of the variables, stationarity of each variable will be tested through unit root tests.

2) UNIT ROOT TESTING

Each variable must be non-stationary 'at level' and stationary 'at first difference' as one of the prerequisites for creating a VECM. Unit root test helps to understand the stationarity of variables. There are several Unit root tests available to test stationarity, but the two most widely used Unit root tests are ADF tests (Augmented Dickey–Fuller) and PP test (Phillips–Perron) [new Reference as 48]. This study also used both ADF and PP tests. The reason for using both tests is that it provides a robust result. Research shows that ADF tests often fail to reject a unit root when the length of time series data is small (i.e. less than 50). Given that this study examined data from 1980 to 2018, the length of the time series data is only 38. Within the ADF and PP tests, this study analyzed both "intercept" and "intercept and trend" values to ensure the reliability of the results.

3) CO-INTEGRATION TESTING

Having at least one con-integrating equation is another prerequisite for creating a VECM. This implies that there must be a minimum of two co-integrated variables (both among the dependent and independent variables). A common test for co-integration is the Johansen's cointegration test, which was also used in this study to look at the co-integration of the variables. To guarantee the robustness and dependability of the test results, Trace Statics and Maximum Eigenvalue Statistics are both considered.

4) CAUSALITY TESTING

Causality testing is the last step of a VECM development. Granger causality is the most widely used causality test as it examines causality as well as the direction of causality. Therefore, this study also performs Granger causality tests to understand the causal relationships among dependent and independent variables as well as among independent variables themselves both in the short and long-run.

III. RESULTS AND DISCUSSION

A. VECM RESULTS

1) UNIT ROOT TEST RESULTS

Unit root test results are presented in II. Results show that all the variables (both dependent and independent) taken in this study are non-stationary 'at levels' and stationary 'at first differences', and the results are significant either at 0.05 or 0.01 level. It is evident from table 2 that PP tests could not reject the presence of unit roots for some variables 'at first differences' (e.g. total population and urban population). Likewise, the ADF test could not reject the presence of a unit root for cement emissions 'at first difference'. However, the combined results based on ADF and tests show that no variables have unit roots 'at first differences'.

2) CO-INTEGRATION TEST RESULTS

Johansen's co-integration test was used in this work to discover co-integrations between variables, and the results are shown in III. There is at least one co-integrating equation at the 0.01 level of significance, according to results based on both Trace Statistics and Maximum Eigen Statistics. This supports the creation of a VECM for this investigation and the execution of causality checks among variables.

3) EQUILIBRIUM RELATIONSHIP RESULTS

Table 4 shows the signs and coefficients of all independent variables where emissions from the cement industry are the dependent variable. Except urban population, the sign for each independent variable is positive. This means there is a positive correlation between cement emissions and population, number of tourists, GDP and energy consumption. In other words, with an increase in population, number of tourists, GDP or energy consumption, Saudi Arabia experiences an increase in cement emissions and vice versa. It's interesting to find that urban population is negatively correlated with cement emissions. This means that with an increase in urban population, emissions from the cement industry decrease. However, it is important to note that co-relation does not always indicate causation. Therefore, this study performed causality tests and the results are presented in V.

TABLE 2. Unit root test results.

At Level	Test statistics (ADF)		PP statistics (PP)	
	I (Intercept)	I&T (Intercept and Trend)	I (Intercept)	I&T (Intercept and Trend)
GHGs	2.06 (3)	0.82 (3)	-0.96 (2)	-1.82 (1)
Pop	2.76 (3)	-5.62 (3)***	-0.96 (2)	-0.65 (3)
U	1.50 (9)	-3.66 (8)**	0.93 (3)	-0.71 (5)
T	1.71 (3)	-0.96 (0)	3.92 (3)	-0.39 (3)
GDP	1.01 (0)	-1.62 (0)	0.85 (1)	-1.58 (3)
E	-1.42 (3)	-5.35 (1)***	-1.81 (3)	-3.70 (3)**
At first difference				
GHGs	1.44 (3)	-0.73 (3)	-3.76 (3)***	-3.71 (3)**
Pop	-3.16 (3)**	-4.63 (3)***	-1.49 (4)	-1.57 (3)
U	-2.41 (8)	-4.19 (9)**	-1.47 (3)	-1.55 (4)
T	-6.52 (3)***	-7.14 (0)***	-6.54 (3)***	-8.33 (3)***
GDP	-4.57 (0)***	-5.11 (0)***	-4.58 (3)***	-5.02 (3)***
E	-4.85 (3)***	-5.01 (0)***	-4.84 (3)***	-5.05 (2)***

Here, ** and *** denote significance level at 0.05 and 0.01, respectively.

TABLE 3. Johansen's co-integration test results.

Co-integrating equation number (CE)	Hypothesis	Trace Statistic	Maximum Eigen Statistic
r = 0	No CE	169.38***	65.21***
r = 1	1 CE at most	104.17***	35.85***
r = 2	2 CE at most	68.33**	29.64**
r = 3	3 CE at most	38.68**	24.02**
r = 4	4 CE at most	14.69*	14.56**
r = 5	5 CE at most	0.10	0.10

Here, *, ** and *** denote significance level at 0.1, 0.05 and 0.01, respectively.

TABLE 4. Co-integrating equation.

Dependent variable: Greenhouse gas emissions (GHGs)

Independent variable	Co-efficient	Standard error	t-statistic
Pop	326.38	23.68	13.78
U	-367.07	24.91	-14.74
T	18.48	2.75	6.71
GDP	1.3E-04	1.0E-05	13.1
E	12759.36	843.77	15.12

4) CAUSALITY TEST RESULTS

For understating the causal relationships among the variables in the short- and long-run, this study adopted Granger Causality test because it has the advantage of indicating the direction of causality as well. V shows that emissions from cement production have a long-run causal relationship with population, urbanization, GDP, and energy consumption of Saudi Arabia. This indicates that with an increase in population, GDP and energy consumption, emissions from cement industry are likely to increase in the long term unless these factors are emissions decoupled from cement emissions. Given that urban population has a negative causal relationship with cement emissions, the policy makers need to promote urbanization and urban density in the long run. To reduce emissions from the cement industry in the long-run, GDP and energy consumption need to be clean and steps need

TABLE 5. Short- and long-run causality test results.

Short-run Granger causality (F-statistic)							Long-run Granger Causality (t-statistic)
	Ln(GHGs)	Ln(Pop)	Ln(U)	Ln(T)	Ln(GDP)	Ln(E)	Error Correction term
Ln(GHGs)	-	2.02 (0.15)	0.91 (0.42)	0.93 (0.45)	4.06 (0.03)**	2.25 (0.14)	2.45 (0.03)**
Ln(Pop)	1.83 (0.18)	-	0.51 (0.68)	1.62 (0.23)	2.34 (0.11)	0.49 (0.69)	2.04 (0.06)*
Ln(U)	- 0.14 (0.94)	4.97 (0.014)**	-	0.56 (0.65)	0.51 (0.68)	1.49 (0.26)	- 2.08 (0.05)**
Ln(T)	1.23 (0.33)	0.80 (0.51)	0.35 (0.79)	-	1.31 (0.31)	1.94 (0.17)	0.37 (0.71)
Ln(GDP)	0.09 (0.97)	1.31 (0.31)	0.59 (0.63)	2.65 (0.08)*	-	1.27 (0.32)	3.40 (0.004)***
Ln(E)	0.79 (0.52)	2.35 (0.11)	2.35 (0.11)	0.71 (0.56)	2.08 (0.15)	-	2.11 (0.05)**

Values within parentheses are p-values, and significance level at 0.1, 0.05, and 0.01 are indicated using *, **, and ***, respectively.

to be taken by the policy makers to ensure a rapid transition to low or zero carbon economy and energy sources. In addition, added population in the future needs to be accommodated within urban areas to reduce cement emissions in the long run.

