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SPECIALITY: System Analysis for Green Hydrogen Production

MASTER THESIS

Topic:

Defining current and future process routes of the global cement sector and showing pathways for the cement industry of Senegal

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ABSTRACT

The cement industry is a substantial source of global carbon dioxide emissions, and its challenges are growing due to rising demand for cement driven by population growth and infrastructure development. Cement production is responsible for about 7% to 8% of the world's carbon dioxide emissions, with over 60% of these emissions stemming from the decomposition of raw materials and the rest from fossil fuel usage. These emissions have detrimental effects on the climate, particularly by contributing to global warming. Consequently, the search for cleaner methods of cement production becomes increasingly paramount. This study offers a thorough evaluation of current cement production processes and presents strategies to mitigate carbon dioxide emissions. It also envisions future pathways for sustainable cement production with a primary goal of utilizing near term available technologies to achieve a substantial reduction in carbon emissions. Additionally, an analysis involving the cement industries of Senegal, China, and Germany was conducted. To achieve these goals, a model was developed to assess parameters such as energy and raw material requirements during cement production, as well as associated carbon dioxide emissions and techno-economic factors. The outcome of this study revealed that carbon dioxide emissions in current cement production processes in selected countries vary between 524 kg of CO_2 and 612.2 kg of CO_2, with production costs ranging from 53.7 to 64.8 Euros per ton of cement. In contrast, the novel cement production pathways proposed in this study emit between 0 and 33.6 kg of CO_2 in the selected countries, with production costs ranging from 62 Euros to 106 Euros per ton of cement. Therefore, this study benefits in reducing environmental impacts, improving energy efficiency, and meeting international climate commitments.

Key words: Cement, carbon dioxide emissions, alternative fuels, alternative materials, carbon capture, hydrogen, process electrification, Senegal

RESUME

L'industrie du ciment est une source importante d'émissions mondiales de dioxyde de carbone, et les défis liés la production du ciment s'accroissent en raison de la demande croissante de ciment entraînée par la croissance démographique et le développement des infrastructures. En effet, la production de ciment est responsable d'environ 7 à 8 % des émissions mondiales de dioxyde de carbone, dont plus de 60 % proviennent de la décomposition des matières premières et le reste de l'utilisation de combustibles fossiles. Ces émissions ont des effets néfastes sur le climat, notamment en contribuant au réchauffement climatique. Par conséquent, la recherche de méthodes de production de ciment plus propres devient de plus en plus primordiale. Cette étude propose une évaluation approfondie des processus actuels de production de ciment et présente des stratégies pour atténuer les émissions de dioxyde de carbone. Il envisage également les futures voies de production de ciment durable avec pour objectif principal d'utiliser les technologies disponibles pour parvenir à une réduction substantielle des émissions de carbone. En outre, une analyse impliquant les industries cimentières du Sénégal, de la Chine et de l'Allemagne a été menée. Pour atteindre ces objectifs, un modèle a été conçu pour évaluer des paramètres tels que les demandes en énergie et en matières premières lors de la production de ciment, ainsi que les émissions de dioxyde de carbone qui y sont associées et autres paramètres technico-économiques. Le résultat de cette étude a montré que les émissions de dioxyde de carbone dans les processus actuels de production de ciment varient entre 524 kg de CO_2 à 612,2 kg de CO_2 dont les prix de production varient entre 53,7 et 64,8 Euro par ton de ton ciment pour les industries cimentières dans diffèrent pays sélectionnés. En revanche, les nouvelles voies de production du ciment proposées dans cette étude émettent entre 0 et 33,6 kg de CO_2 par ton de ciment dans ces pays pour un prix de production variant de 62 Euro à 106,9 Euro par ton de ciment. Par conséquent, cette étude contribue à réduire les impacts environnementaux, à améliorer l'efficacité énergétique et à respecter les engagements internationaux en matière climatique.

Mots clés : Ciment, émission de dioxyde de carbone, combustibles alternatifs, matériaux alternatifs, captage du carbone, hydrogène, électrification des procédés, Sénégal

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List of Abbreviations

IEA: International Energy Agency

IPCC: Intergovernmental Panel on Climate Change

CO_2: Carbon Dioxide

SMCs: Supplementary Cementitious Materials

EN 197: European standard for cement specification

ASTM: American Society for Testing and Materials

MEA: Monoethanolamine

EU: European Union

ECRA: European Cement Research Academia

GIZ: Deutsche Gesellschaff fur Internationale Zusammenarbeit

MUSD: Million United State Dollars

M_{cement}: Mass of cement

$M_{clinker}$**:** Mass of clinker

M_{gypsum}: Mass of gypsum

C/Cr: Clinker-to-cement ratio

kWh: kilowatt-hour

kWh/t: kilowatt-hour per ton

GJ : Gigajoule

GJ/t : Gigajoule per ton

$E_{GJ/t\ cement}$: Total energy consumption per ton of cement

$E_{th\ (GJ/t\ clinker)}$: thermal energy consumption per ton of clinker

$E_{el\ (GJ/t\ cement)}$: electrical energy consumption per ton of cement

EF: emission factor

$\mathbf{P_{emission}}$**:** Process emission

$\mathbf{F_{emission}}$**:** Fuel emission

$\mathbf{E_{emission}}$**:** Electricity

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Dedicated to my FAMILY!

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Chapter 1: Introduction

The global population is on the path of growth, with projections from the United Nations indicating an estimated increase to 9.7 billion people by 2050 [1]. This upward trend will necessitate expanded infrastructure development, including buildings and roads, wherein cement and concrete will play fundamental roles. Cement, as a binding agent, exhibits the ability to solidify upon contact with water. It holds immense significance in producing concrete for diverse applications such as residential structures, roadways, and dams. Notably, cement ranks as the second most consumed substance worldwide, trailing only behind potable water [2]. However, the production of cement is intrinsically linked to substantial carbon dioxide emissions. Approximately 8% of the global carbon dioxide (CO_2) emissions stem from cement production, primarily arising from the processes of material calcination and fuel combustion [3].

1.1 Cement demand

Over the years, the global cement production has witnessed remarkable growth, soaring from 1453 million tons (Mt) in 1995 [4] to approximately 4100 million tons in 2020 [5]. Notably, a significant portion of this production is concentrated in countries like China, which contributes to 54% of the worldwide output, followed by India at 8% [3]. As of 2021, the cumulative global cement production stands at roughly 4.4 billion metric tons [86]. This volume is projected to experience further escalation due to the increasing global population, urbanization, and infrastructural advancements, particularly in developing nations across Africa and Asia. According to the International Energy Agency (IEA) [6], the global cement production is anticipated to expand by 12% to 23% by the year 2050, relative to the levels in 2014, and highlighted that India and Africa, are set to increase their domestic cement production capacity to fulfill their infrastructure development needs. Moreover, International Finance cooperation [7] stated that cement demand growth in Senegal has also increased by about 8% within the period 2010 to 2015. The cement production per year is presented in Figure 1-1.

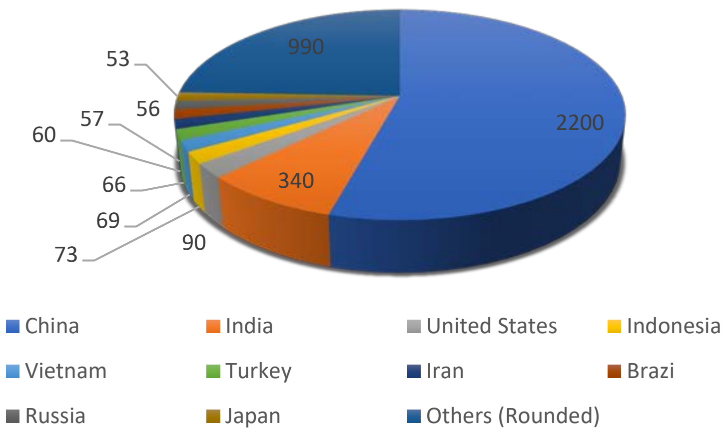


Figure 1-1: Global cement production in 2020 including the high-producing countries [8]

1.2 Problem statement and Research questions

1.2.1 Contribution of the cement industry to the anthropogenic carbon dioxide emission

Cement production accounts for approximately 7% to 8% of the global CO_2 emissions and roughly 27% of the direct industrial emissions worldwide (refer to Figure 1-2) [10]. These emissions contribute to the overall concentration of these gases in the atmosphere. These elevated levels of greenhouse gases enhance the natural greenhouse effect, leading to global warming and subsequent climate change [87]. It is important to mention that cement production stands as an energy-intensive and emissions-intensive sector [2]. To produce one ton of cement, an average of 3.5 gigajoules (GJ) of energy and approximately 90 to 150 kilowatt-hours (kWh) are typically consumed [9]. This energy demand primarily relies on fossil fuels such as coal, natural gas, and oil [10], thereby contributing to the emission of greenhouse gases like carbon dioxide. Furthermore, over half of the carbon dioxide emissions are originated from the calcination process of limestone, the principal raw material in cement production [3].

Despite the enormous efforts that have been made to abate CO_2 emissions from cement about 2.7 billion_of CO_2 were emitted in 2017 [12]. To achieve the climate goals of 1.5 ºC and 2 ºC set by the Paris agreement [5], emissions from the cement industry need to be reduced by 16% by 2030 and by 24% by 2050 [3].

Therefore, it is imperative to implement more effective practices for cement production. All countries around the globe, including developing countries, need to make substantial efforts to reduce considerably greenhouse gas emissions from all the emitting sectors including the cement sector.

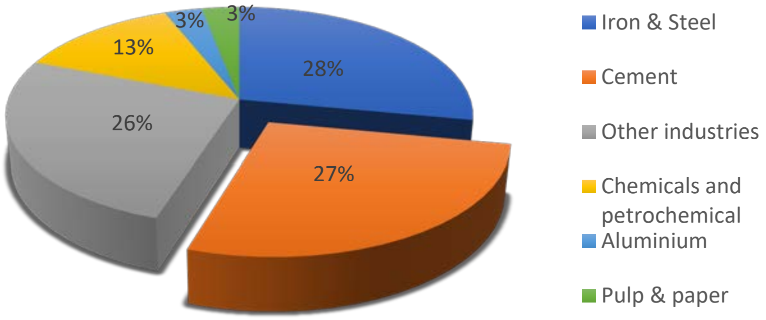


Figure 1-2: Share of the global cement emission from the total direct industrial CO_2 emission in 2014 [10]

1.2.2 Research questions

- What are the current cement production processes globally and especially in Germany, China, and Senegal?
- What could be the future process routes for the efficient, sustainable, and environmentally friendly making of cement in the selected countries?
- How can the adoption of carbon dioxide abatement strategies and best available technologies can help improve sustainability in cement production in Senegal.

1.3 Objectives and contributions of this work

The cement industry falls within the group of seven challenging-to-address sectors (including aluminum, aviation, cement and concrete, chemicals, chipping, steel, trucking) that collectively contribute to approximately 30% of the global CO_2 emissions [25]. According to a report by the European Cement Research Academia (ECRA) [25], if these sectors continue with business-as-usual practices, they are projected to compromise the target of limiting global temperature rise to 1.5 degrees Celsius by 2030. In this work three countries were selected, Germany, China and Senegal.

The main objective of this thesis was to assess the current process routes of cement manufacturing process in order to identify their environmental impacts in terms of carbon dioxide emission on the global scale. The specific objectives were to design a model which take into account the current pathways and explores future representative cement production pathways, evaluating the material demand, the energy demands and carbon dioxide emissions in cement sectors of Germany, China and Senegal. This examination aims to present a perspective on future carbon dioxide reducing alternatives in line with the goals stipulated in the Paris climate agreement. Also, it shows guidance of the global cement sector towards more efficient, sustainable, and reduced environmental impacts.

The methods developed in this work help cement producers to quickly assess the energy requirement for their cement and to easily calculate the associated CO_2 emissions.

The expected outcome of this study is a well-defined set of process routes including key parameters such as energy demand, material consumption, carbon dioxide emissions, and pertinent economic factors. This comprehensive outline will serve as a strategic blueprint, facilitating modelers, policymakers, industry pioneers, and stakeholders to collaboratively design a future where the cement industry plays a role in achieving the Paris agreement.

1.4 Boundaries of the research topic

The research englobes the estimation of CO_2 emissions and the assessment of costs associated with future process routes for sustainable cement production. The scope of this study includes the following key points:

- A primary focus on the cement production process.
- Evaluation of material, energy requirements, and CO_2 emissions.
- Literature review on the existing global strategies for carbon dioxide emission reduction in cement sector.
- Examination of both current and potential future process routes for cement production, alongside their associated costs

It is important to note that this work did not factor the economic status of countries into the design of the representative process routes. This approach was taken considering many governments prioritizing climate change mitigation by reducing greenhouse gas emissions, irrespective of their economic circumstances. Furthermore, it is worth noting that this study did not involve simulation or laboratory experimentation. Consequently, the compatibility of alternative fuels or materials with the selected countries' kilns was not considered. However, the study did incorporate the costs associated with modifying cement plants, monitoring processes, and implementing control measures. Moreover, certain aspects were not addressed in this thesis, such as the social implications and market acceptance of these changes in the cement production process.

Chapter 2：Literature review

In this section, the theory of the cement production process is briefly described and different strategies that are currently proposed to reduce the cement sector CO_2 emission are assessed.

2.1 Cement production process

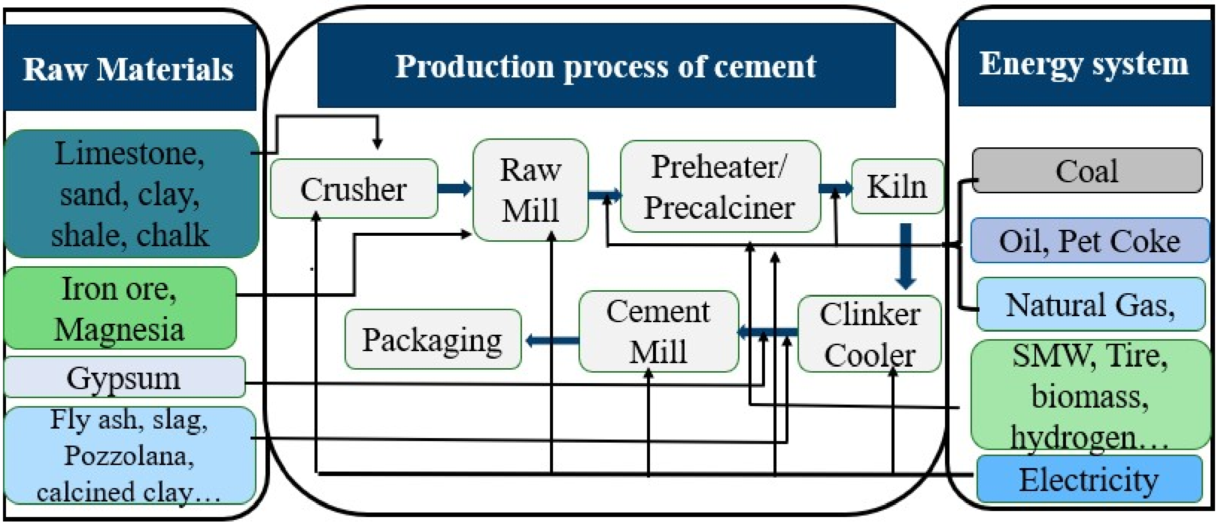
2.1.1 Process flow

A simplified process flow diagram of the cement production is shown in Figure 3. The basic steps of cement manufacturing are briefly described and discussed. The figure also includes the materials and energy demand.