Regarding short-run causal relationships, Table 5 indicates that there is a causal relationship running from GDP to cement emissions. This justifies that appropriate policy interventions need to be taken immediately to support a low carbon economy. There are also short-run causal relationships among independent variables themselves. For example, results show that population has a causal relationship with urban population and the relationship is unidirectional running from population to urban population. This is an encouraging finding because an increased number of urban populations can help reduce Saudi Arabi's cement emissions. Also, results show that the number of tourists in Saudi Arabia has a unidirectional causal relationship with GDP and the relationship is running from the number of tourists to GDP. Given that both GDP and tourist numbers could increase cement emissions in the long-run, the government should focus more on reducing tourist-induced emissions by offering low carbon services and facilities in the future.

B. MITIGATION OPPORTUNITIES

With large scale deployment of carbon capture technologies, enabling policies, public-private partnership and economic support, an International Energy Agency (IEA) study [54] concluded that an average decrease of 18 percent or 5Gt in cement CO2 emissions by 2050 would be needed to meet the target of 50 per cent global warming to sustain a pre-industry level at < 2°C [55]. To achieve this set target, it is imperative to put in place different mitigation strategies, from fuel and energy efficiencies to adoption of alternative clinker and carbon capture and storage – the main solution proposed by IEA.

1) INNOVATIVE USE OF EXISTING MATERIALS

The innovative utilization of existing supplementary cementitious materials (SCM) has the double benefits of reducing raw materials responsible for CO2 emission and thermal energy reduction from reduced material processing. Existing SCM are remixed or redesigned in innovative ways to partially replace the current Portland cement clinkers. For instance, calcined clays originally were used as pozzolanic materials, but the calcination as a treatment on the clay limits its use in beneficial pozzolanic blend quantity bearing in mind the environment. A higher level of clinker substitution (around 50%) is possible when calcined clay and limestone filler are combined, without losing mechanical characteristics or durability performance. In addition, the cost of concrete production and adverse impact on the environment are greatly reduced. In a pioneering work by Karen Scrivener team and later joined by many other researchers [56], [57], [58], [59], calcined clays and limestone filler (LC3) were used as innovative solution to not only reduce the materials responsible for CO2 emission but also leads to thermal energy in processing the material. LC3 builds of existing technologies to cut on the existing clinker content used in OPC production in order to reduce CO2 emissions while maintaining comparable rt better performance with OPC [56]. More research efforts [60], [61], [62], [63], [64] have been directed towards the development of LC3 material and it is becoming progressively fascinating for the cement industry. In another attempt at reducing CO2 emission, John et al. [65] reports the utilization of high volume ($\sim$ 70 %) limestone filler, which shares similar purity with clinker grade. Higher substitution percentage was possible with the use of an innovative technology, which allows for separate grinding of the filler, clinker and other minerals, which are later combined in optimized proportions to hugely reduce the demand for water dues to high volume of fines, a dispersant is used for adequate rheological behavior to be achieved in the blended product [65], [66]. This method is expected to considerably reduce CO2 emissions and energy usage during the life cycle of cement-based products at low investment and operational costs, especially in comparison to anticipated carbon capture and storage prices. The limestone filler was strategically used to dilute the reactive ingredients in the clinker and to increase the mass and quantity of the eventual product. Apart from the technical and economic reasons, the limestone filler was used for environmental reasons [67], [68] for instance, low-grade fillers can be used in the cement industry to minimize production energy and CO2 emissions and extend the useful life of limestone quarries [65].

2) NEW CEMENTS AND CLINKERS

Mitigation strategy through alternative cement binders is in different stages of development, some are in commercial stage like belite clinker, calcium sulfoaluminate (CSA) clinker and alkali-activated binder, while other are in pilot and, research and development stages. Belite calcium sulphoaluminate (BCSA) clinker, cements based on carbonation of calcium silicates (CACS), cement based on prehydrated calcium silicates (PHCS), etc. are all in pilot stage. Mainly, cements based on magnesium oxides derived from magnesium silicates (MOMSs) are one of the binders still in the research and development stage [19]. Assessed to reduce CO2 emissions, alkali-activated binder and geopolymer [69], [70], [71], Belite-Ye'elimite-Ferrite (BYF) [72] clinkers and Carbonatable Calcium Silicate (CCS) clinkers [72] are some of the few developed technologies proposed to replace or at least rival the OPC. The advantage alkali-activated binder and geopolymers have is the variety of source materials and activator that can be used in their development inasmuch as the source materials contain silica and alumina. Many studies have proven the CO2 reduction potential of the alkali-activated binders relative to the OPC [73]. Like alkali-activated binder, BYF also presents a dual benefit in comparison with OPC and its production. It requires different raw materials feed with lower limestone content, which implies lowering the CO2 emissions quantity. Secondly, the kiln temperature in the BYF production is much lower than for OPC production reducing the fuel energy required and associated emissions [65]. One of the stumbling blocks against the widespread acceptance of BYF is its loss of strength to carbonation due to high ettringite content. Another impediment is the limited availability of high alumina source materials, which might hinder its ability to compete as a new technology [74]. With CCSC, the mitigating strategy to reduce CO2 emissions is no different in that the raw material was also reduced and the fuel energy was reduced to achieve a 30 % CO2 emissions reduction relative to OPC. One unique benefit of CCSC is that it is cured with CO2 thereby valorizing the emitted CO2 [65]. Another binder that shares semblance with belite (C2S) hydraulic binder is the hydrated calcium silicate compound developed through a CO2 efficient approach by autoclaving lime-silica mixtures at low temperature [55], [75], [76]. For activation and partial dehydration, celitement (hard filler) was interground with αC2SH and heated at low temperature to bring it closer to belite composition (C2S) albeit far more reactive. The advantage of this material is in its increased level of dilution with low-CO2 fillers. There are [77], [78], [79] ongoing efforts to replace limestone raw material with ultramafic rock (magnesium silicate) to manufacture magnesium-based cements. The idea is for magnesium-based cement to capture CO2 and form magnesium carbonate ($MgO + CO2 = MgCO3$), which is an advantage over limestone based. Recently, CO2-containing flue gas and cement kiln dust (CKD) were proposed as an option to reduce CO2 emissions by producing mineral carbonation of CKD (MCCKD), which converts CO2 to synthetic carbonates after reacting with calcium or magnesium containing species, such as oxides, hydroxides, and silicates [80]. Alternative cement binding materials face stiff barriers to wider market deployment in comparison with the Portland cement clinker. These barriers stem from material performance, standardization, cost of technology and base materials, and available market applications. Technological savings can be made on some of the alternative clinkers/binders since the same Portland cement manufacturing plant could be used in their production.

3) CARBON CAPTURE AND STORAGE

Direct sequestration, which has a history of successfully capturing CO2 at its release sites before it escapes to the atmosphere, is without a doubt one of the most promising solutions to the CO2 emission problem. The CO2 must be removed from the source of emission before being compressed, transported, and stored in the allocated reservoirs [81]. Although the production of cement produces the most CO2 of any industrial sector, significant amounts of CO2 are produced in the oil and gas processing industries. About 6% of all stationary sources' emissions of CO2 are produced by the cement industry, which includes both large industrial production facilities and smaller, more dispersed residential or commercial buildings [82]. According to the 2005 special report by the Intergovernmental Panel on Climate Change (IPCC), the technology utilized for capturing largely depends on the properties of the exiting gas such as concentration of gas (CO2), streaming pressure of the gas released, and the fuel type used. By 2050, the IPCC advised an 80% reduction in CO2 emissions, which necessitates a sharp decrease in emissions from industry. The focus of the International Energy Agency (IEA) is in four improvement categories available to cement industry for improved CO2 emissions: alternate fuel, clinker substitution, energy efficiency and, carbon capture and sequestration (CCS) [83]. Meeting this target require technologies like CCS to be part of the industry's economic package of decarbonization alternatives [84] being one of the best approaches to reducing CO2 emissions. By methodically injecting the released CO2 into suitable underground storage reservoirs, a group of technologies has been developed to prevent CO2 emissions from the production of traditional energy and industrial production processes.

The use of CCS in the manufacturing of cement is a recent innovation that has gained popularity in recent years because of its environmental friendliness and bright economic prospects. CCS is a method of capturing that uses oxy-fuel combustion [85], pre-combustion, post-combustion, chemical looping combustion [86], [87], transport, processing and storage. This is accomplished through mineral carbonation, ocean storage, or deep geological sequestration. The process of CCS in cement production includes the capture of CO2 emitted from pulverized coal combustion and its subsequent injection into a geological formation. The benefits of CCS in cement production include reduced emissions, increased energy efficiency and increased process capacity because the by-product CO2 is used.

Three methods of reducing CO2 emissions were and are still taken into consideration in the cement industry: oxy-fuel combustion, pre-combustion, and post-combustion. When it comes to pre-combustion, the CO2 collection exercise is more appropriate to the CO2 emitted in new cement plants that have gasification technology built into them to produce syngas (a mixture of CO, CO2 H2 and H2O). The demerit of this approach is that only the CO2 emitted from the fuel will be captured leaving that emitted from limestone calcination. In addition, there is a prerequisite of new energy efficient burner technology and cement kiln for the pre-combustion approach. This gives advantage to the post-combustion approach where the CO2 from the fuel and limestone calcination will both be captured [88]. The use of purified oxygen for burning in the cement kiln to generate a N2-free flue gas is known as oxy-fuel combustion (mainly consisting of CO2 and H2O) where a clean CO2 stream will be obtained after condensation. Though, using pure oxygen in current cement kilns will necessitate significant changes to the burner design, kiln, and industrial layout. As a result, post-combustion CO2 collection appears to be the simplest for cement plant upgrade. Cement plants produce a lot of CO2 caused by certain stages in the production process, if managed properly, it can be channeled safely to the ground for permanent sequestration. With selective chemical reactions to remove CO2 from the gases generated during the production of cement, CCS offers ways to lower the amount of CO2 that is released into the atmosphere. Prior to entering the atmosphere, CO2 is captured by CCS, and it is then transported there by pipeline or tanker for long-term storage underground. Even though CCS is a practical solution, it can be expensive to implement but has been found to increase efficiency while reducing NOX and VOC emissions. As CCS is an expensive mitigation option, it can be deployed as a midterm solution to reduce environmental impact of CO2 while fossil fuel is continually used in anticipation of the maturity of renewable energy technologies [89]. The post-combustion CO2 capture methods stand out due to four crucial and illuminating characteristics that could be used in the cement industry: compatibility with the existing cement plant conditions technically, use of non-toxic, non-hazardous materials, reduced influence on cement production plants activities and harmony with the existing expertise in the cement production plants [88].

According to the 2020 Global CCS Institute report [90], it was forecasted that the volume of CO2 captured will rise from around 2 Mtpa in 2019 to well over 100 Mtpa by 2040 [91]. In Saudi Arabia, cement production is a major industry, which makes it an important part of the CO2 abatement policy for the country being a highly polluting sector. In the Kingdom, over 61 million tons of cement was produced in 2015 and to put the figure in perspective, in the same year, the US produced approximately 80 million tons according to the US Geological Survey (USGS) [24]. The population of this nation is ten times more than Saudi Arabia's, and its GDP is twenty-seven times larger. Due to the nation's rapid development, this serves to demonstrate the size of the Saudi Arabian cement industry. Environmental rules and strategies must be developed that consider the Saudi cement industry's high level of CO2 emissions. This might be accomplished by enhancing energy efficiency and implementing CCS technology [24]. The Saudi cement industry struggles between competing objectives (profit and CO2 emissions) that affect the performance of the industry [92]. Being the ninth largest CO2 emitter in the world, Saudi Arabia has its cement manufacturing industry as the major contributor to the global CO2 emissions [93]. The CO2 emission mitigation is a significant part of Saudi Arabia's future development policies as a crucial long-term strategy in managing CO2 emissions especially from major sources like the cement production plants. Although the current CCS development program in the Kingdom remains minimal with regards to CO2 emissions and stated goals, significant pilot ongoing studies among energy and industrial companies are evident. Currently in Saudi Arabia, some of the ongoing CCS activities across the Kingdom are:

a) Saudi Aramco's Uthmaniyah oil production plant, a part of the Ghawar field. The plant uses 0.8 Mtpa of captured CO2 from Haniyah Natural Gas Liquid (NGL) plant.
b) Saudi Basic Industries Corporation (SABIC)'s facility at its ethylene plants in Jubail captures about 0.5Mtpa of CO2 for use in methanol and urea production [94], [95].

The reliance of Saudi Arabia on oil for cement production and power generation is the greatest in the region followed closely by Kuwait and Iraq. The alternative energy initiatives and policies such as the adoption of CCS may reduce KSA's reliance on oil in addition to its reduced dependence on fossil fuels. The reduction as reported by Matar et al. [96] will be about 2 million barrels of oil equivalent per day in 2032. With this kind of progress, big impacts are expected in the region's CCS deployment rates and cost. According to the Leeson et al. [97], they found that the chunk of the cost of CCS using a techno-economic model for implementing CCS across sectors like the cement industry, is between the initial deployment cost and the launch of operation [98]. In its 2020 annual report [95], Saudi Aramco reinforced their commitments in reducing Kingdom's emissions through investments in carbon capture, utilization and

TABLE 6. Some demonstration projects around the world for CCS [101].