The process of cement production initiates in quarries, where essential raw materials like limestone, marl, or chalk are extracted as sources of calcium carbonate ($CaCO_3$) [13]. Typically, the exaction is carried out through blasting, employing explosives at a rate of around 200 grams per ton of limestone [14]. Additional materials like sand, clay, iron ore, and gypsum can be incorporated to introduce silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), ferrous oxide (Fe_2O_3), and calcium sulfate dihydrate ($CaSO_4.2H_2O$) respectively. These materials are added to modify the chemical composition of the raw mixture, ultimately producing the desired cement type [4], [11]. The extracted raw materials are transported by tracks to the cement plant, usually located near the mining zone [14]. The raw materials are then crushed to small sizes approximately [11], using crushers such as Jaw crushers or hammer crushers and stored in silos [14]. The grinding process, utilizing machines like vertical roller mills or ball mills, further reduces the raw material to a finer powder (dry process) or slurry (wet process), termed as raw meal, raw mix, or kiln feed. The composition typically consists of around 75-80% limestone and 20-25% clay, supplemented by minor proportions of iron ore, sand among others to achieve specified material [13]. The kiln feed is homogenized, involving precise control and monitoring to ensure the production of high-quality cement [13]. This feed is directed to the kiln or subjected to preheating and pre-calcination stages, which initiate the decomposition of limestone. Subsequently, the material passes through a rotating kiln or vertical kiln fueled from the base by fossil fuels such as ground coal, petcock, or natural gas. Alternatively, fuels like tires, RDF, or biomass can be employed to reduce fossil fuel reliance and associated carbon dioxide emissions. The kiln's flame can attain temperatures up to 2000°C, triggering chemical and physical transformations within the meal. Around 550°C, calcium carbonate and magnesium carbonate present in the limestone or chalk commence decomposition into calcium oxide (CaO) and magnesium oxide (MgO) respectively, liberating CO_2 as indicated by equations (1 and 2). Complete decomposition concludes within the kiln at 960°C [11]. At higher temperatures, the interaction of calcium carbonate with silicon oxide, aluminum oxide, and ferrous oxide yields tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium alumino-ferrite (C_4AF). These compounds constitute the primary components of cement known as clinkers. The composition of clinker may vary based on the type of cement, yet a significant proportion of tricalcium and/or dicalcium silicate is crucial for clinker quality and soundness. For instance, typical white cement clinkers consist of tricalcium silicate (C_3S) at 69.89%, dicalcium silicate (C_2S) at 19%, tricalcium aluminate (C_3A) at 8.08%, and tetracalcium alumino-ferrite (C_4AF) at 1% [9]. Due to the instability of these chemical compounds at lower temperatures, clinkers are rapidly cooled to around 100°C using grate or tube coolers placed immediately after the kiln [14]. Subsequently, the cooled clinkers are either sold or combined with approximately 5% gypsum to produce the final cement product [15]. The cement produced is then packaged and distributed. alternative materials like fly ash, ground granulated blast furnace slag, limestone fillers, silica fume, or pozzolans can replace a portion of the clinker content in the cement mixture. This results in a product referred to as blend cement [4], a practice that contributes to the reduction of associated carbon dioxide emissions from cement production.

Reactions involved in cement production are presented below [11].

- $CaCO_3 \longrightarrow CaO + CO_2$ (heat at 550 ºC) (1)
- $MgCO_3 \longrightarrow MgO + CO_2$ (heat at 550 ºC) (2)
- $2CaO + SiO_2 \longrightarrow Ca_3SiO_4 = C_2S$ (Dicalcium Silicate) (3)
- $3CaO + SiO_2 \longrightarrow Ca_3SiO_5 = C_3S$ (Tricalcium Silicate) (4)
- $3CaO + Al_2O_3 \longrightarrow Ca_3Al_2O_6 = C_3A$ (Tricalcium Aluminate) (5)
- $4CaO + Al_2O_3 + Fe_2O_3 \longrightarrow 2Ca_4AlFeO_5 = C_4AF$ (Tetra-calcium Alumino- Ferrite) (6)



a: SMW: Solid Municipal Waste

Figure 2-1: Simplified diagram of the cement production process including material and energy input (own depiction based on cement production process described in the above section).

It is important to note that Figure 2-1 only provides a brief description of the cement production process. However, a standard cement plant is outfitted with various components, including hoppers and conveyors for charging and transporting raw meals. Additionally, provisions like dust collectors, flue gas desulfurization units, and synthetic catalytic reactors are incorporated to mitigate emissions of dust, sulfur oxides, and nitrous oxide respectively. Storage silos and cooling systems are also integral, ensuring the seamless and uninterrupted operation of the cement plant.

2.1.2 Raw Material Demand

As previously mentioned, limestone constitutes the primary raw material for cement production, accounting for approximately 70% to 80% of the total raw material weight [13]. The remaining composition is comprised of components like sand, clay, iron ore, and others. Roughly 1.7 tons of raw materials [16] are utilized to generate 1 ton of clinker. The proportion of clinker content varies depending on the required cement type, ranging from 20% to around 100% according to European cement norms. The remainder of the mixture is supplemented with materials such as gypsum and other additives, including natural pozzolans like volcanic materials or artificial options such as calcined clay. Industrial waste materials such as fly ash from coal plants, ground granulated blast furnace slag from the iron and steel industry, and silica fume from semiconductor production can also be incorporated to complete the composition. Reported raw materials are presented in Table 2-1 and Table 2-2.

Table 2-1: Amount of raw material input per ton of clinker [16], [17], [18], [19], [20]

Authors	Materials	Quantity (t/t of clinker)	References
Verma [16]	raw material	1.7	[16]
Worrell [17]	raw material	1.7	[17]
Berdowski [18]	raw material	1.57	[18]
Rahman *et al.* [19]	raw material	1.7	[19]
Wie *et al.* [20]	raw material	1.55	[20]
Average (Chosen Value)	raw material	1.644	

Table 2-2: Share of raw material mainly used during clinker production [14], [21], [22], [23]

Raw materials	Huntzinger[21]a	Chatterjee[14]	Al-Dhamri[22]	IEAGHG[23]a	Averagea
Limestones	88.125	84.54	86.03	80.66	84.83875
Clay/Shale	8.6875	3.42	3.74	18.39	8.559375
Iron ore	0.9375	5	2.93	0.48	4.23625
Sand	2.125	7.04	7.3	0.48	2.336875

a: calculated.

2.1.3 Process and Kiln types

There are different processes used to manufacture cement, these include:

Dry process: This method involves employing a dry rotary kiln with a configuration that includes preheaters and precalciner stages (1 – 6 stages). It stands as the most widely utilized kiln globally. The material's moisture content typically ranges between 0% to 0.7% [14]. In terms of thermal energy consumption, this process ranks as the most efficient, utilizing around 3 – 4 GJ per ton of clinker [15], see Figure 2-2.

Wet process: Among the oldest approaches to cement production, the wet process utilizes a vertical shaft kiln, often referred to as a wet kiln, which is also one of the earliest kiln types. This method entails higher thermal energy consumption due to a notably elevated water content, ranging from about 30% to 40% according to Benhelal *et al.* [11] or between 24% to 48% according to Worrell *et al.* [4]. It stands as the most energy-intensive technique, necessitating approximately 6.1 GJ per ton of clinker, refer to Figure 2-4.

Semi-dry / Semi-wet processes: These processes involve the addition of water to dry materials to achieve moisture levels of about 11% to 14%, or the dewatering of wet materials to achieve water contents of approximately 17% to 22% according to Worrell *et al.* [4]. Kilns used in this approach are referred to as long dry or semi-dry kilns. These processes consume thermal energy in the range of 4 to 4.5 GJ per ton of clinker, refer to Figure 2-4.

Figure 2-2 displaces different processes used around the world.

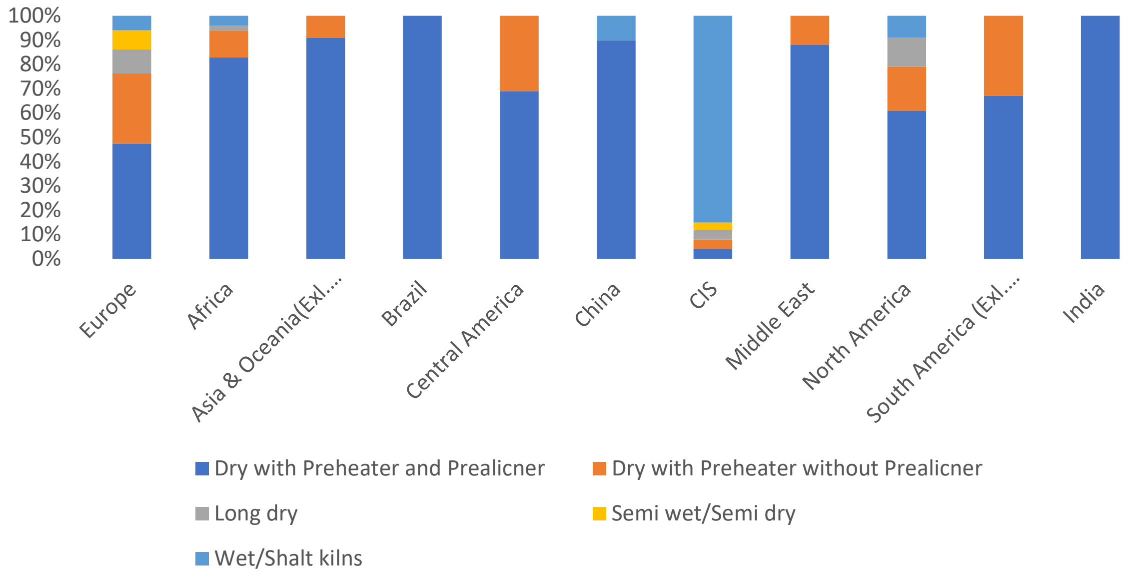


Figure 2-2: Cement kiln types and global share [38]

2.1.4 Energy demand

The manufacturing of cement requires a high input of thermal and electrical energy. This section will discuss the demands of thermal energy and electricity. About 7% of global energy is used in the cement industry [6].

2.1.4.1 Thermal energy demand

The theoretical minimum thermal energy demand to produce cement clinker was reported be in the range 1.59 - 1.84 GJ/t clinker [24]. However, due to high losses and the cement production process adopted, the thermal energy demand per ton of clinker could be as high as two to three times this theoretical amount (refer Figure 2-3).

Thermal energy demand in cement production exhibits substantial variation depending on the chosen manufacturing process, primarily categorized into two main processes: wet and dry. The dry process generally entails lower thermal energy consumption compared to the wet process as displaced Figure 2-3. The elevated energy usage associated with the wet process is largely attributed to the high moisture content of raw materials. Notably, around 30% of the overall thermal energy is consumed in drying these materials. Both the wet and dry processes experience significant heat losses, accounting for approximately 35% to 39% of the inputs [16]. These losses emanate from exhaust gases, coolers, and radiation heat emitted from the kiln cell, as detailed by Verma *et al.* [16]. In the dry process, the thermal energy consumption typically ranges from about 3 to 4 gigajoules per ton of clinker. On the other hand, the wet process can demand a substantially higher amount, reaching approximately 6 gigajoules per ton of clinker due to the energy requirement for water evaporation [25],[26]. Madlool *et al.* [26] reported values of around 3.2 gigajoules per ton for the dry process and approximately 5.8 gigajoules per ton of clinker for the wet process.

Within cement plants, the predominant utilization of thermal energy revolves around the calcination process (clinkerizaton). In fact, Afkhami *et al.* [27] indicated that nearly 99% of thermal energy within cement plants is allocated to this purpose.

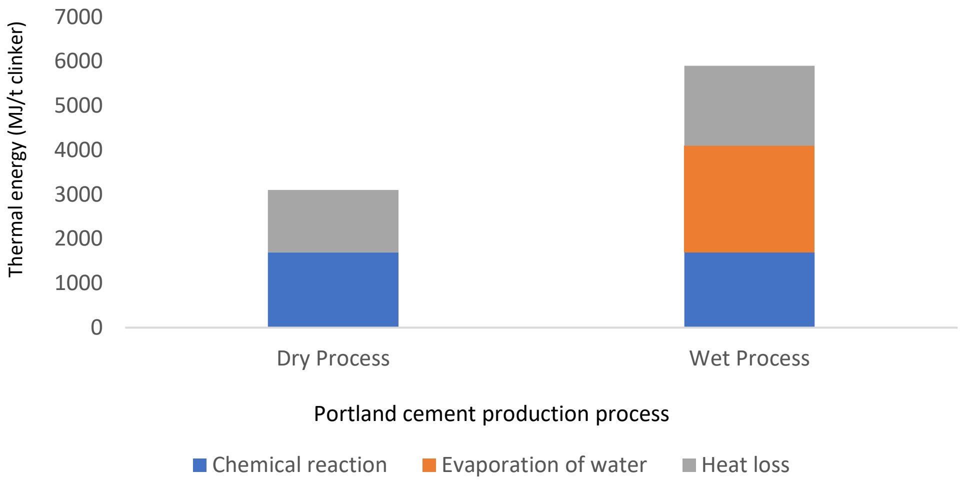


Figure 2-3: Thermal energy consumption distribution for dry and wet processes [26]

2.1.4.2 Electrical energy demand

The amount of electricity required for cement production is between 90 – 150 kWh per ton of cement, reported by Schorcht *et al.*[9] or in the range 85 kWh – 129 kWh /t cement as it was indicated in [45]. Although electricity is needed in small quantities compared to the thermal energy, it is used in all the process steps (See Table 2-3).

It has been reported that the wet process, despite its higher thermal energy consumption, consumes less electricity compared to the dry process. This variance could be attributed to the hardness of the raw materials used in the dry process. Due to their hardness, these materials necessitate more time for complete grinding. Interestingly, a substantial portion of approximately 38% of the total electricity consumed in the cement production process is allocated to the grinding of these raw materials [26]. Therefore, the electricity consumption per ton of cement is significantly influenced by the manufacturing process employed and the specific types of materials utilized. On a global scale, the average electricity consumption fluctuates within the range of 103 kWh to 110 kWh per ton of cement, as documented by Schneider [28]. In most cement plants, this energy is taken from the grid, Consequently, it is pertinent to note that carbon dioxide emissions stemming from electricity use and transportation constitute approximately 10% of the total emissions within the cement industry [29]. Furthermore, it is worth emphasizing that the average specific electricity consumption per ton of cement differs significantly between countries. According to the IEA's report [30], this variance spans from approximately 90 kWh per ton of cement in India to about 140 kWh per ton of cement in the USA, as observed in 2005.

Table 2-3: Electricity demand distribution in the different cement production steps [11], [31], [32].

Schneider[31]**; Benhelal** [11]**; Atmaca**[32]	**About 100 kWh/t of cement**
Mining & Extraction	5%
Crushing	3%
Raw material grinding	26%
Coal grinding	4%
Clinker burning/cooling	24%
Cement grinding	30%
Rest	7%

2.1.5 Carbon dioxide emission from cement production process

The cement industry accounts for approximately 8% of the global carbon dioxide (CO_2) emissions and ranks as the third-largest consumer of industrial energy [3]. Carbon dioxide emissions from cement sector increase with the increase in cement production. In 1990, global emissions from the cement industry amounted to approximately 576 million tons of CO_2, however, by 2014, this figure had tripled, reaching 2.083 billion tons [33]. According to Czigler *et al.* [12], if the current emission rate persists, projections indicate that by 2050, CO_2

emissions could potentially escalate to as high as 2.9 billion tons compared to 2.7 billion tons in 2017.

Carbon dioxide emissions from the cement sector are typically categorized into two distinct types: direct emissions encompassing process emissions and emissions from fuel combustion, and indirect emissions stemming from imported electricity. The process emissions constitute around 60% to 70% of the overall emission total [42]. These emissions primarily arise from the decomposition of raw material components, particularly limestone, containing calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$), into calcium oxide (CaO) and carbon dioxide (CO_2) in the presence of heat, as elaborated in preceding sections. The theoretical specific process emission is estimated at 514 kg CO_2 per ton of clinker using empirical calculations [2]. However, the IPCC Tier 1 method recommends a widely used emission factor of 510 kg CO_2 per ton [2]. Energy-related emissions constitute approximately 30% to 40% of the total emissions, predominantly attributed to the combustion of fossil fuels like coal, oil, and natural gas during the limestone calcination process and about 10% electricity-related emission [24].

It is worth noting that specific carbon dioxide emissions can vary across different sources of literature. Benhelal *et al.* [11] and Tomatis *et al.* [35] reported a specific emission of around 900 kg per ton of cement. This value contrasts with the figures reported by Plaza *et al.*[36] and Schorcht *et al.* [9] who indicated an approximate emission of 950 kg per ton of clinker. Nonetheless, lower emission intensities have also been documented by Farfan *et al.* [37] at about 866 kg per ton of clinker, as well as by Schneider *et al.* [28] at approximately 841 kg per ton of clinker. These discrepancies can be attributed to various factors such as the utilization of different clinker-to-cement ratios, distinct manufacturing processes, levels of heat recovery, fuel types, raw material characteristics, plant capacities, material efficiencies, and equipment effectiveness, among others. These factors can vary from one cement plant to another or from one country to another. IEA [30] reported process and energy emissions for 2003 – 2004, ranging from 650 kg per ton of cement for countries like Spain and Italy to 930 kg per ton of cement in the United State.

2.2 Cement Types and Applications

It is complex to define the type of cement in terms of material composition due to a wide range of globally existing standards. These standards include the American Society for Testing and Materials (ASTM C150), the European specification for cement (EN 197), South

African cement specification (SANS 50197), Chinese national standard for Portland cement (GB/T 175-2007), Indian Standard for Ordinary Portland cement (IS 269), and more. In West Africa, ASTM and EN standards are predominantly utilized.

These standards establish specifications, chemical compositions, and physical requirements for different cement types. By manipulating the composition of raw materials, cement with distinct properties can be produced. For instance, within the EN 197 standard, five main cement types are defined, while over 20 sub-types are derived through the replacement of part of the clinker-to-cement ratio with supplementary cementitious materials (SCMs) like fly ash, ground granulated blast furnace slag (GGBFS), limestone filler, pozzolans, and more.

Nonetheless, cements are globally classified in terms of performance, the commonly used cements are the followings:

- Ordinary Portland Cement (OPC) stands as the most commonly produced cement variant, and it is often categorized into different grades, such as 33, 43, or 53, which correspond to the strength achieved within a 28-day period. It finds suitability in various applications including the construction of buildings, roads, bridges, and more. In terms of standards, this type of cement aligns with CEM I in the EN 197-1 specifications [84] and with Type I in the ASTM C150 standards [85]. OPC is characterized by a substantial clinker-to-cement ratio of approximately 95%.
- Portland Pozzolana Cement (PPC): it is a blended cement resulting from a combination of Portland clinker, and some pozzolanic materials such as fly ash, volcanic ash, silica fume, and gypsum. In EN specifications, this type is designated as CEM II/A-P [84], while in ASTM standards, it corresponds to Type IP [85]. PPC cement finds extensive application in structures like dams, hydraulic systems, and marine constructions.
- Portland Slag Cement (PSC): is formulated through a blend of ground slag, Portland clinker, and gypsum/anhydrite, as outlined by Bijen *et al.* [83]. This type of cement comprises approximately 36% to 95% of blast furnace slag, clinker, and gypsum. Within EN 197 specifications, it is classified as CEM III [84], while ASTM standards refer to it as Type IS.

Numerous other cement types also exist, encompassing Rapid Hardening, Sulfate Resisting Cement, Masonry Cement, and several others.

2.3 Carbon dioxide emission abatement strategies from cement sector

The cement industry is one of the largest emitting, and some strategies have been deployed over the years to reduce CO_2 emissions. Because of the huge share of the process emission make the cement sector is hard to abate sector.

2.3.1 Energy efficiency improvement

While energy-related emissions constitute approximately 40% of the total emissions from cement plants [24], implementing energy-saving best practices can significantly contribute to curbing CO_2 emissions in cement production. As previously highlighted in this thesis, waste heat comprises more than 30% of the energy utilized in cement manufacturing [16]. Various approaches are employed to mitigate these losses, including upgrading outdated grinding and calcination systems with more efficient energy-saving technologies, process optimization, and harnessing waste heat for electricity or hydrogen generation [3]. However, on a global scale, this strategy is projected to have limited potential in terms of reducing carbon dioxide emissions from the cement industry, only a mere 3% of the cumulative global CO_2 emission reduction will result from efficiency improvements Plaza *et al.* [36]. This limitation could arise from the widespread adoption of advanced and efficient dry kiln technologies worldwide [38].

2.3.1.1 Process switching

Process switching is a technique that holds the potential to not only minimize waste heat in cement plants but also significantly reduce the overall energy consumption during the production process. The conventional approach involved employing the wet process with outdated kilns, which necessitated over 6 GJ/t of clinker production [26]. In contrast, modern dry kiln technologies incorporating suspension preheaters and pre-calciners have emerged over time, demanding notably lower energy inputs. According to Benhelal *et al.*[33], dry process consumes about 28% less fuel than a wet process Ali *et al.* [39]**.** The transition from the wet to the dry process has led to an enhancement in energy efficiency, surging up to 50% and a substantial reduction of nearly 20% in carbon dioxide emissions [40].

Kermeli *et al.* [38] documented a widespread adoption of dry kiln technologies across various regions, such as 100% utilization in India, Central and South America (e.g., Brazil), the Middle East, and others. Notably, dry kilns were used in about 76% of cases in Europe, 90% in China, and 90% in Africa and other, all in the year 2013. This significant transition has resulted in a reduction in thermal energy requirements, dropping from 6.07 GJ/t clinker for wet kilns to approximately 3 – 4 GJ/t clinker for dry kilns, consequently leading to a decline in emission intensity per ton of cement. Marmier [24] reported thermal energy requirement of 3.81 and 3.52 GJ/t clinker for 2019, respectively for the EU27 and global average. Figure 2-4 highlights the energy savings by switching from wet to 6 stages cyclones preheaters and precalciner

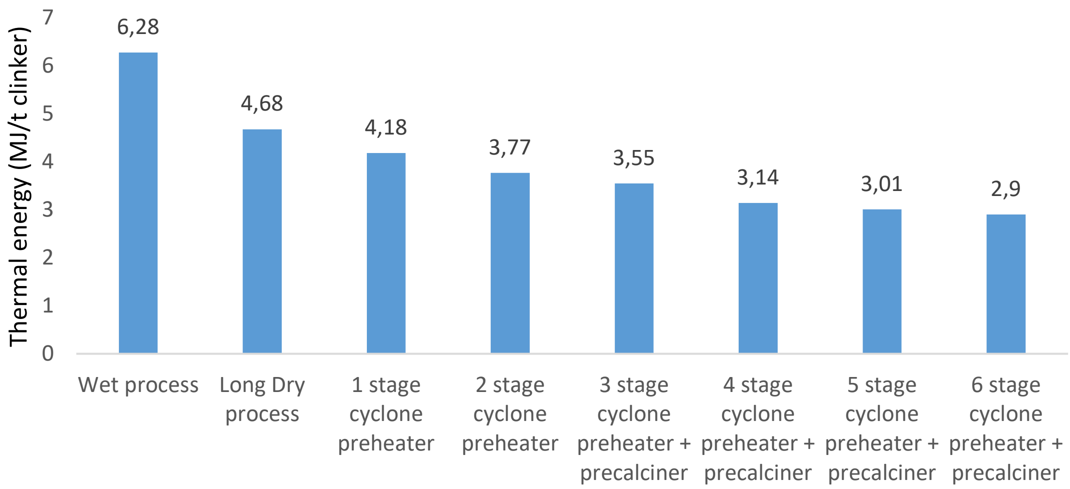


Figure 2-4: Thermal energy demand (GJ/t of clinker) per kiln type [26]

2.3.1.2 Waste Heat Recovery

Waste heat recovery plays a pivotal role in mitigating energy losses throughout the cement production process, even with the utilization of the dry process. This is due to the existence of approximately 30% waste heat. Modern kilns are outfitted with preheater and pre-calciner stages that strategically minimize heat losses by harnessing the hot air derived from both the cooler and the kiln. This hot air is employed to elevate the temperature of the raw meal, along with other materials such as coal, petcock, or cement constituents like granulated blast furnace slag [25].

Other methods, such as electricity generation through Rankine cycles (Organic and Steam) or Kalina cycle, have gained widespread adoption in countries like China and Japan [28]. These methods have the potential to harness around 25-45 kWh/t clinker of electricity [28], [34]. This amount equates to approximately 20 to 30% of the total electricity demand within cement plants, resulting in a reduction of about 15 to 23 kg CO_2/t cement [34]. As a result, waste heat recovery stands as an effective strategy for both energy conservation and emissions reduction. According to [28], the return on investment for a cement plant producing 5000 tons per day utilizing the Rankine cycle for electricity generation is estimated at 3.9 years. This estimation is based on an assumed electricity price of $60/MWh and a waste heat recovery capacity of 9 MW. It is important to note that this approach does not directly impact the thermal energy demand or the direct CO_2 emissions [28], Nonetheless, it contributes to the mitigation of emissions stemming from grid electricity and lowers the cost of electricity procurement.

Another approach to recover this heat loss involves the utilization of the thermochemical copper chloride (CuCl) cycle, which results in on-site hydrogen production [3]. The author emphasized the advantages of this method, which includes the option to employ the generated hydrogen for Power-to-Grid applications or other uses. This approach is considered more advantageous than traditional electrolysis or the conversion of hydrogen into electricity. Furthermore, the byproduct O2 can be sold or employed for oxyfuel Carbon Capture and Storage (CCS). In support of this concept, Nhuchhen *et al.* [43] conducted a study that demonstrated the cost-effectiveness of this approach in comparison to using Air Separation Units (ASU) for oxygen purification.

2.3.2 Alternative fuels

Traditionally, cement kilns have relied on non-renewable energy sources like coal, petroleum coke, and natural gas for cement production. However, due to the associated CO_2 emissions from these energy sources, the focus on using Alternative Fuels (AF) has been steadily increasing in recent years. This strategy for mitigating CO_2 emissions from cement production was initiated around 1980 [60]. A diverse range of alternative fuels is now being employed to reduce the dependence on fossil fuels and lower CO_2 emissions from cement plants, ultimately leading to a reduction in production costs. Among the fuels commonly used as substitutes for fossil fuels in the cement industry are waste materials such as Tire-Derived Fuels (TDF), Refuse-Derived Fuels (RDF) from processed Municipal Solid Waste (MSW), and various forms of biomass including wood and agricultural biomass [31]. Recently some researchers have given attention to hydrogen as a potential fuel for cement kilns. However, this alternative is in the R&D phase and is not yet applicable to the cement sector.

2.3.2.1 Wastes and biomass utilization

Billions of tons of waste are generated annually worldwide. In 2016, the global waste generation exceeded 2 billion tons, and projections indicate that this could increase to 2.6 billion tons by 2030 and further to 3.4 billion tons by 2050 [41]. Unfortunately, a substantial portion of these waste materials ends up in landfills or is subjected to incineration. This waste encompasses a wide range of materials including Municipal Solid Waste (MSW), paper, plastics, sewage sludge, waste solvents, and more, which could be subjected to pre-processing and utilized as inputs in cement kilns and pre-calciners. Research has stipulated the feasibility of employing 100% waste as fuel in the cement calciner, while around 50% is deemed acceptable in the main kiln burner [25]. Modern kilns equipped with preheaters and precalciner configurations offer three zones for the introduction of Alternative Fuels (AF): the precalciner (accounting for 55-65% of the total kiln system energy demand), secondary firing at the kiln inlet (5-10%), and the kiln firing process itself (35-45% of the total). Typically, a calorific value ranging from 11 to 13 GJ/t is required for the calciner and from 18 to 22 GJ/t for the main firing process [42]

However, the utilization of Alternative Fuels (AF) is not without its constraints. Challenges include the availability of suitable waste materials for kiln use and potential deficiencies in waste management policies [42]. Moreover, there remains considerable uncertainty concerning the future cost of these AF, as projected by Benhelal *et al.* [21], indicating potential prices 30% to 70% higher than fossil fuels by 2030 and 2050. Additionally, the diverse physical and chemical properties of these alternative fuels compared to traditional fuels, including their lower calorific value, varying moisture content, and potentially toxic compositions, complicate their utilization. While certain alternative fuels can be directly employed in the precalciner, they often require preprocessing to meet the specifications of the main burning zone in cement kilns. Such treatments may involve processes like shredding, mechanical and biological treatments, and physical and chemical transformations. It is noteworthy that certain types of waste, such as radioactive waste, whole batteries, explosives, among others, are typically restricted from being used as alternative fuels due to safety and environmental concerns [42].

2.3.2.2 Hydrogen utilization

The utilization of hydrogen within the cement sector represents a novel area of exploration aimed at further curtailing the CO_2 emissions associated with the combustion of fossil fuels during cement production. This technology holds immense potential for substituting traditional fuels with hydrogen, particularly within a framework focused on decarbonization [43]. However, it is crucial to acknowledge that the existing infrastructure and technology are presently tailored for coal, petcock, and natural gas utilization. Introducing hydrogen as a fuel would necessitate extensive modifications or substantial investments in new cement kiln setups. Moreover, researchers have highlighted that the utilization of a hydrogen-biomass fuel blend in cement production is currently in its nascent stages of investigation (Technology Readiness Level 2) [44].

Nevertheless, Rami *et al.* delved into the interconnection between cement and hydrogen production, using H_2 to partially fulfill the thermal energy requirements. In comparison to coal-fired kilns, their findings indicated a potential reduction in CO_2 emissions ranging from 15% to 19.6%. The integration of hydrogen into the cement sector not only contributes to carbone dioxide mitigation but also holds the promise of heightened efficiency in contrast to other industries [25].

2.3.3 Solar calcination process

This method entails the utilization of concentrated solar technology for the process of limestone calcination. A fraction of the calcined limestone is introduced into the kiln, while the remainder can be stored for future use, particularly during periods lacking solar insolation [35]. Part of the calcinated limestones is fed to the kiln and the rest can be stored for later use when there is no solar insolation for instance [35]. As it was stated earlier, the modern kiln is equipped with preheaters and calciner. In solar calcination technology, the more commonly found approach is the usage of solar calciner to replace the conventional calciner. Given that roughly 65% of the energy is consumed by the calciner, this technology emerges as a highly promising contender in terms of conserving energy and mitigating CO_2 emissions. Cement production with calcination process is presented in Figure 2-5 below.

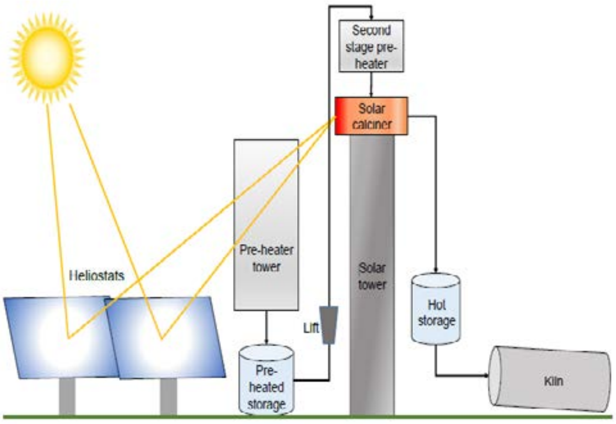


Figure 2-5: Solar calcination [22]

2.3.4 Kiln electrification process

As the cost of Solar Photovoltaic and Wind as well as the storage facilities like batteries and Hydrogen decreases there is a growing interest in using the renewable electricity for industrial decarbonization [46]. As the cost of Solar Photovoltaic and Wind as well as the storage facilities like batteries and Hydrogen decreases there is a growing interest in using renewable electricity for industrial decarbonization [46]. In fact, electrical power can be used to calcine limestone for cement production.

The benefit of electrified heating systems is that the carbon dioxide concentration in the flue gas is close to 100%, which would allow easier capture and purification of CO_2 from process emission [47].