Name of project	Type of industry	Technology used	CO2 capturing capacity	Sequestration method	Start year	Country
Captain Clean Energy Project	Captain Clean Energy Limited, Grangemouth, Scotland, UK	Siemens Pre-Combustion Gasification	3.8 Mt/y	351–400 km pipeline to offshore deep saline formations	2022	UK
HeidelbergCement Norwegian Subsidiary, Norcem	Cement Plant	Chemical absorption, adsorption and membrane technologies	400,000 t/y	Capture the CO2 and release it into the atmosphere afterwards	2020	Norway
Don Valley Power Project, Stainforth, South Yorkshire, UK	Sargas Power (sold in 2014 by 2 Co Energy Ltd)	IGCC: Pre-combustion	4.5 Mt/y	175 km onshore to offshore pipeline for sequestration in offshore deep saline formations	2020	UK
Texas Clean Energy Project (TCEP), USA	Summit Power Group Inc, and Texas Bureau of Economic Geology	Pre-Combustion: Siemens IGCC technology and Linde Rectisol acid-gas capture technology (90% CO2 capture)	2.0 Mt/y	EOR in the Permian Basin	2019	USA
Taweelah Project	Abu Dhabi Future Energy Company and Taweelah Asia Power Company	Post Combustion absorption	2.0 Mt/y	EOR	2018	UAE
Petra Nova W.A. Parish, USA	NRG Energy and JX Nippon Oil & Gas Exploration Corp., Texas, USA	Post-combustion: KM-CDR amine scrubbing CO2 developed by MHI and KEPCO	1.4 Mt/y	Pipeline for onshore EOR in Hilcorp's West Ranch Oil Field in Jackson County, Texas	2016	USA
Peterhead Project	Scottish and Southern Energy (SSE) and Shell	Post-combustion retrofit	1.0 Mt/y	Onshore to offshore 102 km pipeline to offshore depleted Goldeneye gas reservoirs at a depth of 2 km	2015	UK
Dongguan, China	Dongguan Taiyangzhou Power Corporation, Xinxing Group, Nanjing Harbin Turbine Co	Pre-combustion capture (KBR and Southern Company Technology)	1.0 Mt/y	Transported 51–100 km via pipeline for use in EOR in the Shangdong Province	2015	China
Capitol SkyMine, Skyonic Corp, San Antonio, Texas	Cement plant, acid gases and heavy metals	Transform CO2 discharge from exhaust streams into solids	83,000 t/y	Mineralization of CO2 as Sodium bicarbonate	2013	USA
Taiwan Cement Corp	Cement plant and power plant	Calcium looping process	8,760 t/y	Pumping to underground to enhance the production of natural gas	2013	Taiwan
Kemper County IGCC	Mississippi Power, Southern Energy, KBR	Pre-combustion IGCC plant using TRIG™ technology (65% capture)	3.0 Mt/y	Pipeline for onshore EOR	2010	USA
Shengli Oil Field EOR	Sinopec, Shengli power plant, Dongying, Shangdong Province, China	Post-combustion-Retrofit	40,000 t/y	Transported 80 km via pipeline for use in EOR at 3 km depth in the Shangdong Province	2007	China

TABLE 6. ***(Continued.)*** **Some demonstration projects around the world for CCS [101].**

Pond Biofuels, Canada	St. Marys Cement in South-western Ontario	Photo-bioreactor of 1,500 square foot facility	NA	Production of Algae	NA	Canada
Mantra Energy, Canada	Lafarge Cement, Richmond, Canada	Electro-reduction of carbon dioxide	36,500 t/y	CO2 is transferred to formic acid and O2 as by-product	NA	Canada

storage amongst other technologies, which is expected the company a competitive edge in the market. The availability of safe geological storage for the captured CO2 is a crucial condition for the success of CCS systems in all these projects. Other variables that can aid in the implementation of CCS projects include stable financial financing and supporting regulatory and legal frameworks [99], [100].

As a high CO2 discharging sector, the Saudi Arabian cement industry requires demonstration projects using different technologies like those shown in VI in capturing the discharged CO2 before escaping from cement plants. Apart from investing in a more efficient CCS system in mitigating CO2 emissions, equally important is the efficiency of operational kilns, the fuel type the kilns consume and meeting the myriads of contents requirements during the process of mixing. While the choice of investing in more efficient kilns reduces process-based emissions might stand in the way of company's profit, it however, gives room to observe the policymaker's and industry practitioner's space for possible compromise to achieve effective policies [92], [96].

4) DEMAND AND WASTE MANAGEMENT

The demands of the construction industry are increasing owing to urbanization and population growth [102]; however, unsustainable disposal methods create substantial environmental risks [103]. As the second-largest emitter of GHGs globally, the construction industry faces arduous tasks in managing generated construction site waste, which has become a challenge, especially during demolition and site cleanup. Waste recycling has become an alternative to landfill disposal, which has become more prevalent nowadays because of its capacity to solve this problem by either using it immediately or storing it until it can be reused for a new purpose [104]. Material efficiency strategies potentially contribute to GHG reduction throughout the material life cycle. Strategies to mitigate GHGs are evaluated mainly by their economic benefits and potential to reduce GHGs without considering their direct impacts on human lives [105].

Recycling and reuse of construction materials has become a valuable option for minimizing construction and demolition (CDW) in landfills and mitigating primary mineral resource depletion to reduce their carbon footprints. In many countries, traditional disposal routes dominate waste management practices. Recently, there has been a steady flow of legislation focusing on reducing the environmental impact of waste [106]. Invariably, construction activities such as new construction or restoration/repair of old construction lead to waste generation. Construction waste recycling is predicted to be an integral part of the construction industry in the near future. This will help reduce GHG emissions, pollution and energy consumption.

The waste management hierarchy is an integrated approach that uses the philosophy of ordering to layer different options into the scale of preference before underpinning the strategy(ies) with the most sustainable option (s). Although its approach is integrative, its prescriptive approach lends little to alleviating the reliance on end-of-pipe solutions. Demand management and other efficient processes that reduce energy and consumed resources by having a direct impact on waste generation have received minimal attention [106].

The demand management framework is a responsive strategy that has been successfully deployed in many industries for handling and managing overproduced waste. Demand management and construction waste recycling are designed processes to alter the way materials are produced and consumed to reduce the need for new manufacturing materials, which helps to reduce GHG emissions. In regard to construction and building wastes, demand management is achieved by making materials with longer lifespans, reusing products, and buying recyclable products. Increased efforts in end-of-life repurposing, reuse, and recycling are crucial steps that would be highly impactful when users play an imperative role in increasing the demand for material-efficient products that contribute to reducing GHG emissions.

Over time, the increasing supply chain complexities existing between countries have made governance difficult and led to an increased likelihood of problems shifting from one country to another. The most significant mitigation wedge was energy efficiency, which frankly did not record much progress in reducing GHG emissions. Reports have shown that there would be decreased efficiency potential in the coming decades due to the drastic exhaustion of available technological options. As a result, there has been increased focus on "weak drivers" of carbon footprint reduction, such as demand management. In straightforward terms, waste elimination for material lifecycle processes using demand management methodologies and supply chain efficiencies are the most efficient solutions to material conservation and waste reduction.

Generally, the reduction of waste can be achieved through the development of more efficient processes (to reduce waste) or reduce the demand for new materials so that the focus can be shifted from producing more new units to recycling, reusing and repurposing more units and producing few units. True sustainability can only be achieved by minimizing resources and energy use. This can only occur because of demand management and the creation of more efficient operations, as it relates to waste recycling and reuse. The demand management option offers two vital benefits: reducing resource use and reducing waste generated from the built environment. While there are many clear benefits associated with demand management, consumer demand for products manufactured using recycled materials is low. This low demand for remanufactured products may be explained by user biases, which are based on the status-quo rationality of accepting products that are based on recycled waste materials [107].