Various electrification technologies have the potential to be incorporated into the cement production process. For instance, plasma technology stands out as a method capable of generating temperatures exceeding 2000°C [13], which are essential for both the calcination and clinkerization processes. Another approach involves the utilization of resistive electrical heating, a method already employed in glass melting procedures, that could be adapted to replace traditional heating techniques in cement production [46]. Electromagnetic heating technologies like inductive and microwave heating also hold promise, as they utilize electromagnetic waves to attain the high temperatures required for limestone calcination. Further scripts on the different methods for cement production process electrification can be found in literature [46], [47].

A study of plasma technology with carbon capture in cement plant was also done by Wilhelmsson *et al.* [48] in the CemZero project, they stated 100% of CO_2 capture was possible, the cement production cost was 110.6 Euro/t lower the cost than monoethanolamine carbon capture fueled with electricity, 117.2 Euro/t cement. This technology was competitive with the reference plant (without carbon capture) when the cost of carbon reached 100 Euro/t CO_2, reported by Wilhelmsson *et al.*[48].

Tokhleim *et al.* [47] integrated successfully an electrified calciner and carbon capture. They found about 72% avoided CO_2 at an annualized cost of 67 Euro/t CO_2 avoided. They compared this approach with the amine carbon capture, they concluded that electrified calcination could compete with post-combustion carbon capture in system without waste heat available.

Other electrification projects include the LEILAC (Low emissions Intensity Lime and Cement) project test already successfully at lab scale and deploy is except in 2023 [46].

2.3.5 Alternative raw materials: clinker substitution

Clinker production is the most energy intensive step in cement production and accounts for about two thirds of the total CO_2 emissions [38]. New and sustainable pathways that reduce the clinker content in cement will contribute to reduction of process emission. Huntzinger and Eatmon, 2009 [21]consider clinker reduction as the most efficient ways to reduce cement sector overall CO_2 emission. Additionally, this strategy reduces the thermal energy demand. Although, some studies have shown the domination of the Portland-based cement approaches in the near future [46], supplementary cementitious materials (SCMs) such as fly ash, slag, pozzolans, concrete crusher sand [31] and limestone filler can be used. Kermeli *et al.* [38] reported about 200 Mt of granulated blast furnace slag, 500 Mt of fly ash and 5.6 Mt of natural pozzolan are produced every year worldwide. These materials offer the possibility of replacing a part of cement clinkers; however, the maximum rate of replacement varies depending on the chemical composition of the SCMs used. For instance, the limestone content could be as high as 25 – 35% [38] to about 50% possible in the future as reported by IEA, 2018 [6]. Krishnan *et al.* reported a ternary blend (clinker, limestone, calcined clay) that allows for 50% substitution of clinker [49].

According to IEA and CSI the global average clinker-to-cement ratio was 0.65 in 2014 [6], however the material substitutes are predominantly limestone, slag and fly ash [50].

Although several studies have shown the possibility of using fly ash and slag to replace high quantity of clinkers in cement, it should be noted that the combination of both only represents of the one million tons, about one quart of the total cement production. Furthermore, these two materials are faced with uncertainty of availability due to environmental concerns and they are also unevenly distributed around the world. For fly ash for instance which a byproduct of coal plants, its availability will reduce due to coal power reduction, as for slag which a waste from steel and iron, a shift from blast furnace route towards scrap-based electric arc furnaces will reduce its availability [6]. To these two materials, there are many others that are well studied and was proven to be adapted to substitute clinkers for example some agricultural wastes such as rice husk or sugar cane bagasse, but they are locally available and, in some region, especially in some part of Africa, they depend on the season [7]. Another well researched alternative raw material in calcined clay, especially when combined with limestone. The combination is proved to be able to 50% of clinker [50] However, the use of calciner clay is expected to increase the energy demand [6].

Another approach usually discussed as a potential strategy for reducing carbon dioxide emission in cement is the circular economy. This strategy consists of recycling and reusing construction waste such as aggregates, bricks, sand, cement powder, among others [51]. Implementing this approach reduces the need for extraction of some raw materials, thus reducing carbon emission associated with the extraction and crushing.

Some disadvantages of SCMs highlighted by previous papers include the slow early-age strength development and uncertainty on the long-term durability [46] that also limit their usage to specific areas.

Despite the above-mentioned limitations, IEA, 2018 roadmap projected a global clinker reduction of only about 5% between 2014 to 2050 under Degree Scenario (2DS) low-variability case scenario. Yet this reduction favors a drop of 30% of the process CO_2 intensity of cement by 2050 from 2014's level [6].

2.3.6 Alternative cement materials

This topic has been investigated due to about 60% of material-related emissions, therefore finding materials or new technologies able to replace the traditional raw materials for cement production is becoming important. These materials are different from the Portland cement clinker based. These materials include:

- Belite rich clinker: this type of clinker is made from the same limestone (about 10% less-Antunes) and in similar kiln as the conventional Portland cement clinker; however, it has less alite known as tricalcium silicate but around 40 – 90% belite (dicalcium silicate). This process operates at lower temperature compared to the traditional process and emits about 6 to 8% less CO_2 [28]. This process operates at lower temperature compared to the traditional process and emits about 6 to 8% less CO_2 [28]. These clinkers have been in use since the roman empire [46]. These clinkers have been in use since the roman empire [46]. Moreover, according to IEA [6], belite-rich cements is already commercialized and in use in countries like China, Japan, and so.

The limitation of belite-rich clinker includes the hardness which requires extra electricity for grinding and the low heat of hydration which affect the slow early strength gain; therefore, its application is more suitable in mass concrete where low heat of hydration is required.

- Calcium sulphoaluminate clinkers (CSA): this type of clinkers is made from raw materials such as limestone, calcium sulfate and aluminum-rich minerals. They are generally produced at temperature around 1250°C [46] and easier to grind in comparison with the conventional clinkers. They are generally produced at temperature around 1250°C [46] and easier to grind in comparison with the conventional clinkers. The main phases of these clinkers are ye'elimite ($Ca_4(AlO2)_6SO_3$), belite and gypsum. The CO_2 emission associated with the production is relatively lower compared to the OPC clinker. [28]. These clinkers also are commercialized in China [6].

However, they show quick setting properties and a higher degree of early strength development, which could limit its application. Additionally, the production requires concentrated aluminum and sulfur materials which will likely increase the production cost.

- Alkali-activated binders: Also known as geopolymer, they have been commercialized in some countries like Australia, Brazil, Canada, China, among others [6], [28]. They are formed by reacting alumino-silicate with an alkali activator like sodium silicate [28]. They have the potential to reduce CO_2 from cement production. However, due to the alkali-activator requirement, for which the production is associated with CO_2 emissions would reduce the net CO_2 reduction of this technology. Furthermore, its production relies on supplementary cementitious materials such fly ash, natural pozzolans or GGBFS that are already in use in blended cements.
- Belite calcium sulphoaluminate clinkers (BCSA)**:** this technology is at demonstration and pilot phases [6]. Its production is carried out by the increase of belite and addition of alumino-ferrite to the earlier introduced CSA clinkers, mainly the belite phase replaces ye'elimite phase in CSA clinker [28].
- Carbonation of Calcium Silicates (CACS) or Solidia Technology: Introduced in 2016, this approach employs materials similar to those in Ordinary Portland Cement (OPC) clinker. However, the resulting products undergo curing in a pure CO_2 environment at atmospheric pressure, controlled temperature, and specific relative humidity. Interestingly, the CO_2 released during production is reabsorbed by the formed concrete. Notably, this technology does face challenges in terms of safeguarding conventional steel reinforcement against corrosion. Additionally, the curing process necessitates precise control over CO_2 concentration conditions.
- Magnesium Oxide-based Cements Derived from Magnesium Silicates (MOMSs): These cements are crafted using magnesium silicate rocks, which serve as abundant raw materials. One significant advantage is that the usage of these materials does not incur process-related emissions. However, the progress of this technology is constrained by its current state in the research and development phase. Furthermore, the uneven distribution of magnesium silicate rocks across the globe poses a limitation. As of now, this practice has yet to achieve commercial development [37], or is in the Research and Development according to IEA [6].

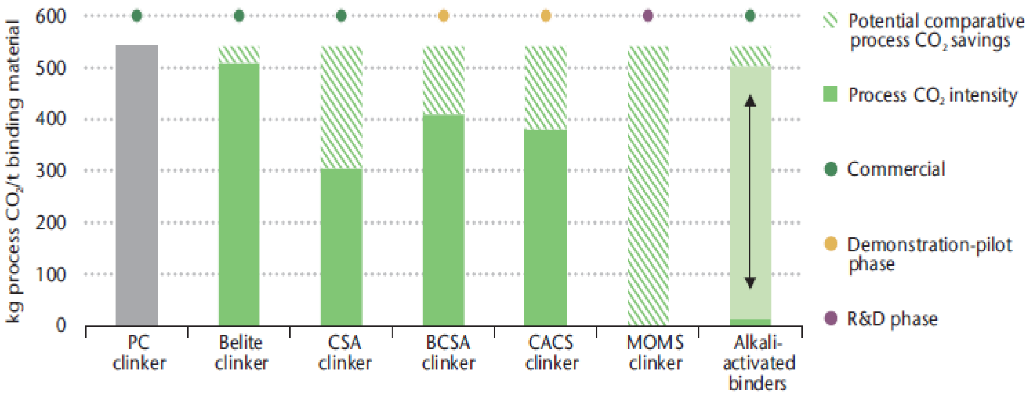


Figure 2-6: Alternative clinkers including CO_2 saving and maturity [6]

Due to aforementioned limitation this strategy of CO_2 reduction is not included in the traced future process routes.

2.3.7 Carbon capture technologies

Given the challenges posed by the emissions stemming from the decomposition of raw materials, the adoption of emerging carbon capture technologies emerges as a promising avenue essential for the decarbonization of the cement sector. Research underscores that in order to effectively combat anthropogenic climate change, it will be imperative to target direct specific emissions in the range of 350 – 410 kg CO_2 per ton of cement [52]. Moreover, in pursuit of meeting the 2050 mitigation targets, a substantial global capture of approximately 552 to 707 million metric tons of CO_2 annually is required [28]. Given that thermal efficiency enhancements, material utilization, and fuel substitution could only bring down emissions to a range of 540−590 kg CO_2 per ton of cement [52], it becomes evident that alternative strategies are indispensable. In addition to its contributions to achieving carbon neutrality within the cement industry, carbon capture also opens doors to the concept of Power-to-X (PtX), where captured CO_2 finds use in the production of chemicals and hydrocarbons. Farfan[37] in his work showed a globally distributed potential of captured CO_2 for PtX use by 2050. The resultant synthetic fuel has the benefits of not only replacing the emission from fossil fuels, but also avoiding the emissions associated with the extraction and refining of these fuels.

Numerous carbon capture and storage (CCS) technologies can be applied to the cement production process to effectively curtail direct CO_2 emissions. These encompass precombustion, post-combustion with amine solvents, membrane-assisted liquefaction, oxyfuel combustion, calcium looping technologies, and more [54]. However, this thesis will primarily focus on the utilization of two specific technologies, monoethanolamine (MEA) carbon capture and oxyfuel carbon capture technologies.

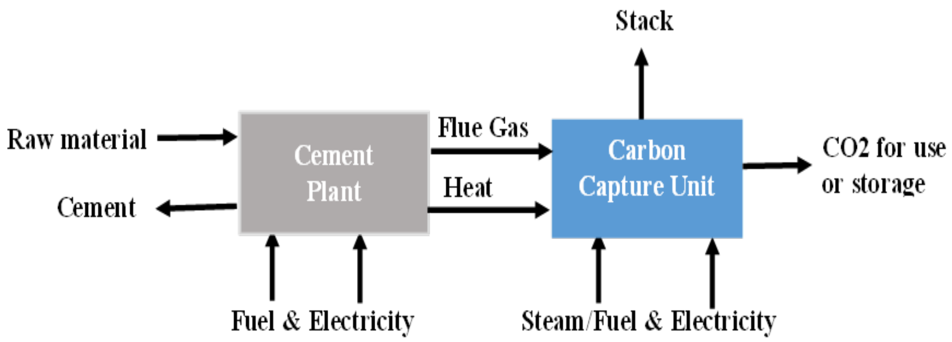


Figure 2-7: Cement plant integrated with carbon capture system [36]

2.3.7.1 Monoethanolamine (MEA) carbon capture technology

This technology was chosen for its advanced level of development, registering a Technology Readiness Level (TRL) of 8 to 9. Its applicability extends even to existing cement plants [6] although it mandates the utilization of a solvent that is regenerated through a thermal process incurring a cost of approximately 2 gigajoules (GJ) per ton of CO_2 [52]. The purification of flue gases entails the use of a synthetic non-catalytic reactor to eliminate impurities like nitrogen oxide, along with a direct contact cooler to address sulfur oxide, prior to absorption within the Carbon Capture and Storage (CCS) unit's absorber [36],[54]. The flue gas then enters the absorber containing the monoethanolamine (MEA) solvent, which forms a complex MEA-CO_2 (aq) compound upon interaction with carbon dixiode. The subsequent step involves desorption or regeneration, wherein the MEA-CO_2 (aq) compound is heated to liberate CO_2, which is subsequently compressed and stored, while the MEA solvent is recycled for the capture of further CO_2 compounds. In addition to this extra electricity is essential to power the compressor and other auxiliary components [54].

Step1 Absorption: CO_2 (g) + 2 MEA (l) → MEA-CO_2 (aq) + MEA (l)

Step2 Desorption: MEA-CO_2 (aq) → CO_2 (g) + 2 MEA (l)

Certain challenges highlighted by prior researchers encompass the substantial thermal energy demand required for MEA solvent regeneration, the costs associated with the solvent and its degradation, as well as equipment corrosion [53].

2.3.7.2 Oxyfuel combustion technology

This emerging technology is currently under investigation in the cement sector. Its implementation is based on the use of pure oxygen instead of ambient air, a resource that can either be generated on-site through Air Separation Units (ASUs) [52] or obtained externally, for instance, from an electrolysis plant [43]. The employment of pure oxygen during fuel combustion results in a flue gas enriched with carbon dioxide, rendering it more amenable to capture. Nonetheless, the process of extracting oxygen from air comes with a notable electricity penalty due to the significant power demands of ASUs, up to 60 kWhe/t clinker [52]. Additional power is also essential for compression units and other auxiliary devices, amounting to around 200 – 240 kWh per ton of oxygen [48].

Two oxyfuel technologies have been developed: oxyfuel with a portion of the flue gas recirculated. This can be applied to existing conventional cement plants. The second is pure oxyfuel technology, which operates without flue gas recirculation. However, this technology is only viable for new installations. Importantly, both variants offer equivalent CO_2 capture rates [25].

Oxyfuel technology can be implemented in two primary configurations. The first configuration involves a partial approach, where solely the calciner is subjected to oxy-firing [53]. This setup has the capacity to capture approximately 60% to 70% of the total CO_2 emissions. An additional advantage lies in its facile retrofitting for existing plants, as modifications are confined to the calciner and preheater, leaving the kiln, cooler, and raw mill untouched [52],[53]. In contrast, the second configuration is a full oxy-fuel arrangement, wherein both the calciner and the kiln are oxy-fired. For this configuration, adaptations must be made to the kiln to ensure compatibility with CO_2/O2 operational conditions [53]. This configuration, however, provides a significantly higher CO_2 capture rate high than 90% [53].

Hills *et al.* [52] have underscored certain limitations, notably the need for extensive land to accommodate the facilities necessary for both oxyfuel and MEA carbon capture methods.

For an extensive discussion on the techno-economic analysis of carbon capture technologies, the reader is referred to the study of Plaza *et al.* [36] and Voldsund *et al.* [54].

Chapter 3：Materials and Method

An Excel spreadsheet (provided in Appendix A) was created with the aim of facilitating the straightforward estimation of material and energy requirements for manufacturing one ton of cement. This serves as the basis for constructing the model, enabling the calculation of associated carbon dioxide emissions. The primary objective is to establish cleaner and more sustainable pathways for the cement manufacturing process.

This section outlines the methodology employed to compute the energy and material demands, as well as the costs associated with representative process routes. It is important to note that while the current study focuses on the production of one ton of cement capacity, the methodologies presented can be applied to any cement plant provided that specific parameters of the cement plant are available.

3.1 Study area

This master's thesis will revolve around various strategies outlined earlier, serving as a study of the cement production process. The objective was to establish pathways for cement manufacturing that are both sustainable and minimize carbon dioxide emissions. Essential data including material demand, energy requirements, and techno-economic parameters crucial for the success of the study were gathered. A comparative analysis of these pathways was conducted. Additionally, the study selected three regions, each with distinct characteristics, where the process routes were applied within their respective cement sectors. The chosen countries for this study included China, Germany, and Senegal.

China has been the leading country in terms of cement production for many years. Indeed, China was producing 36% of the global cement in 1999. This share has reached 55% in 2019 [24]. However, the production was seen to reach a peak and will decrease over the coming years, will fall from 2.38 billion tons in 2021 to 750 million tons in 2050 [55]. The cement sector in China has experienced an increase in new suspension pre-heater and pre-calciner (NSP) kilns that has led to a decrease in thermal energy demand such as coal consumption [20]. Additionally, the country leads in waste heat recovery, resulting in a decrease in electricity demand [34]. However, fuels substitution is very low, only about 2% was reported [55]. China is leading as well in terms of renewable energy deployment with 1,160,799 MW of installed capacity in 2022 [56], which could play a crucial role in decarbonization of industrial sector, including cement industry.

Germany also is the European leading country in cement production. The German's production was about 34 million tons in 2019, which represents 19% of European cement production [24]. The country has a good waste management policy, about 68% of the municipal solid waste is recycled, 31% is transformed to energy, and only 1% is landfilled [24]. German cement sector sourced about 68.5% of thermal energy requirement from waste in 2019, just behind Czech Republic and Austria using 76.4% and 78.44%, respectively [57].

Senegal is a country where a growth of cement production is expected. According to the International Energy Agency, cement production capacity is set to increase in Africa to fulfil their infrastructure development needs [6]. Additionally, the International Finance Corporation (IFC) reported a nearly 50% projected increase in cement demand across Sub-Saharan Africa between 2015 and 2020. In parallel, Senegal has experienced an impressive 8% growth in cement demand from 2010 to 2015 [7]. The surge in cement demand is attributed to various developmental initiatives, including the implementation of the "Plan Sénégal Émergent" and an urbanization rate of 3.59% annually [76]. The country is also well-positioned in the deployment of renewable energy, with several projects currently in progress. As per the International Renewable Energy Agency (IRENA), the installed renewable energy capacity in 2022 amounts to 446 MW. This capacity encompasses 159 MW from onshore wind, 263 MW from solar, and other sources [56]. These potentials could contribute significantly to the decarbonization of sectors known for greenhouse gas emissions, particularly the power generation and industrial sectors such as cement production. The country is actively engaged in the process of decarbonizing its cement sector as well. Notably, the largest cement manufacturer, SOCOSIM industry has secured a 120 million euro loan from the International Finance Corporation to support the production of cement with minimal CO_2 equivalent annually by the year 2030 [58].

3.2 Scenario analysis

The proposed scenarios involve an analysis of pathways towards cleaner and more sustainable cement production. For each of the selected countries, the reference case reflects the business-as-usual scenario, using the latest available data for analysis. Alternative cases were formulated and assessed, encompassing factors such as material and energy demands, along with techno-economic parameters. The ultimate goal was to design process routes that would minimize or even reduce to zero emission of carbon dioxide from cement. The table below shows the basis in which these scenarios were constructed.

Table 3-1: Reference data for scenario design [24],[25],[26],[28][48],[59]

Parameters and Technology	Unit	Best practice	Reference
Thermal energy demand	MJ/t clinker	< 2900	[26]
Electricity demand	kWh/t cement	< 80	[59]
Clinker-to-cement ratio	%	< 50	[28]
Fuel subtitution (including Biomass)	%	100	[24]
MEA carbon capture efficiency	%	95	[25]
Oxy-fuel carbon capture efficiency	%	95	[25]
Plasma technology efficiency	%	100	[48]

Table 3-2: Scenario input data [9],[24],[25],[26],[30],[44],[49]

Parameters and Technology	Unit	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Thermal energy demand	GJ/t clinker	Current Level	3 [26][24]	3	3	3
Electricity demand	kWh/t clinker	Current Level	90 [9][30]	90	90	90
Clinker-to-cement ratio	%	Current Level	50a [49]	50	50	50
Fuel substitution (including Biomass)	%	Current Level	50b	100[44; 24]	0	0
Hydrogen	%	Current Level	0	0	100	0
Plasma technology efficiency	%	Current Level	0	0	0	100 [48]
Carbon capture technology: rate	%	Yes 95[25]	Yes 95	Yes 95	Yes 95	Yes 95

a: 50% of the clinker were replaced by SCMs such as limestone, slag, calcined clay, and others.

b: 50% of the thermal energy was substituted by wastes and biomass and 50% of fossil fuels (25% gas and 25% coal)

The common factors in this study are that coal remains the predominant source of thermal energy from fossil fuels in all selected countries, this assumption was based on these studies [7], [10], [55], [61]. As such, the current scenario assumes coal provides 100% of the thermal energy from fossil fuels, and the rest of the thermal energy was provided by alternative fuels.

This assumption is also carried into Scenario 0. Another consideration is that all the scenarios utilize renewable solar energy to fulfill the electricity requirements.

The energy and material demands are held constant across Scenarios 1 to 4 in term of quantity, however the energy and material sources vary across scenarios and across selected countries. This approach was selected to facilitate a comparison of the impact of varying strategies (pathways) on total carbon dioxide emissions and the actual cost of cement production. The scenarios are structured as follows: (refer to Table 3-2)

- **Scenario 0:** This represents the current context, or business-as-usual situation, where only carbon capture technologies are integrated into the cement production process.
- **Scenario 1:** In this scenario, both alternative fuels and the clinker ratio are considered at a rate of 50%, along with the application of carbon capture technology.
- **Scenario 2:** This scenario involves a 50% clinker ratio and 100% utilization of alternative fuels, including biomass, alongside carbon capture technology.
- **Scenario 3:** This scenario considers a 50% clinker-to-cement ratio. However, it relies exclusively on 100% hydrogen to fulfill the thermal energy requirement, and carbon capture technology is employed to capture process emissions.
- **Scenario 4:** In this scenario, the 50% clinker-to-cement ratio was maintained, and plasma technologies, along with carbon capture, are implemented.

The selection of the clinker to cement ratio have been made based on the following explored literature. According to IEA [6], the estimated global average clinker ratio would be 0.6 by 2050. Furthermore, it was possible for some countries like Netherland to reach an average of 0.46 by Schneider [28]. Additionally, Krishnan *et al.* [49] reported the possibility of producing limestone calcined clay (LC3) which had a composition of 50% clinker, 30% calcined clay, 15% limestone and 5% gypsum.

The future routes also consider the usage of waste, biomass and hydrogen or fully electric cement process to replace fossil fuel-based thermal energy and reduce the related emission as supported by Farfan *et al.* [37]. Additionally, waste heat recovery into electricity was also considered to cover about 37 kWh/t cement in accord with the reported range 25 – 45 kWh/t cement [34].

Regarding the carbon capture technology, the monoethanolamine and oxyfuel carbon capture were applied to scenario 0 until scenario 3. The scenario 4 is a noble application of plasma with carbon capture, from research previously conducted by Wilhelmsson *et al.* [48].

It should be noted that, it was found in the literature conducted by IEA that using supplementary cementitious materials such calcined clay might lead to an increase in electricity demand [6]. However, the exact magnitude of this increase was not quantified in the literature.

For the purposes of this study, the electricity demand is assumed to be consistent across all processes, without considering any variations resulting from the incorporation of supplementary cementitious materials. Moreover, photovoltaic electricity was used to avoid accountability for indirect emissions related to electricity consumption, more importantly this source of energy was the cheapest in all the selected countries (see Table 3-6).

Finally, a sensitivity analysis was conducted for these pathways to support the implementation of the scenarios.

3.3 Data collection

All the data used in this study have been collected from various sources in the literature, including published articles, reports, and publicly accessible websites. To gather this information, search tools like Google, Google Scholar, and Scopus were employed. It is important to acknowledge that the issue of data accuracy is a concern. Therefore, to ensure precision, the collected data were meticulously cross-referenced, and Excel spreadsheets were utilized to perform calculations for material and energy requirements per ton of cement, along with associated carbon dioxide emissions and production costs, among other factors. Moreover, comparative and illustrative graphs were generated using Excel as well.

However, it is crucial to highlight that all the data used in this study represent average values for the selected regions; they are not specific to any single cement plant. Detailed tables outlining the methodology for calculating material demand, energy demand, and carbon dioxide emissions can be found in Appendix A-1, Appendix A-2, and Appendix A-3, respectively. Furthermore, an economic analysis of various parameters and the associated costs of the applied technologies are presented in Appendix B.

3.3.1 General assumption

This section points out some assumptions which were made during the work.

- For all the selected countries, the material demand was taken the same. Therefore, the collected data on this parameter were summed and the average was chosen. This assumption stands true for the components of cement such as limestone, sand, iron ore, and clay.

- The cost of the raw materials, and cost of technology equipment and installation were also taken as similar for all the selected countries in all scenarios. However, parameters such as cost of energy, and others are taken separately.
- It was also assumed that only the variable cost can change when changing scenario, except the scenario 4 which has totally in different configuration.
- For scenarios that involved high rate of clinker and fuel substitution, no modification in cement plant was considered.
- Carbon capture technologies were applied to the cement production process for many reasons. First, the usage of alternative materials and fuels was not able to achieve deep decarbonization due to limited suitable substitutes [33]. Additionally, materials such as fly ash and slag are expected to decrease in the future due energy transition. Same notice holds for alternative fuels, especially biomass, while could face competition between cement industry and other industries [12], [24].
- Scenario 3 in which hydrogen was used as fuel substitute to the conventional fuels, the cost of equipment in the conventional cement plant were maintained. Therefore, only the cost of hydrogen to fulfill the thermal requirement was considered.

3.3.2 Data collection in selected countries

This section describes the current situation of cement production. It compares the energy and emission intensity globally and in some country like China, Germany, and Senegal.

3.3.3 Case of China

China accounts for over 50% of global cement production. Developing decarbonization strategies for China's cement sector holds the potential for rapidly achieving carbon-neutral cement manufacturing. A comprehensive evaluation of the current state of the cement industry in China was conducted, and potential pathways for future sustainable processes were identified. Information concerning China's cement industry was obtained from published papers that provided average values for electricity demand, emission factors, and thermal substitution rates.

Different values of clinker-to-cement ratio were reported in the literature to be 57% in 2014 by IEA [6], 60% by Andrew [63], 63.13% WEI *et al.* [20], 65% by Schneider [28] and 63.4% by Shen *et al.* [2]. Although, these values are reported in different years, it important to note that the clinker-to-cement ratio is not always constant. It depends on several factors including the chemical composition of the materials and fuels (ash incorporation). Therefore, an average of these values was considered as the clinker-to-cement ratio for China's cement sector, and the rest of the materials was assumed to be completed with supplementary cementitious materials such as fly ash, slag, and others, which are widely used in China [28]. As for the thermal energy consumption about 3.3 GJ/t of clinker was reported in IEA[6] for the year 2014. The electricity per ton of cement was given by Wei *et al.* as 90 kWh/t cement in 2015[20]. The fuel substitution of China's cement sector was extremely low only about 2 % [6], [20], [55].

Regarding the CO_2 emissions, the process emission factor was reported as 538.3 $kgCO_2$ /t clinker [63], and the electricity emission factor as 0.8843 $kgCO_2$/kWh in 2012 [5]. Waste heat recovery has already been in function in China as reported by Schneider [28], this technology is considered in this work to compensate partly the electricity demand for cement production process. The electricity price for the year 2020 and 2050 were collected from the work of Franzmann *et al.* [64] , equal to 6.602 EURct/kWh and 2.69 EURct/kWh respectively, as well as the cost of hydrogen, 2.771 Euro per kg. The following Table 3-3 gives the details in the input data for the China's cement sector.

Table 3-3: Cement plant input data for China's cement sector [2],[6],[20],[28][55],[63]

Strategies	Materials & Technology	Unit	Value	References
Thermal energy demand	New suspension Preheaters/Precalciner kilns	GJ/t clinker	3.5	[6], [20]
Electricity demand	NSP kilns	kWh/t clinker	90	[20]
Fuel substitution	Biomass, wastes	%	2	[20], [55]
Clinker substitution	Pozzolans, limestone, calicned clay	%	60.88 a	[2], [20], [28], [63]
Process emission factor	/	$kgCO_2$/t clinker	538.3	[63]
Electricity emission factor	/	$kgCO_2$/kWh	0.8843	[5]
Electricity price (2020)	/	EURct/kWh	6.602	[64]
Electricity price (2050)	/	EURct/kWh	2.69	[64]

a: Calculated average

3.3.4 Case of Germany

Germany produced 19% of all European union cement in 2019 [24]. Markewitz *et al.* [65] reported that the German government has plan to reduce greenhouse gas (GHG) emissions by at least 55% by 2030 and by 80–95% through 2050 against 1990's emission level. However, in 2017 about 2.5 % of the German national CO_2 emission was originated from the cement industry [65]. The goal set by the government of Germany can hardly be achieved without deep decarbonization of its cement sector. This work attempts to retrace the current scenario of cement production process in Germany and show sustainable process route for future cement production.

The necessary data were collected from online published papers and open sources. The material demands for the German cement sector is constituted with a clinker-to-cement ratio of 68 % in 2012 as it was reported in work of Branger[66], the rest of the materials are mainly completed by the use of supplementary cementitious materials such limestone, slag, among others. The thermal energy demand is taken as 3.6 GJ/t clinker and the electricity as 100 kWh/t cement in 2012as reported Branger *et al.*[66]. As for thermal substitution rate, in 2019 about 68.9% were reported by Uliasz-Bocheńczyk [57], mainly dominated by industrial/commercial waste, tires, treated municipal waste, sewage sludge, and others [61]. The process emission of the German cement was taken as 526 kgCO_2/t, value reported by Marmier *et al.* [24]. The electricity emission factor for German cement industry was reported in the study of Branger *et al.* [66] as 44 kgCO_2/kWh. As for the electricity prices, Franzmann *et al.* [64] published 7.198 EURct/kWh and 4.615 EURct/kWh for 2020 and 2050, respectively. Summary of the input data in presented in Table 3-4.

Table 3-4: Cement plant input data for German's cement sector [24],[57],[64],[66]

Strategies	Materials & Technology	Unit	Value	References
Thermal energy demand	New suspension Preheaters/Precalciner kilns	GJ/t clinker	3.6	[66]
Electricity demand	Dry kilns	kWh/t clinker	100	[66]
Fuel substitution	Biomass, wastes	%	68.5	[57]
Clinker substitution	Pozzolans, limestone, calicned clay	%	71	
Process emission factor	/	kgCO_2/t clinker	526	[24]
Electricity emission factor	/	kgCO_2/kWh	0.44	[66]
Electricity price (2020)	/	EURct/kWh	7.198	[64]
Electricity price (2050)	/	EURct/kWh	4.615	[64]

3.3.5 Case of Senegal

The data collection of cement sector in Senegal also was carried out in open sources and published documents.

Some calculations were however made considering a reported total capacity of 7.5 Mt/a of cement, 5.1 Mt/a of clinker and annual thermal energy demand about 18.5 GJ from [7]. The ratio clinker-to-cement was calculated at 68%, the thermal energy demand per ton of clinker was calculated 3.63 GJ/t clinker. The electricity demand of 100 kWh/t cement was taken from literature as present case and 90 kWh/t cement as future case, as a general case for Africa [6] The electricity price was collected in the “globalpetrolprices”, 0.172 US$/ kWh (Euro 0.158 / kWh) for the current case [77]. However, the future scenarios consider the use of renewable electricity such as solar energy. The process and electricity emission factors are chosen from the reported values in the following literature. The electricity emission factor estimated 0.563 kg CO_2/kWh [25]. As for the process emission, Cement Sustainability Initiative default value of 525 kgCO_2/t cement was used [2].