IV. CONCLUSION

This study develops a Vector Error Correction Model in order to investigate the short-run and long-run causal links between emissions from cement production and the important factors that contribute to those emissions. The paper also discusses the difficulties and potential solutions for lowering greenhouse gas emissions in the cement industry in the Kingdom of Saudi Arabia. Cement industry is one of the major industries in Saudi Arabia. The local production of cement depends on many factors including demography, urbanization, tourism, and GDP. Cement production has been following an increasing trend with significant downfall in last few years. The main reason cited for a recent downfall of cement production is the global economic slowdown which affected the industry hugely especially since the industry was not operating at full capacity even before the pandemic. The possible ways of mitigation focusing on process emissions include innovative utilization of existing supplementary cementitious materials, carbon capture, storage, utilization (CCUS), and sequestration, demand management, and recycle and re-use of materials. As far as renewable energy is concerned, studies have focused on biofuels and their benefits in cement manufacturing. Utilizing biofuels made from food waste can lower CO2 emissions. The Kingdom has taken many initiatives to meet its climate change mitigation pledges. Many landmark initiatives are taken focusing on CCUS especially by oil and gas industries, and petrochemical industries. In addition, the government should focus on policies that will offer a sustainable transition to low-carbon GDP and energy consumption because both GDP and energy consumption have long-term causal relationships with cement emissions. The total population of Saudi Arabia also has a long-term positive causal relationship with cement emissions while the causal relationship between urban population and cement emissions is negative. This suggests that the government should emphasize increasing urban population density to accommodate additional population in the future so that it contributes to reduced cement emissions.

ACKNOWLEDGMENT

The authors would like to thank the research support provided by the King Fahd University of Petroleum & Minerals (KFUPM) in conducting this study.

REFERENCES

[1] D. Wiedenhofer, D. Virág, G. Kalt, B. Plank, J. Streeck, M. Pichler, A. Mayer, F. Krausmann, P. Brockway, A. Schaffartzik, T. Fishman, D. Hausknost, B. Leon-Gruchalski, T. Sousa, F. Creutzig, and H. Haberl, "A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, Part I: Bibliometric and conceptual mapping," *Environ. Res. Lett.*, vol. 15, no. 6, Jun. 2020, Art. no. 063002, doi: 10.1088/1748-9326/ab8429.

[2] E. A. Olson, "Rethinking sustainable development in South Africa through an integrated biodiversity conservation and climate change adaptation approach," Dept. Global Int. Stud., Univ. California, Irvine, Santa Barbara, CA, USA, Tech. Rep. 1548275, 2013.

[3] E. Elahi, Z. Khalid, and Z. Zhang, "Understanding farmers' intention and willingness to install renewable energy technology: A solution to reduce the environmental emissions of agriculture," *Appl. Energy*, vol. 309, Mar. 2022, Art. no. 118459, doi: 10.1016/j.apenergy.2021.118459.

[4] M. Landler and S. Sengupta. (2020). *Trump and the Teenager: A Climate Showdown at Davos*. Accessed: Jun. 29, 2020. [Online]. Available: https://www.nytimes.com/2020/01/21/climate/greta-thunberg-trump-davos.html

[5] S. Cohen. (2020). *Economic Growth and Environmental Sustainability*. Accessed: Jun. 29, 2020. [Online]. Available: https://blogs.ei.columbia.edu/2020/01/27/economic-growth-environmental-sustainabilit

[6] Supriya, R. Chaudhury, U. Sharma, P. C. Thapliyal, and L. P. Singh, "Low-CO_2 emission strategies to achieve net zero target in cement sector," *J. Cleaner Prod.*, vol. 417, Sep. 2023, Art. no. 137466, doi: 10.1016/j.jclepro.2023.137466.

[7] Y. Guo, L. Luo, T. Liu, L. Hao, Y. Li, P. Liu, and T. Zhu, "A review of low-carbon technologies and projects for the global cement industry," *J. Environ. Sci.*, vol. 136, pp. 682–697, Feb. 2024, doi: 10.1016/j.jes.2023.01.021.

[8] H. U. Sverdrup and A. H. Olafsdottir, "Dynamical modelling of the global cement production and supply system, assessing climate impacts of different future scenarios," *Water, Air, Soil Pollut.*, vol. 234, no. 3, p. 191, Mar. 2023, doi: 10.1007/s11270-023-06183-1.

[9] R. M. Andrew, "Global CO_2 emissions from cement production, 1928–2017," *Earth Syst. Sci. Data*, vol. 10, pp. 2213–2239, 2018, doi: 10.5194/essd-10-2213-2018.

[10] M. Schneider, M. Romer, M. Tschudin, and H. Bolio, "Sustainable cement production—Present and future," *Cement Concrete Res.*, vol. 41, no. 7, pp. 642–650, Jul. 2011, doi: 10.1016/j.cemconres.2011.03.019.

[11] *Theft of Construction Plant and Equipment*, IMIA, Int. Assoc. Eng. Insurers, U.K., 2005.

[12] E. Worrell, L. Price, N. Martin, C. Hendriks, and L. O. Meida, "Carbon dioxide emissions from the global cement industry," *Annu. Rev. Energy Environ.*, vol. 26, no. 1, pp. 303–329, Nov. 2001, doi: 10.1146/annurev.energy.26.1.303.

[13] R. M. Andrew, "Global CO_2 emissions from cement production, 1928–2018," *Earth Syst. Sci. Data*, vol. 11, no. 4, pp. 1675–1710, Nov. 2019, doi: 10.5194/essd-11-1675-2019.

[14] E. Gartner, "Industrially interesting approaches to 'low-CO_2' cements," *Cement Concrete Res.*, vol. 34, no. 9, pp. 1489–1498, Sep. 2004, doi: 10.1016/j.cemconres.2004.01.021.

[15] R. Maddalena, J. J. Roberts, and A. Hamilton, "Can Portland cement be replaced by low-carbon alternative materials? A study on the thermal properties and carbon emissions of innovative cements," *J. Cleaner Prod.*, vol. 186, pp. 933–942, Jun. 2018, doi: 10.1016/j.jclepro.2018.02.138.

[16] A. J. Schokker. (2010). *The Sustainable Concrete Guide: Applications*. [Online]. Available: https://library.fce.vutbr.cz/files/e-book/SCGAApplications.pdf

[17] A. Hasanbeigi, L. Price, and E. Lin, "Emerging energy-efficiency and CO_2 emission-reduction technologies for cement and concrete production: A technical review," *Renew. Sustain. Energy Rev.*, vol. 16, no. 8, pp. 6220–6238, Oct. 2012, doi: 10.1016/j.rser.2012.07.019.

[18] T. Hills, N. Florin, and P. S. Fennell, "Decarbonising the cement sector: A bottom-up model for optimising carbon capture application in the UK," *J. Cleaner Prod.*, vol. 139, pp. 1351–1361, Dec. 2016, doi: 10.1016/j.jclepro.2016.08.129.

[19] *Technology roadmap low-carbon transition in the Cement Industry*, Int. Energy Agency, France, 2011.

[20] *KSA Third National Communication (TNC), Designated National Authority (DNA)*, TNU, Designated Nat. Authority (DNA), Kingdom of Saudi Arabia, 2016.

[21] Q. Tarawneh and S. Chowdhury, "Trends of climate change in Saudi Arabia: Implications on water resources," *Climate*, vol. 6, no. 1, p. 8, Jan. 2018, doi: 10.3390/cli6010008.

[22] HCDP. (2020). *Human Capital Development Program | Saudi Vision 2030*. [Online]. Available: https://www.vision2030.gov.sa/en/programs/HCDP

[23] NIDLP. (2020). *National Industrial Development & Logistics Program: Delivery Plan 2018–2020*. [Online]. Available: https://www.vision2030.gov.sa/sites/default/files/attachments/NIDLPDeliveryPlan-EnglishJan. 2019.pdf

[24] GASTAT. (2019). *Statistical Yearbook, General Authority for Statistics*. [Online]. Available: https://www.stats.gov.sa/en/1006

[25] M. Placet and K. Fowler, "Toward a sustainable cement industry: How innovation can help the cement industry move toward more sustainable practices," An Independent Study Commissioned By World Business Council For Sustainable Development, World Bus. Council Sustain. Develop., Switzerland, Tech. Rep. 18627, 2002.