Table 3-5: cement plant data for Senegal’s cement sector [2],[6],[7],[25],[79]

Strategies	Materials & Technology	Unit	Value	References
Thermal energy demand	New suspension Preheaters/Precalciner kilns	GJ/t clinker	3.68 c	[7]
Electricity demand	Dry kilns	kWh/t clinker	100	[6]
Fuel substitution	Biomass, wastes	%	25	[7]
Clinker substitution	Pozzolans, limestone, calicned clay	%	68 c	[7]
Process emission factor	/	kgCO_2/t clinker	525a	[2]
Electricity emission factor	/	kgCO_2/kWh	0.563b	[25]
Electricity price (2022)	/	EUR/kWh	0.158	[79]
PV Electricity price (2050)	/	EURct/kWh	1.79	[79]

a: CSI recommended default value in absence of data[2]

b: Global average electricity emission factor in 2020[25]

c: Calculated value

Table 3-6: Cost of electricity [64], [79]

	Cost of electricity			Cost of H_2
COUNTRY	**PV (EURct/kWh)**	**Wind (EURct/kWh)**	**Grid (EURct/kWh)**	**Euro per kg**
China	2.317	5.522653908	2.690035426	2.771
Germany	3.08	4.984672244	4.615649558	3.026
Senegal	1.79	6.31	15.8	1.96

Remark: 1Euro = 100 EURct

3.4 Mathematical calculations

3.4.1 Raw materials

The estimation of the amount of raw material required for production of one clinker are based on a critical comparison of the reported values from literature. The formula below was used to derive the raw materials required for 1 ton of cement.

$$M_{cement(t)} = C/Cr(\%) \times M_{clinker(t)} + (100 - 5 - C/Cr(\%)) \times M_{SCMs} + 5\% \times M_{gypsum}$$

$C/Cr(\%)$: clinker-to-cement ratio

3.4.2 Energy demand

The energy required to produce 1 ton of cement was calculated also with respect to clinker to cement ratio. This method facilitated a quick estimation of the energy demand per ton of cement. The impact of the clinker ratio on the electricity demand was neglected since clinker burning/cooling process represents only about 24% of the total electricity demand [31]. Also, it should be noted that the use of some materials such calcined clay requires more electricity which is difficult to quantify [6]. However due to the waste heat recovery about 37 kWh/t [34], additional electricity demand was offset. Cement kilns can burn up to 100% of waste or biomass fuels as it was reported by Marmier [24].

$$E_{\mathrm{GJ/t\ cement}} = C/Cr(\%) \times E_{th\left(\frac{\mathrm{GJ}}{\mathrm{t}}\mathrm{clinker}\right)} + E_{el\left(\frac{kWh}{t}cement\right)} \times 0.0036$$

Remark: the factor 0.0036 is used for the conversion from kWh/t clinker to GJ/t clinker.

3.4.3 Carbon dioxide emissions

The overall cement plant CO_2 emissions were calculated considering a constant process emission factor per ton of clinker of 538.3 kg, 526 kg and 525 kg per ton of cement respectively for China, Germany and Senegal (refer to Table 3-3 – Table 3-5). However, process emissions took into consideration the variation of the clinker ratio. Likewise, the electricity emission factor for all the scenarios and for all the selected country was 0 kg/kWh per ton of cement since renewable solar was utilized. As for the fuel emissions, specific emissions per fuel type were used for all the scenarios (refer to Appendix A-3). The energy emission was calculated by considering the consumption of each fuel time the emission factor which was associated. Alternative fuel emissions were also taken into account to accurately calculate emissions and assess the carbon footprint of cement production. Biomass emission was accounted for zero (0) emissions [42]. The following formulas were used to determine carbon dioxide emission [20].

$$P_{emission} = EF_{clinker} \times C/Cr(\%)$$

$$F_{emission(\boldsymbol{kg}/t\ cement)} = \sum E_{\mathrm{th(GJ/t\ clinker)}} \times\ EF_{\mathrm{Fuel(kgCO2/GJ)}}$$

$$E_{emission(\boldsymbol{kg}/t\ cement)} = E_{el\ (kWh/t\ cement)} \times EF_{grid\ (kgCO2/kWh)}$$

$$Total_{CO2\ emission\ (\frac{kg}{cement})} = P_{emission} + F_{emission} + E_{emission}$$

These methods of CO_2 emission calculation were also used by Kermeli *et al.*[38].

Additional formulas for processes involving carbon capture technologies, the following formulas were adopted [69], [70].

$$Captured\ CO2 = \frac{(P_{emission}\ +\ F_{emission} + Added_{F_{emission}})}{Capture_{rate}}$$

$$Added_{CO2}\ = Added_{F_{emission}} + Added_{E_{emission}}$$

$$CO2\ Released = (Total_{CO2\ emission} + Added_{CO2}) - Captured\ CO2$$

$$Avoided\ CO2 = Total_{CO2\ emission} - CO2\ realised$$

3.4.4 Cost calculation methods

The costs of the proposed routes as well as those for the current state were derived from previous work on the cement with carbon capture.

Due to the large number of parameters in the analysis of cement plants, the Capital Expenditure (CAPEX) and the Fixed Operational cost (Fixed OPEX) were directly taken from literature, and the average was chosen (see Table 3-7). While the variable operational cost was meticulously calculated for each scenario.

- Capital expenditure (CAPEX): which was considered as the investment costs including the cost of equipment, the cost of installations, and others.
- Operational expenditures (OPEX): was separated into Fixed OPEX which take into account the operation and maintenance cost, cost of supervision and other cost, and a variable OPEX which involves the material and fuel costs as well as the cooling costs.

As for cement plant with carbon capture, additional cost of equipment and their installation and maintenance was considered as well as other cost of materials such as MEA solvent of MEA carbon capture and fuel costs or air separation unit (ASU) for oxyfuel, cooling water and others, classified in this work as other variable cost ($OtherVar_{Opex}$), refer to Appendix B-3. The designed routes benefits from waste heat recovery as it was reported in [34], a project of 9 MW with 12 MUSD (Million United State Dollars) of investment and 0.27 MUSD of O&M in a cement plant of 5000 ton per day operating about 300 days. It yielded a saving of 55.242 GWh of electricity annually which corresponded to about 37 kWh/t clinker. [34]. This cost was added to the calculation in order to benefit from a reduction in electricity demand. Table 3-7 presents the calculated costs of cement plants. Formulas below were used to fill the calculate thre corresponding parameters [70].

$$Annualized\ Investment = CAPEX \times \frac{d}{(1-(1+d)^{-t}}$$

$$Var_{OPEX}: OtherVar_{OPEX} + Cost\ of\ energy + cost\ of\ materials$$

$$Cement\ cost = Annualized\ investment + Fixed\ Opex + Var_{OPEX}$$

d: discount rate

t: lifetime

Table 3-7: Calculated cost of cement plant investments with and without carbon capture (refer to Appendix B-1 and B-2)

Cost of cement plant (Euro/t cement)	Plant W/O CCS	Plant with MEA CCS	Plant with Oxyfuel CCS
CAPEX	183.164	330.44	285.56
Fixed OPEX	16.33	19.64	22.8
Annualized Investment cost	17.15857989	30.95521575	26.75091215

3.5 SWOT Analysis

This section gives some analysis of the methods and routes developed in this thesis.

- The strength of the representative process routes is that they are based on strong investigation and critical analysis of previously published documents, and a scientific mathematical reasoning were used.
- The weakness of the aforementioned approach is the absence of both experimental work and simulation, leading to assumptions regarding feasibility and performance. This lack of empirical validation could potentially constrain the prospective implementation of these routes. Furthermore, this study did not consider future prospects of employing alternative raw materials like belite-clinker or MOMS, despite their potential contribution to the cement sector's decarbonization. These options could prove significant, particularly in areas where the technologies are more advanced, and the necessary materials are readily available.
- The opportunities encompass a significant reduction in the climate impact through a substantial decrease in CO_2 emissions from the cement sector. Furthermore, substantial potential is associated with the implementation of novel technologies like complete electrification, hydrogen integration, and carbon capture, which can foster job creation in research and pilot projects. There is also potential for utilizing captured carbon within the power to x (PtX) framework, leading to the synthesis of novel fuels applicable in other sectors. Moreover, the adoption of alternative fuels and materials is likely to unveil fresh market prospects.
- The threats are mainly linked with the shortage of alternative raw materials such as fly ash and slag that depend on industries like coal which subjected to be phase out due to environmental concern, and iron and steel industry due to uncertainties on the current path of steel and iron making processes. Furthermore, the cost associated with the aforementioned developed approach might not be encouraging for cement producers.

Chapter 4: Results & Discussion

The result for the representative processes for potential future cement production process is presented in this section. Initially, section 4.1 gives an overview of cement sector in Senegal and highlight opportunities for cleaner cement production. The section 4.2 shows the interpretation of the previously developed scenario including their application into China, Germany and Senegal cement industries. Section 4.3 discusses a sensitivity analysis of the designed pathways under carbon cost imposition or electricity price changes.

4.1 In depth study of pathways for the cement industry in Senegal

The cement industry in Senegal is dominated by three major companies operating in the sector, Dangote, SOCOCIM (Vicat Group), and Ciment du Sahel. These industries are strategically located in proximity to the capital city, Dakar (see Figure 4-1). With a production capacity reaching up to 7.5 million tons per annum (Mt/a) of cement, it is estimated that around 5.1 million tons of clinker are manufactured each year [7]. Considering the average emission of about 866 kg CO_2 per ton cement as reported by Farfan *et al.* [37], this production could be associated to 6.64 million ton of CO_2 emission per year.

Furthermore, cement production in Senegal could be driven by its "Plan Senegal Emergent," aspires to elevate the country to a middle-income status by 2035 [82]. This ambitious agenda entails comprehensive developmental initiatives encompassing critical infrastructure projects like roads, buildings, railways, and more. Consequently, this strategic plan could generate a substantial demand for cement products, inevitably driving Senegal towards a pronounced reliance on cement imports or necessitating a substantial escalation in domestic cement production capacity.

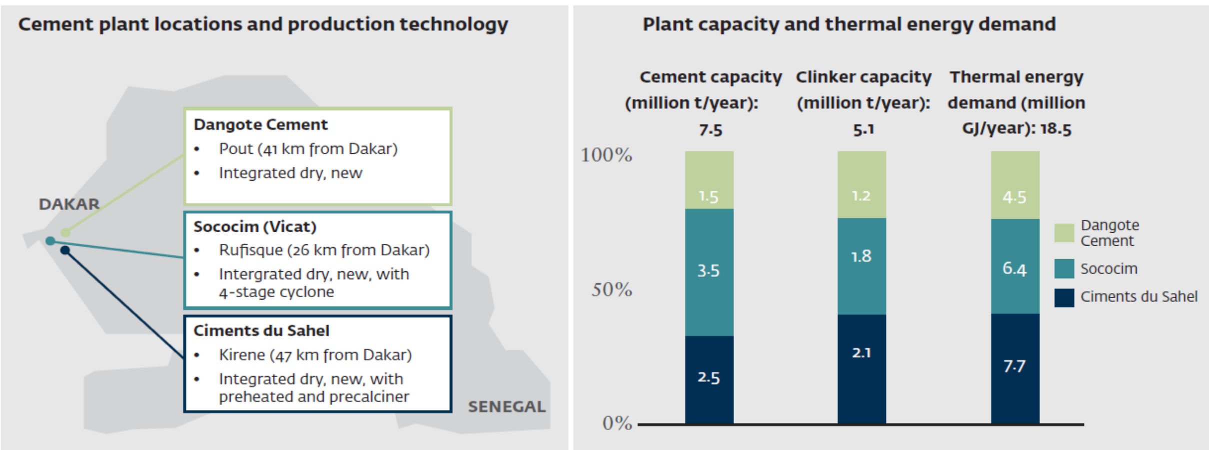


Figure 4-1: Senegal cement plant: location and capacity [7]

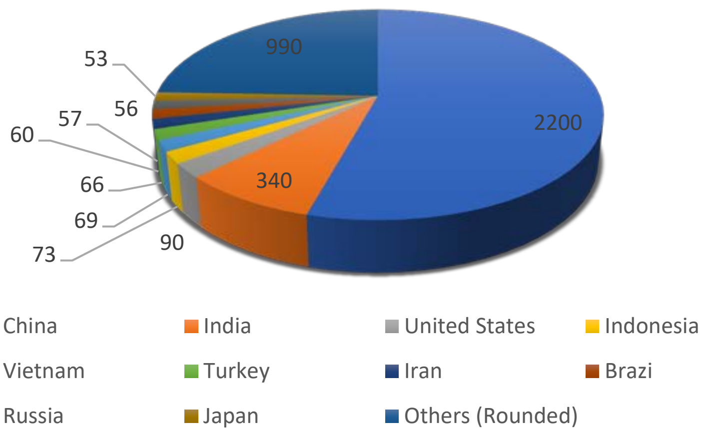


Figure 1-1: Global cement production in 2020 including the high-producing countries [8]

1.2 Problem statement and Research questions

1.2.1 Contribution of the cement industry to the anthropogenic carbon dioxide emission

Cement production accounts for approximately 7% to 8% of the global CO_2 emissions and roughly 27% of the direct industrial emissions worldwide (refer to Figure 1-2) [10]. These emissions contribute to the overall concentration of these gases in the atmosphere. These elevated levels of greenhouse gases enhance the natural greenhouse effect, leading to global warming and subsequent climate change [87]. It is important to mention that cement production stands as an energy-intensive and emissions-intensive sector [2]. To produce one ton of cement, an average of 3.5 gigajoules (GJ) of energy and approximately 90 to 150 kilowatt-hours (kWh) are typically consumed [9]. This energy demand primarily relies on fossil fuels such as coal, natural gas, and oil [10], thereby contributing to the emission of greenhouse gases like carbon dioxide. Furthermore, over half of the carbon dioxide emissions are originated from the calcination process of limestone, the principal raw material in cement production [3].

Despite the enormous efforts that have been made to abate CO_2 emissions from cement about 2.7 billion_of CO_2 were emitted in 2017 [12]. To achieve the climate goals of 1.5 ºC and 2 ºC set by the Paris agreement [5], emissions from the cement industry need to be reduced by 16% by 2030 and by 24% by 2050 [3].

Therefore, it is imperative to implement more effective practices for cement production. All countries around the globe, including developing countries, need to make substantial efforts to reduce considerably greenhouse gas emissions from all the emitting sectors including the cement sector.

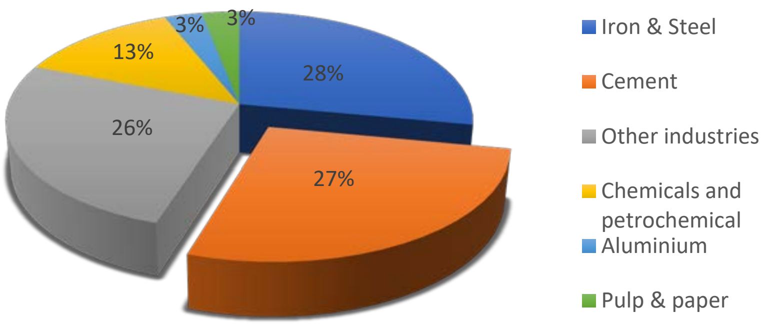


Figure 1-2: Share of the global cement emission from the total direct industrial CO_2 emission in 2014 [10]

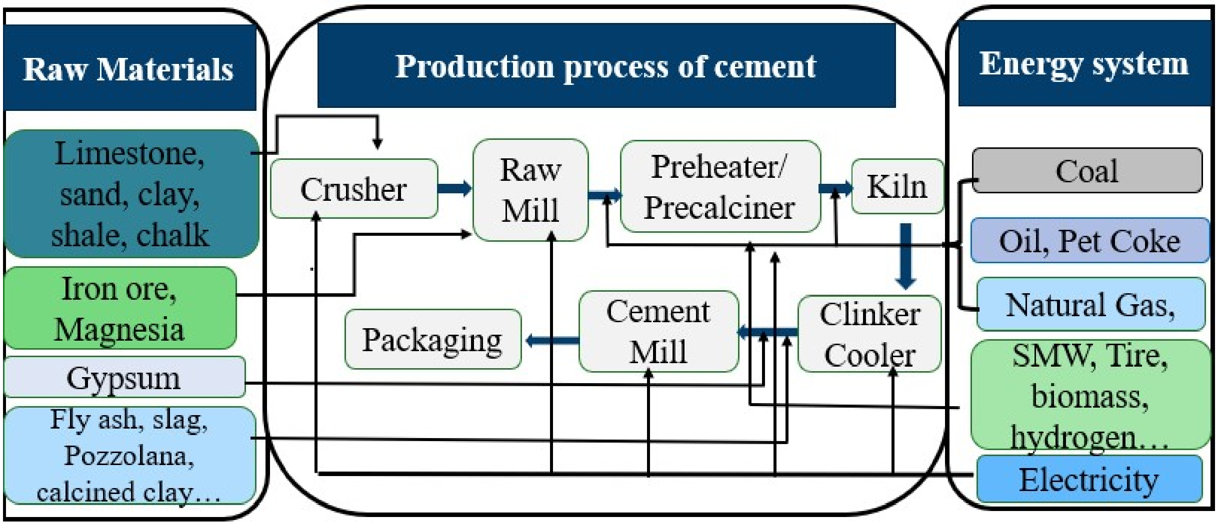
1.2.2 Research questions

- What are the current cement production processes globally and especially in Germany, China, and Senegal?
- What could be the future process routes for the efficient, sustainable, and environmentally friendly making of cement in the selected countries?
- How can the adoption of carbon dioxide abatement strategies and best available technologies can help improve sustainability in cement production in Senegal.

1.3 Objectives and contributions of this work

The cement industry falls within the group of seven challenging-to-address sectors (including aluminum, aviation, cement and concrete, chemicals, chipping, steel, trucking) that collectively contribute to approximately 30% of the global CO_2 emissions [25]. According to a report by the European Cement Research Academia (ECRA) [25], if these sectors continue with business-as-usual practices, they are projected to compromise the target of limiting global temperature rise to 1.5 degrees Celsius by 2030. In this work three countries were selected, Germany, China and Senegal.

The main objective of this thesis was to assess the current process routes of cement manufacturing process in order to identify their environmental impacts in terms of carbon dioxide emission on the global scale. The specific objectives were to design a model which take into account the current pathways and explores future representative cement production pathways, evaluating the material demand, the energy demands and carbon dioxide emissions



a: SMW: Solid Municipal Waste

Figure 2-1: Simplified diagram of the cement production process including material and energy input (own depiction based on cement production process described in the above section).

It is important to note that Figure 2-1 only provides a brief description of the cement production process. However, a standard cement plant is outfitted with various components, including hoppers and conveyors for charging and transporting raw meals. Additionally, provisions like dust collectors, flue gas desulfurization units, and synthetic catalytic reactors are incorporated to mitigate emissions of dust, sulfur oxides, and nitrous oxide respectively. Storage silos and cooling systems are also integral, ensuring the seamless and uninterrupted operation of the cement plant.

2.1.2 Raw Material Demand

As previously mentioned, limestone constitutes the primary raw material for cement production, accounting for approximately 70% to 80% of the total raw material weight [13]. The remaining composition is comprised of components like sand, clay, iron ore, and others. Roughly 1.7 tons of raw materials [16] are utilized to generate 1 ton of clinker. The proportion of clinker content varies depending on the required cement type, ranging from 20% to around 100% according to European cement norms. The remainder of the mixture is supplemented with materials such as gypsum and other additives, including natural pozzolans like volcanic materials or artificial options such as calcined clay. Industrial waste materials such as fly ash from coal plants, ground granulated blast furnace slag from the iron and steel industry, and silica fume from semiconductor production can also be incorporated to complete the composition. Reported raw materials are presented in Table 2-1 and Table 2-2.

Table 2-1: Amount of raw material input per ton of clinker [16], [17], [18], [19], [20]

Authors	Materials	Quantity (t/t of clinker)	References
Verma [16]	raw material	1.7	[16]
Worrell [17]	raw material	1.7	[17]
Berdowski [18]	raw material	1.57	[18]
Rahman *et al.* [19]	raw material	1.7	[19]
Wie *et al.* [20]	raw material	1.55	[20]
Average (Chosen Value)	raw material	1.644	

Table 2-2: Share of raw material mainly used during clinker production [14], [21], [22], [23]

Raw materials	Huntzinger[21]a	Chatterjee[14]	Al-Dhamri[22]	IEAGHG[23]a	Averagea
Limestones	88.125	84.54	86.03	80.66	84.83875
Clay/Shale	8.6875	3.42	3.74	18.39	8.559375
Iron ore	0.9375	5	2.93	0.48	4.23625
Sand	2.125	7.04	7.3	0.48	2.336875

a: calculated.

2.1.3 Process and Kiln types

There are different processes used to manufacture cement, these include:

Dry process: This method involves employing a dry rotary kiln with a configuration that includes preheaters and precalciner stages (1 – 6 stages). It stands as the most widely utilized kiln globally. The material's moisture content typically ranges between 0% to 0.7% [14]. In terms of thermal energy consumption, this process ranks as the most efficient, utilizing around 3 – 4 GJ per ton of clinker [15], see Figure 2-2.

Wet process: Among the oldest approaches to cement production, the wet process utilizes a vertical shaft kiln, often referred to as a wet kiln, which is also one of the earliest kiln types. This method entails higher thermal energy consumption due to a notably elevated water content, ranging from about 30% to 40% according to Benhelal *et al.* [11] or between 24% to 48% according to Worrell *et al.* [4]. It stands as the most energy-intensive technique, necessitating approximately 6.1 GJ per ton of clinker, refer to Figure 2-4.

Semi-dry / Semi-wet processes: These processes involve the addition of water to dry materials to achieve moisture levels of about 11% to 14%, or the dewatering of wet materials to achieve water contents of approximately 17% to 22% according to Worrell *et al.* [4]. Kilns used in this approach are referred to as long dry or semi-dry kilns. These processes consume thermal energy in the range of 4 to 4.5 GJ per ton of clinker, refer to Figure 2-4.

Figure 2-2 displaces different processes used around the world.

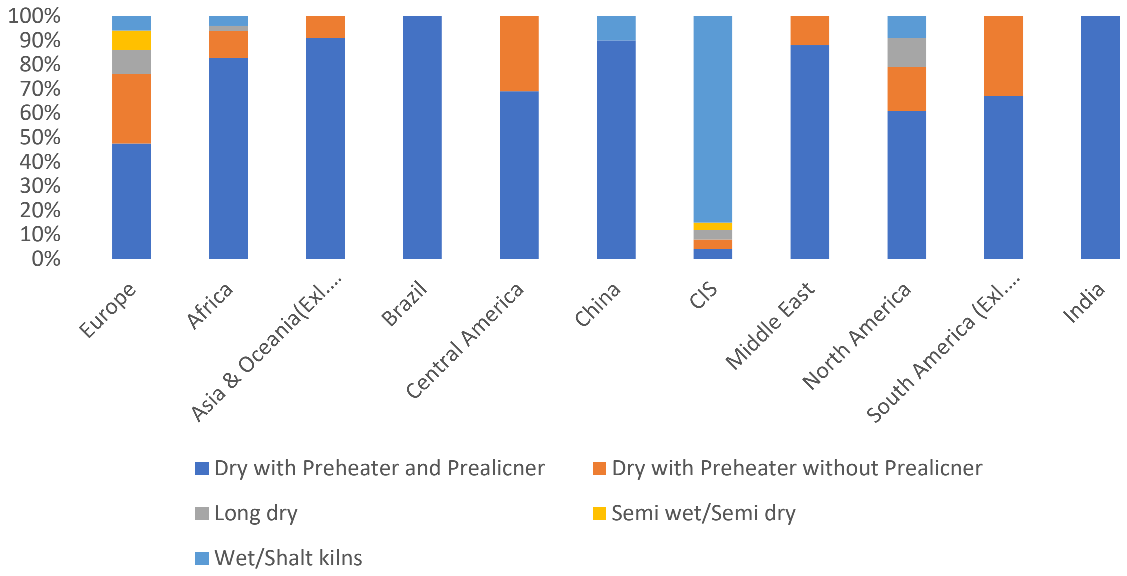


Figure 2-2: Cement kiln types and global share [38]

2.1.4 Energy demand

The manufacturing of cement requires a high input of thermal and electrical energy. This section will discuss the demands of thermal energy and electricity. About 7% of global energy is used in the cement industry [6].

2.1.4.1 Thermal energy demand

The theoretical minimum thermal energy demand to produce cement clinker was reported be in the range 1.59 - 1.84 GJ/t clinker [24]. However, due to high losses and the cement production process adopted, the thermal energy demand per ton of clinker could be as high as two to three times this theoretical amount (refer Figure 2-3).

Thermal energy demand in cement production exhibits substantial variation depending on the chosen manufacturing process, primarily categorized into two main processes: wet and dry. The dry process generally entails lower thermal energy consumption compared to the wet process as displaced Figure 2-3. The elevated energy usage associated with the wet process is largely attributed to the high moisture content of raw materials. Notably, around 30% of the overall thermal energy is consumed in drying these materials. Both the wet and dry processes experience significant heat losses, accounting for approximately 35% to 39% of the inputs [16]. These losses emanate from exhaust gases, coolers, and radiation heat emitted from the kiln cell, as detailed by Verma *et al.* [16]. In the dry process, the thermal energy consumption typically ranges from about 3 to 4 gigajoules per ton of clinker. On the other hand, the wet process can demand a substantially higher amount, reaching approximately 6 gigajoules per ton of clinker due to the energy requirement for water evaporation [25],[26]. Madlool *et al.* [26] reported values of around 3.2 gigajoules per ton for the dry process and approximately 5.8 gigajoules per ton of clinker for the wet process.

Within cement plants, the predominant utilization of thermal energy revolves around the calcination process (clinkerizaton). In fact, Afkhami *et al.* [27] indicated that nearly 99% of thermal energy within cement plants is allocated to this purpose.

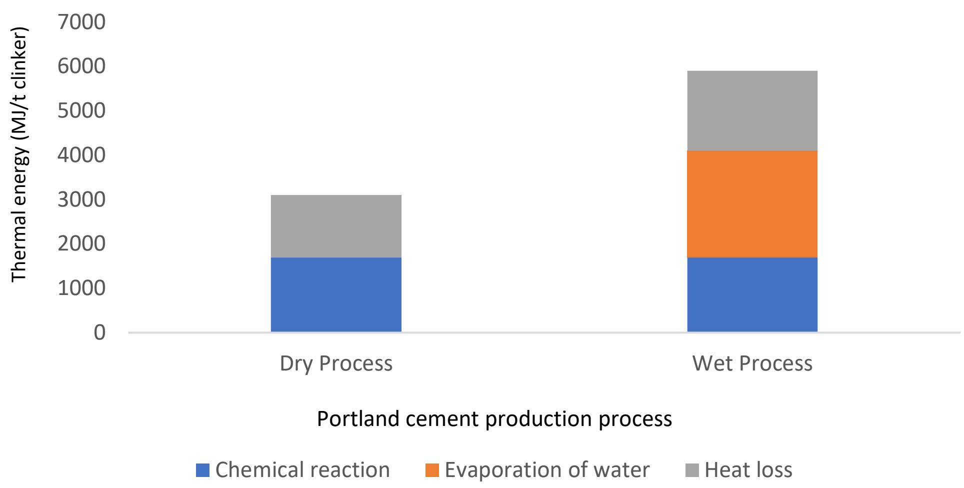


Figure 2-3: Thermal energy consumption distribution for dry and wet processes [26]

2.1.4.2 Electrical energy demand

The amount of electricity required for cement production is between 90 – 150 kWh per ton of cement, reported by Schorcht *et al.*[9] or in the range 85 kWh – 129 kWh /t cement as it was indicated in [45]. Although electricity is needed in small quantities compared to the thermal energy, it is used in all the process steps (See Table 2-3).

It has been reported that the wet process, despite its higher thermal energy consumption, consumes less electricity compared to the dry process. This variance could be attributed to the hardness of the raw materials used in the dry process. Due to their hardness, these materials necessitate more time for complete grinding. Interestingly, a substantial portion of approximately 38% of the total electricity consumed in the cement production process is allocated to the grinding of these raw materials [26]. Therefore, the electricity consumption per ton of cement is significantly influenced by the manufacturing process employed and the specific types of materials utilized. On a global scale, the average electricity consumption fluctuates within the range of 103 kWh to 110 kWh per ton of cement, as documented by Schneider [28]. In most cement plants, this energy is taken from the grid, Consequently, it is pertinent to note that carbon dioxide emissions stemming from electricity use and transportation constitute approximately 10% of the total emissions within the cement industry [29]. Furthermore, it is worth emphasizing that the average specific electricity consumption per ton of cement differs significantly between countries. According to the IEA's report [30], this variance spans from approximately 90 kWh per ton of cement in India to about 140 kWh per ton of cement in the USA, as observed in 2005.

Table 2-3: Electricity demand distribution in the different cement production steps [11], [31], [32].

Schneider[31]**; Benhelal** [11]**; Atmaca**[32]	**About 100 kWh/t of cement**
Mining & Extraction	5%
Crushing	3%
Raw material grinding	26%
Coal grinding	4%
Clinker burning/cooling	24%
Cement grinding	30%
Rest	7%

2.1.5 Carbon dioxide emission from cement production process

The cement industry accounts for approximately 8% of the global carbon dioxide (CO_2) emissions and ranks as the third-largest consumer of industrial energy [3]. Carbon dioxide emissions from cement sector increase with the increase in cement production. In 1990, global emissions from the cement industry amounted to approximately 576 million tons of CO_2, however, by 2014, this figure had tripled, reaching 2.083 billion tons [33]. According to Czigler *et al.* [12], if the current emission rate persists, projections indicate that by 2050, CO_2

wet kilns to approximately 3 – 4 GJ/t clinker for dry kilns, consequently leading to a decline in emission intensity per ton of cement. Marmier [24] reported thermal energy requirement of 3.81 and 3.52 GJ/t clinker for 2019, respectively for the EU27 and global average. Figure 2-4 highlights the energy savings by switching from wet to 6 stages cyclones preheaters and precalciner

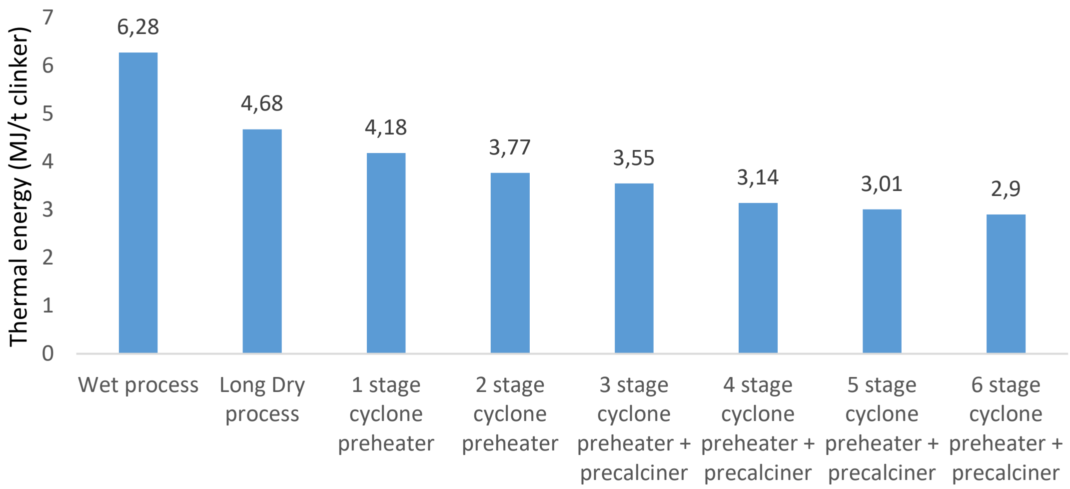


Figure 2-4: Thermal energy demand (GJ/t of clinker) per kiln type [26]

2.3.1.2 Waste Heat Recovery

Waste heat recovery plays a pivotal role in mitigating energy losses throughout the cement production process, even with the utilization of the dry process. This is due to the existence of approximately 30% waste heat. Modern kilns are outfitted with preheater and pre-calciner stages that strategically minimize heat losses by harnessing the hot air derived from both the cooler and the kiln. This hot air is employed to elevate the temperature of the raw meal, along with other materials such as coal, petcock, or cement constituents like granulated blast furnace slag [25].