[26] U. Al-Suhaimy, "Saudi Arabia: The desalination nation," in *Asharq Al-Awsat, Last Modified Tuesday*, vol. 2. London, U.K.: Asharq Al-Awsat, 2013.

[27] *The First Biennial Update Report (BUR1) Kingdom of Saudi Arabia, Designated National Authority (DNA)*, BUR1, Designated Nat. Authority (DNA), Kingdom of Saudi Arabia, 2018.

[28] World Bank. (2022). *Data Bank: World Development Indicators*. World Development Indicators. Accessed: Sep. 19, 2022. [Online]. Available: https://databank.worldbank.org/source/world-development-indicators

[29] *Saudi Chartbook Summary, Jadwa Investment*, Jadwa, Riyadh, Saudi Arabia, 2020.

[30] ARGAAM. (2020). *Saudi Cement Sales Jump 15% to 4.9 Million Tons in November*. [Online]. Available: https://www.arabnews.com/node/1774871/business-economy

[31] I. R. Abubakar and Y. A. Aina, "Achieving sustainable cities in Saudi Arabia: Juggling the competing urbanization challenges," in *E-Planning and Collaboration: Concepts, Methodologies, Tools, and Applications*. Pennsylvania, PA, USA: IGI Global, 2018, pp. 234–255.

[32] *United Nation World Urbanization Prospects: The 2018 Revision, Population Division of the Department of Economic and Social Affairs of the United Nations*, UNWUP, Dept. Econ. Social Affairs, USA, 2018.

[33] *Saudi Arabia—Urban Issues | UN-Habitat, United Nations Habitat*, UN Habitat, United Nations Hum. Settlements Programme, Kenya, 2019.

[34] FSCP. (2019). *Saudi Cities Report 2019 | UN-Habitat, UN-Habitat*. Accessed: Jan. 27, 2021. [Online]. Available: https://unhabitat.org/saudi-cities-report-2019

[35] *USSABC Economic Brief: Saudi Arabian Cement Sector Looks to Rebound, USSaudi Arabian Business Council*, USSABC, U.S.-Saudi Bus. Council, USA, KSA, 2019.

[36] *Saudi: A Belief in Brighter Days, International Cement Review*, CEMNET, U.K., 2020.

[37] MAS. (2012). *MAS: Saudi Tourism Outlook, Tourism Information and Research Centre*. [Online]. Available: http://www.mas.gov.sa/publications

[38] Experience AlUla. (2020). *The World's Masterpiece | Experience Alula*. Accessed: Jan. 23, 2021. [Online]. Available: https://www.experiencealula.com

[39] Oxford Business Group. (2020). *The Report—Saudi Arabia 2020 [Tourism & Entertainment]*. [Online]. Available: https://www.sidf.gov.sa/en/Documents/TheReportSaudiArabia2020-Digitalversion.pdf

[40] USSABC. (2019). *USSABC Economic Brief: Saudi Arabia's Tourism Sector Update, US-Saudi Arabian Business Council*. [Online]. Available: https://ussaudi.org/wp-content/uploads/2020/01/Economic-Brief-Saudi-Arabias-Tourism-Sector-Update.pdf

[41] SPA-Arab News. (2020). *Saudi Aramco Discovers 4 New Oil, Gas Fields, Saudi Press Agency*. [Online]. Available: https://www.arabnews.com/node/1783511/saudi-arabia

[42] *Saudi Arabian Monetary Agency Annual Statistics 2019*, Saudi Arabian Monetary Agency, Saudi Central Bank, KSA, 2019.

[43] R. W. Powers, L. F. Ramirez, C. D. Redmond, and E. L. Elberg Jr., "Geology of the Arabian Peninsula: Sedimentary geology of Saudi Arabia. No. 560-D. US geological survey," 1966.

[44] NIDC. (2021). *Natural Resources in Saudi Arabia*. National Industrial Development Center. Accessed: Jan. 28, 2021. [Online]. Available: https://www.ic.gov.sa/en/invest-in-saudi-arabia/natural-resources/

[45] H. Al Shammari. (2020). *Saudi Arabia Identifies 54 Mineral-Mining Sites*. Accessed: Jan. 23, 2021. [Online]. Available: https://www.arabnews.com/node/1664696/saudi-arabia

[46] MEP. (2010). *National Economy Under the Ninth Development Plan (2010–2014)*. [Online]. Available: https://www.mep.gov.sa/en/AdditionalDocuments/PlansEN/9th/NinthDevelopmentPlan-Chapter4-NationalEconomyUnderTheNinthDevelopmentPlan.pdf

[47] N. A. Darwish and A. Butt. (1996). *Mineral Resource Potential and Its Development in SaudiArabia*. [Online]. Available: https://www.kau.edu.sa/Files/320/Researches/52520_22827.pdf

[48] A. A. El Aal, "Identification and characterization of near surface cavities in Tuwaiq Mountain Limestone, Riyadh, KSA, 'detection and treatment,'" *Egyptian J. Petroleum*, vol. 26, no. 1, pp. 215–223, Mar. 2017, doi: 10.1016/j.ejpe.2016.04.004.

[49] A. E.-A. Ak, "Geomechanical aspects and suitability of the limestone (Sulaiy limestone formation) for foundation bedrock, Sulaiy Region, Saudi Arabia," *J. Geol. Geophys.*, vol. 4, no. 6, p. 2, 2015.

[50] A. S. El-Sorogy, M. Gameil, M. Youssef, and K. M. Al-Kahtany, "Stratigraphy and macrofauna of the lower Jurassic (Toarcian) Marrat Formation, central Saudi Arabia," *J. Afr. Earth Sci.*, vol. 134, pp. 476–492, Oct. 2017, doi: 10.1016/j.jafrearsci.2017.07.001.

[51] *The Cement Industry in Saudi Arabia, Jadwa Investment*, Jadwa Investment, KSA, UAE, 2008.

[52] M. J. Gibbs, P. Soyka, and D. Conneely. (2000). *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories: CO_2 Emissions From Cement Production*. [Online]. Available: https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/3_1_Cement_Production.pdf

[53] E. Elahi, Z. Khalid, M. Z. Tauni, H. Zhang, and X. Lirong, "Extreme weather events risk to crop-production and the adaptation of innovative management strategies to mitigate the risk: A retrospective survey of rural Punjab, Pakistan," *Technovation*, vol. 117, Sep. 2022, Art. no. 102255, doi: 10.1016/j.technovation.2021.102255.

[54] *Cement Technology Roadmap 2009-Carbon Emissions Reductions up to 2050, in, International Energy Agency [IEA]*, Int. Energy Agency (IEA), France, 2009.

[55] K. L. Scrivener, V. M. John, and E. M. Gartner, "Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry," *Cement Concrete Res.*, vol. 114, pp. 2–26, Dec. 2018, doi: 10.1016/j.cemconres.2018.03.015.

[56] K. Scrivener, F. Martirena, S. Bishnoi, and S. Maity, "Calcined clay limestone cements (LC^3)," *Cement Concrete Res.*, vol. 114, pp. 49–56, Dec. 2018, doi: 10.1016/j.cemconres.2017.08.017.

[57] P. C. R. A. Abrão, R. T. Cecel, F. A. Cardoso, and V. M. John, "Comparing the ecoefficiency of cements containing calcined clay and limestone filler," in *Calcined Clays for Sustainable Concrete* (RILEM Bookseries), vol. 25, S. Bishnoi, Ed. Singapore: Springer, 2020, doi: 10.1007/978-981-15-2806-4_28.

[58] S. E. Schulze and J. Rickert, "Suitability of natural calcined clays as supplementary cementitious material," *Cement Concrete Composites*, vol. 95, pp. 92–97, Jan. 2019, doi: 10.1016/j.cemconcomp.2018.07.006.

[59] A. Tironi, A. N. Scian, and E. F. Irassar, "Blended cements with limestone filler and kaolinitic calcined clay: Filler and pozzolanic effects," *J. Mater. Civil Eng.*, vol. 29, no. 9, Sep. 2017, doi: 10.1061/(ASCE)MT.1943-5533.0001965.

[60] P. Hou, T. R. Muzenda, Q. Li, H. Chen, S. Kawashima, T. Sui, H. Yong, N. Xie, and X. Cheng, "Mechanisms dominating thixotropy in limestone calcined clay cement (LC3)," *Cement Concrete Res.*, vol. 140, Feb. 2021, Art. no. 106316, doi: 10.1016/j.cemconres.2020.106316.

[61] Q. D. Nguyen, T. Kim, and A. Castel, "Mitigation of alkali-silica reaction by limestone calcined clay cement (LC3)," *Cement Concrete Res.*, vol. 137, Nov. 2020, Art. no. 106176, doi: 10.1016/j.cemconres.2020.106176.

[62] J. M. Marangu, "Physico-chemical properties of Kenyan made calcined clay—Limestone cement (LC3)," *Case Stud. Construction Mater.*, vol. 12, Jun. 2020, Art. no. e00333, doi: 10.1016/j.cscm.2020.e00333.

[63] H. Zhu, K. Yu, and V. C. Li, "Sprayable engineered cementitious composites (ECC) using calcined clay limestone cement (LC3) and PP fiber," *Cement Concrete Compos.*, vol. 115, Jan. 2021, Art. no. 103868, doi: 10.1016/j.cemconcomp.2020.103868.

[64] T. R. Muzenda, P. Hou, S. Kawashima, T. Sui, and X. Cheng, "The role of limestone and calcined clay on the rheological properties of LC3," *Cement Concrete Compos.*, vol. 107, Mar. 2020, Art. no. 103516, doi: 10.1016/j.cemconcomp.2020.103516.

[65] V. M. John, B. L. Damineli, M. Quattrone, and R. G. Pileggi, "Fillers in cementitious materials—Experience, recent advances and future potential," *Cement Concrete Res.*, vol. 114, pp. 65–78, Dec. 2018, doi: 10.1016/j.cemconres.2017.09.013.

[66] T. Zhang, Q. Yu, J. Wei, P. Zhang, and P. Chen, "A gap-graded particle size distribution for blended cements: Analytical approach and experimental validation," *Powder Technol.*, vol. 214, no. 2, pp. 259–268, Dec. 2011, doi: 10.1016/j.powtec.2011.08.018.

[67] GCCA. (2019). *GCCA Sustainability Guidelines for the Monitoring and Reporting of CO_2 Emissions From Cement Manufacturing*. Accessed: Jul. 1, 2020. [Online]. Available: https://docs.wbcsd.org/2016/12/GNR.pdf

[68] B. Hansen, "The elephant butte dam: Keeping the peace," *Civil Eng. Mag.*, vol. 79, no. 10, pp. 38–39, Oct. 2009.

[69] J. L. Provis, "Alkali-activated materials," *Cement Concrete Res.*, vol. 114, pp. 40–48, Dec. 2018, doi: 10.1016/j.cemconres.2017.02.009.

[70] B. A. Salami, M. A. Megat Johari, Z. A. Ahmad, and M. Maslehuddin, "Impact of added water and superplasticizer on early compressive strength of selected mixtures of palm oil fuel ash-based engineered geopolymer composites," *Construct. Building Mater.*, vol. 109, pp. 198–206, Apr. 2016, doi: 10.1016/j.conbuildmat.2016.01.033.

[71] B. A. Salami, M. A. Megat Johari, Z. A. Ahmad, M. Maslehuddin, and A. A. Adewumi, "Impact of Al(OH)3 addition to POFA on the compressive strength of POFA alkali-activated mortar," *Construct. Building Mater.*, vol. 190, pp. 65–82, Nov. 2018, doi: 10.1016/j.conbuildmat.2018.09.076.

[72] E. Gartner and T. Sui, "Alternative cement clinkers," *Cement Concrete Res.*, vol. 114, pp. 27–39, Dec. 2018, doi: 10.1016/j.cemconres.2017.02.002.

[73] G. Habert and C. Ouellet-Plamondon, "Recent update on the environmental impact of geopolymers," *RILEM Tech. Lett.*, vol. 1, pp. 17–23, Apr. 2016, doi: 10.21809/rilemtechlett.v1.6.

[74] S. A. Miller, V. M. John, S. A. Pacca, and A. Horvath, "Carbon dioxide reduction potential in the global cement industry by 2050," *Cement Concrete Res.*, vol. 114, pp. 115–124, Dec. 2018, doi: 10.1016/j.cemconres.2017.08.026.

[75] P. Stemmermann, U. Schweike, K. Garbev, G. Beuchle, and H. Müller, "Celitement—A sustainable prospect for the cement industry," *Cement Int.*, vol. 8, no. 5, pp. 52–66, 2010.

[76] T. Link, F. Bellmann, H. M. Ludwig, and M. Ben Haha, "Reactivity and phase composition of Ca_2SiO_4 binders made by annealing of alpha-dicalcium silicate hydrate," *Cement Concrete Res.*, vol. 67, pp. 131–137, Jan. 2015, doi: 10.1016/j.cemconres.2014.08.009.

[77] A. Scott, C. Oze, and M. W. Hughes, "Magnesium-based cements for Martian construction," *J. Aerosp. Eng.*, vol. 33, no. 4, Jul. 2020, Art. no. 04020019, doi: 10.1061/(ASCE)AS.1943-5525.0001132.

[78] J. Morrison, G. Jauffret, J. L. Galvez-Martos, and F. P. Glasser, "Magnesium-based cements for CO_2 capture and utilisation," *Cement Concrete Res.*, vol. 85, pp. 183–191, Jul. 2016, doi: 10.1016/j.cemconres.2015.12.016.

[79] E. Gartner, M. Gimenez, V. Meyer, A. Pisch, and L. P. Technologique, "A novel atmospheric pressure approach to the mineral capture of CO_2 from industrial point sources," in *Proc. 13th Annu. Conf. Carbon Capture, Utilization Storage*, Pittsburgh, PA, USA, 2014, pp. 1–11.

[80] J. Pedraza, A. Zimmermann, J. Tobon, R. Schomäcker, and N. Rojas, "On the road to net zero-emission cement: Integrated assessment of mineral carbonation of cement kiln dust," *Chem. Eng. J.*, vol. 408, Mar. 2021, Art. no. 127346, doi: 10.1016/j.cej.2020.127346.

[81] W. Y. Cheah, T. C. Ling, J. C. Juan, D.-J. Lee, J.-S. Chang, and P. L. Show, "Biorefineries of carbon dioxide: From carbon capture and storage (CCS) to bioenergies production," *Bioresource Technol.*, vol. 215, pp. 346–356, Sep. 2016, doi: 10.1016/j.biortech.2016.04.019.

[82] B. Metz, O. Davidson, H. C. De Coninck, M. Loos, and L. Meyer, *IPCC Special Report on Carbon Dioxide Capture and Storage*. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[83] C. Tam. (2009). *Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050*. Accessed: Jun. 21, 2021. [Online]. Available: www.wbcsd.org

[84] M. Fischedick. (2014). *Industry In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical Report*. Accessed: Jun. 20, 2021. [Online]. Available: http://www.ipcc.ch/report/ar5/wg3/

[85] M. A. Habib, H. M. Badr, S. F. Ahmed, R. Ben-Mansour, K. Mezghani, S. Imashuku, G. J. la O', Y. Shao-Horn, N. D. Mancini, A. Mitsos, P. Kirchen, and A. F. Ghoneim, "A review of recent developments in carbon capture utilizing oxy-fuel combustion in conventional and ion transport membrane systems," *Int. J. Energy Res.*, vol. 35, no. 9, pp. 741–764, Jul. 2011, doi: 10.1002/er.1798.

[86] N. N. A. H. Meis, J. H. Bitter, and K. P. de Jong, "Support and size effects of activated hydrotalcites for precombustion CO_2 capture," *Ind. Eng. Chem. Res.*, vol. 49, no. 3, pp. 1229–1235, Feb. 2010, doi: 10.1021/ie901114d.

[87] M. Rydén and A. Lyngfelt, "Using steam reforming to produce hydrogen with carbon dioxide capture by chemical-looping combustion," *Int. J. Hydrogen Energy*, vol. 31, no. 10, pp. 1271–1283, Aug. 2006, doi: 10.1016/j.ijhydene.2005.12.003.

[88] M. Naranjo, D. T. Brownlow, and A. Garza, "CO_2 capture and sequestration in the cement industry," *Energy Proc.*, vol. 4, pp. 2716–2723, Jan. 2011, doi: 10.1016/j.egypro.2011.02.173.

[89] H. J. Herzog and E. M. Drake, "Carbon dioxide recovery and disposal from large energy systems," *Annu. Rev. Energy Environ.*, vol. 21, no. 1, pp. 145–166, Nov. 1996, doi: 10.1146/annurev.energy.21.1.145.

[90] Global CCS Institute. (2020). *Global Status of CCS 2020*. [Online]. Available: https://www.globalccsinstitute.com/wp-content/uploads/2020/12/Global-Status-of-CCS-Report-2020_FINAL_December11.pdf

[91] Government. (2020). *Policy Paper: Budget*. [Online]. Available: https://www.gov.uk/government/publications/budget-2020-documents/budget-2020

[92] W. Matar and A. M. Elshurafa, "Striking a balance between profit and carbon dioxide emissions in the Saudi cement industry," *Int. J. Greenhouse Gas Control*, vol. 61, pp. 111–123, Jun. 2017, doi: 10.1016/j.ijggc.2017.03.031.

[93] BP. (2020). *Statistical Review of World Energy Globally Consistent Data on World Energy Markets and Authoritative Publications in the Field of Energy the Statistical Review World of World Energy and Data on World Energy Markets From is the Review has Been Providing*. [Online]. Available: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

[94] *International Offering Circular*, Saudi Aramco, Dhahran, Saudi Arabia, 2000.

[95] Saudi Aramco. (2020). *Resilience and Agility Saudi Aramco Annual Report 2020*. [Online]. Available: https://www.aramco.com/-/media/publications/corporate-reports/saudi-aramco-ara-2020-english.pdf

[96] W. Matar, F. Murphy, A. Pierru, B. Rioux, and D. Wogan, "Efficient industrial energy use: The first step in transitioning Saudi Arabia's energy mix," *Energy Policy*, vol. 105, pp. 80–92, Jun. 2017, doi: 10.1016/j.enpol.2017.02.029.

[97] D. Leeson, N. Mac Dowell, N. Shah, C. Petit, and P. S. Fennell, "A techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources," *Int. J. Greenhouse Gas Control*, vol. 61, pp. 71–84, Jun. 2017, doi: 10.1016/j.ijggc.2017.03.020.

[98] E. Akbostanci, G. I. Tunç, and S. Türüt-Asik, "CO_2 emissions of Turkish manufacturing industry: A decomposition analysis," *Appl. Energy*, vol. 88, no. 6, pp. 2273–2278, Jun. 2011, doi: 10.1016/j.apenergy.2010.12.076.

[99] GCCSI. (2009). *Strategic Analysis of the Global Status of Carbon Capture and Storage, Report 1: Status of Carbon Capture and Storage Projects Globally—-Global CCS Institute*. Accessed: Jun. 22, 2021. [Online]. Available: https://www.globalccsinstitute.com/resources/publications-reports-research/strategic-analysis-of-the-global-status-of-carbon-capture-and-storage-report-1-status-of-carbon-capture-and-storage-projects-globally/

[100] M. Bui, C. S. Adjiman, and A. Bardow, "Carbon capture and storage (CCS): The way forward," *Energy Environ. Sci.*, vol. 11, no. 5, pp. 1062–1176, May 2018, doi: 10.1039/c7ee02342a.

[101] B. L. Salvi and S. Jindal, "Recent developments and challenges ahead in carbon capture and sequestration technologies," *Social Netw. Appl. Sci.*, vol. 1, no. 8, pp. 1–20, Aug. 2019, doi: 10.1007/s42452-019-0909-2.

[102] L. van Doorn, A. Arnold, and E. Rapoport, "In the age of cities: The impact of urbanisation on house prices and affordability," in *Hot Property: The Housing Market in Major Cities*, R. Nijskens, M. Lohuis, P. Hilbers, and W. Heeringa, Eds. Cham, Switzerland: Springer, 2019, doi: 10.1007/978-3-030-11674-3_1.

[103] N. Ferronato and V. Torretta, "Waste mismanagement in developing countries: A review of global issues," *Int. J. Environ. Res. Public Health*, vol. 16, no. 6, p. 1060, Mar. 2019, doi: 10.3390/IJERPH16061060.

[104] K. Lai, L. Li, S. Mutti, R. Staring, M. Taylor, J. Umali, and S. Pagsuyoin, "Evaluation of waste reduction and diversion as alternatives to landfill disposal," in *Proc. Syst. Inf. Eng. Design Symp. (SIEDS)*, Apr. 2014, pp. 183–187, doi: 10.1109/SIEDS.2014.6829877.

[105] IDB. (2013). *Mitigation Strategies and Accounting Methods for Greenhouse Gas Emissions From Transportation*. Inter-American Development Bank Regional Environmentally Sustainable Transport. Accessed: Jan. 10, 2022. [Online]. Available: https://publications.iadb.org/publications/english/document/Mitigation-Strategies-and-Accounting-Methods-for-Greenhouse-Gas-Emissions-from-Transportation.pdf

[106] J. L. Price and J. B. Joseph. (2000). *Demand Management—A Basis for Waste Policy: A Critical Review of the Applicability of the Waste Hierarchy in Terms of Achieving Sustainable Waste Management*. Sustainable Development. Accessed: Jan. 9, 2022. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/%28SICI%291099-1719%28200005%298%3A2%3C96%3A%3AAID-SD133%3E3.0.CO%3B2-J

[107] P. Söderholm and J. E. Tilton, "Material efficiency: An economic perspective," *Resour., Conservation Recycling*, vol. 61, pp. 75–82, Apr. 2012, doi: 10.1016/J.RESCONREC.2012.01.003.

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