Other methods, such as electricity generation through Rankine cycles (Organic and Steam) or Kalina cycle, have gained widespread adoption in countries like China and Japan [28]. These methods have the potential to harness around 25-45 kWh/t clinker of electricity [28], [34]. This amount equates to approximately 20 to 30% of the total electricity demand within cement plants, resulting in a reduction of about 15 to 23 kg CO_2/t cement [34]. As a result, waste heat recovery stands as an effective strategy for both energy conservation and emissions reduction. According to [28], the return on investment for a cement plant producing 5000 tons per day utilizing the Rankine cycle for electricity generation is estimated at 3.9 years. This estimation is based on an assumed electricity price of $60/MWh and a waste heat recovery blend in cement production is currently in its nascent stages of investigation (Technology Readiness Level 2) [44].

Nevertheless, Rami *et al.* delved into the interconnection between cement and hydrogen production, using H_2 to partially fulfill the thermal energy requirements. In comparison to coal-fired kilns, their findings indicated a potential reduction in CO_2 emissions ranging from 15% to 19.6%. The integration of hydrogen into the cement sector not only contributes to carbone dioxide mitigation but also holds the promise of heightened efficiency in contrast to other industries [25].

2.3.3 Solar calcination process

This method entails the utilization of concentrated solar technology for the process of limestone calcination. A fraction of the calcined limestone is introduced into the kiln, while the remainder can be stored for future use, particularly during periods lacking solar insolation [35]. Part of the calcinated limestones is fed to the kiln and the rest can be stored for later use when there is no solar insolation for instance [35]. As it was stated earlier, the modern kiln is equipped with preheaters and calciner. In solar calcination technology, the more commonly found approach is the usage of solar calciner to replace the conventional calciner. Given that roughly 65% of the energy is consumed by the calciner, this technology emerges as a highly promising contender in terms of conserving energy and mitigating CO_2 emissions. Cement production with calcination process is presented in Figure 2-5 below.

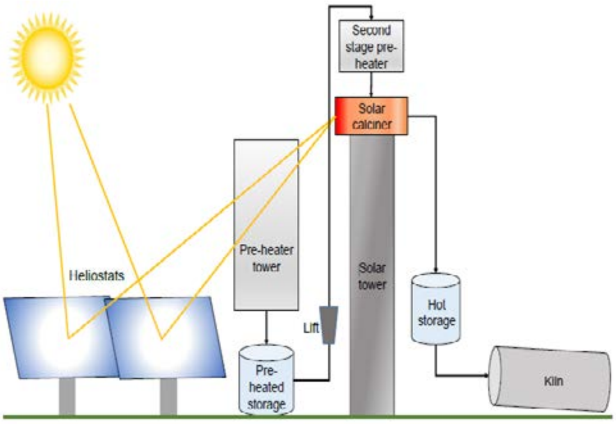


Figure 2-5: Solar calcination [22]

2.3.4 Kiln electrification process

As the cost of Solar Photovoltaic and Wind as well as the storage facilities like batteries and Hydrogen decreases there is a growing interest in using the renewable electricity for industrial decarbonization [46]. As the cost of Solar Photovoltaic and Wind as well as the storage

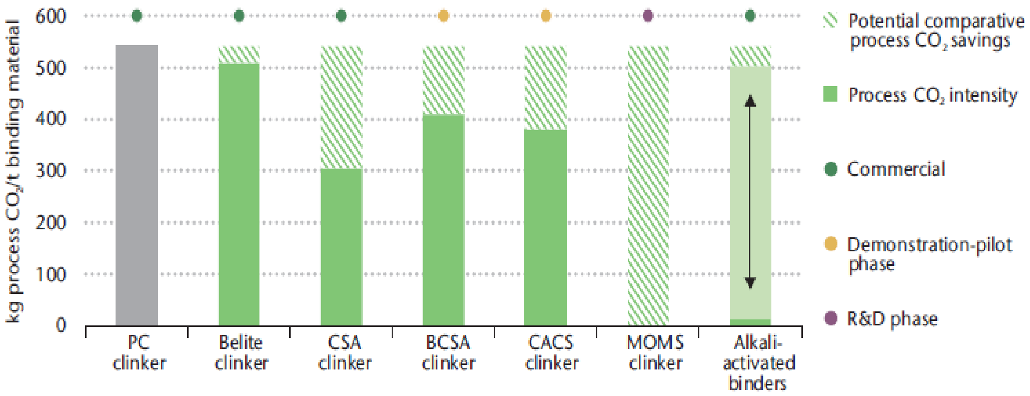


Figure 2-6: Alternative clinkers including CO_2 saving and maturity [6]

Due to aforementioned limitation this strategy of CO_2 reduction is not included in the traced future process routes.

2.3.7 Carbon capture technologies

Given the challenges posed by the emissions stemming from the decomposition of raw materials, the adoption of emerging carbon capture technologies emerges as a promising avenue essential for the decarbonization of the cement sector. Research underscores that in order to effectively combat anthropogenic climate change, it will be imperative to target direct specific emissions in the range of 350 – 410 kg CO_2 per ton of cement [52]. Moreover, in pursuit of meeting the 2050 mitigation targets, a substantial global capture of approximately 552 to 707 million metric tons of CO_2 annually is required [28]. Given that thermal efficiency enhancements, material utilization, and fuel substitution could only bring down emissions to a range of 540−590 kg CO_2 per ton of cement [52], it becomes evident that alternative strategies are indispensable. In addition to its contributions to achieving carbon neutrality within the cement industry, carbon capture also opens doors to the concept of Power-to-X (PtX), where captured CO_2 finds use in the production of chemicals and hydrocarbons. Farfan[37] in his work showed a globally distributed potential of captured CO_2 for PtX use by 2050. The resultant synthetic fuel has the benefits of not only replacing the emission from fossil fuels, but also avoiding the emissions associated with the extraction and refining of these fuels.

Numerous carbon capture and storage (CCS) technologies can be applied to the cement production process to effectively curtail direct CO_2 emissions. These encompass precombustion, post-combustion with amine solvents, membrane-assisted liquefaction, oxyfuel combustion, calcium looping technologies, and more [54]. However, this thesis will primarily focus on the utilization of two specific technologies, monoethanolamine (MEA) carbon capture and oxyfuel carbon capture technologies.

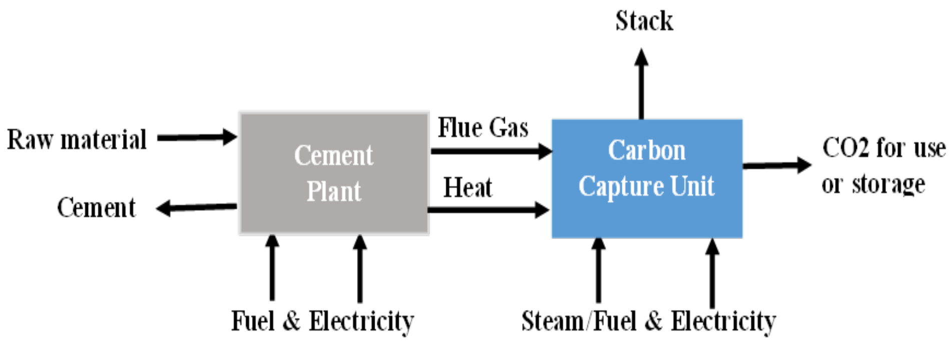


Figure 2-7: Cement plant integrated with carbon capture system [36]

2.3.7.1 Monoethanolamine (MEA) carbon capture technology

This technology was chosen for its advanced level of development, registering a Technology Readiness Level (TRL) of 8 to 9. Its applicability extends even to existing cement plants [6] although it mandates the utilization of a solvent that is regenerated through a thermal process incurring a cost of approximately 2 gigajoules (GJ) per ton of CO_2 [52]. The purification of flue gases entails the use of a synthetic non-catalytic reactor to eliminate impurities like nitrogen oxide, along with a direct contact cooler to address sulfur oxide, prior to absorption within the Carbon Capture and Storage (CCS) unit's absorber [36],[54]. The flue gas then enters the absorber containing the monoethanolamine (MEA) solvent, which forms a complex MEA-CO_2 (aq) compound upon interaction with carbon dixiode. The subsequent step involves desorption or regeneration, wherein the MEA-CO_2 (aq) compound is heated to liberate CO_2, which is subsequently compressed and stored, while the MEA solvent is recycled for the capture of further CO_2 compounds. In addition to this extra electricity is essential to power the compressor and other auxiliary components [54].

Step1 Absorption: CO_2 (g) + 2 MEA (l) → MEA-CO_2 (aq) + MEA (l)

Step2 Desorption: MEA-CO_2 (aq) → CO_2 (g) + 2 MEA (l)

Certain challenges highlighted by prior researchers encompass the substantial thermal energy demand required for MEA solvent regeneration, the costs associated with the solvent and its degradation, as well as equipment corrosion [53].

Table 3-1: Reference data for scenario design [24],[25],[26],[28][48],[59]

Parameters and Technology	Unit	Best practice	Reference
Thermal energy demand	MJ/t clinker	< 2900	[26]
Electricity demand	kWh/t cement	< 80	[59]
Clinker-to-cement ratio	%	< 50	[28]
Fuel subtitution (including Biomass)	%	100	[24]
MEA carbon capture efficiency	%	95	[25]
Oxy-fuel carbon capture efficiency	%	95	[25]
Plasma technology efficiency	%	100	[48]

Table 3-2: Scenario input data [9],[24],[25],[26],[30],[44],[49]

Parameters and Technology	Unit	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Thermal energy demand	GJ/t clinker	Current Level	3 [26][24]	3	3	3
Electricity demand	kWh/t clinker	Current Level	90 [9][30]	90	90	90
Clinker-to-cement ratio	%	Current Level	50a [49]	50	50	50
Fuel substitution (including Biomass)	%	Current Level	50b	100[44; 24]	0	0
Hydrogen	%	Current Level	0	0	100	0
Plasma technology efficiency	%	Current Level	0	0	0	100 [48]
Carbon capture technology: rate	%	Yes 95[25]	Yes 95	Yes 95	Yes 95	Yes 95

a: 50% of the clinker were replaced by SCMs such as limestone, slag, calcined clay, and others.

b: 50% of the thermal energy was substituted by wastes and biomass and 50% of fossil fuels (25% gas and 25% coal)

The common factors in this study are that coal remains the predominant source of thermal energy from fossil fuels in all selected countries, this assumption was based on these studies [7], [10], [55], [61]. As such, the current scenario assumes coal provides 100% of the thermal energy from fossil fuels, and the rest of the thermal energy was provided by alternative fuels.

that the clinker-to-cement ratio is not always constant. It depends on several factors including the chemical composition of the materials and fuels (ash incorporation). Therefore, an average of these values was considered as the clinker-to-cement ratio for China's cement sector, and the rest of the materials was assumed to be completed with supplementary cementitious materials such as fly ash, slag, and others, which are widely used in China [28]. As for the thermal energy consumption about 3.3 GJ/t of clinker was reported in IEA[6] for the year 2014. The electricity per ton of cement was given by Wei *et al.* as 90 kWh/t cement in 2015[20]. The fuel substitution of China's cement sector was extremely low only about 2 % [6], [20], [55].

Regarding the CO_2 emissions, the process emission factor was reported as 538.3 $kgCO_2$ /t clinker [63], and the electricity emission factor as 0.8843 $kgCO_2$/kWh in 2012 [5]. Waste heat recovery has already been in function in China as reported by Schneider [28], this technology is considered in this work to compensate partly the electricity demand for cement production process. The electricity price for the year 2020 and 2050 were collected from the work of Franzmann *et al.* [64] , equal to 6.602 EURct/kWh and 2.69 EURct/kWh respectively, as well as the cost of hydrogen, 2.771 Euro per kg. The following Table 3-3 gives the details in the input data for the China's cement sector.

Table 3-3: Cement plant input data for China's cement sector [2],[6],[20],[28][55],[63]

Strategies	Materials & Technology	Unit	Value	References
Thermal energy demand	New suspension Preheaters/Precalciner kilns	GJ/t clinker	3.5	[6], [20]
Electricity demand	NSP kilns	kWh/t clinker	90	[20]
Fuel substitution	Biomass, wastes	%	2	[20], [55]
Clinker substitution	Pozzolans, limestone, calicned clay	%	60.88 a	[2], [20], [28], [63]
Process emission factor	/	$kgCO_2$/t clinker	538.3	[63]
Electricity emission factor	/	$kgCO_2$/kWh	0.8843	[5]
Electricity price (2020)	/	EURct/kWh	6.602	[64]
Electricity price (2050)	/	EURct/kWh	2.69	[64]

a: Calculated average

3.3.4 Case of Germany

Germany produced 19% of all European union cement in 2019 [24]. Markewitz *et al.* [65] reported that the German government has plan to reduce greenhouse gas (GHG) emissions by at least 55% by 2030 and by 80–95% through 2050 against 1990's emission level. However, in 2017 about 2.5 % of the German national CO_2 emission was originated from the cement industry [65]. The goal set by the government of Germany can hardly be achieved without deep decarbonization of its cement sector. This work attempts to retrace the current scenario of cement production process in Germany and show sustainable process route for future cement production.

The necessary data were collected from online published papers and open sources. The material demands for the German cement sector is constituted with a clinker-to-cement ratio of 68 % in 2012 as it was reported in work of Branger[66], the rest of the materials are mainly completed by the use of supplementary cementitious materials such limestone, slag, among others. The thermal energy demand is taken as 3.6 GJ/t clinker and the electricity as 100 kWh/t cement in 2012as reported Branger *et al.*[66]. As for thermal substitution rate, in 2019 about 68.9% were reported by Uliasz-Bocheńczyk [57], mainly dominated by industrial/commercial waste, tires, treated municipal waste, sewage sludge, and others [61]. The process emission of the German cement was taken as 526 $kgCO_2/t$, value reported by Marmier *et al.* [24]. The electricity emission factor for German cement industry was reported in the study of Branger *et al.* [66] as 44 $kgCO_2/kWh$. As for the electricity prices, Franzmann *et al.* [64] published 7.198 EURct/kWh and 4.615 EURct/kWh for 2020 and 2050, respectively. Summary of the input data in presented in Table 3-4.

Table 3-4: Cement plant input data for German's cement sector [24],[57],[64],[66]

Strategies	Materials & Technology	Unit	Value	References
Thermal energy demand	New suspension Preheaters/Precalciner kilns	GJ/t clinker	3.6	[66]
Electricity demand	Dry kilns	kWh/t clinker	100	[66]
Fuel substitution	Biomass, wastes	%	68.5	[57]
Clinker substitution	Pozzolans, limestone, calicned clay	%	71	
Process emission factor	/	$kgCO_2/t$ clinker	526	[24]
Electricity emission factor	/	$kgCO_2/kWh$	0.44	[66]
Electricity price (2020)	/	EURct/kWh	7.198	[64]
Electricity price (2050)	/	EURct/kWh	4.615	[64]

3.3.5 Case of Senegal

The data collection of cement sector in Senegal also was carried out in open sources and published documents.

Some calculations were however made considering a reported total capacity of 7.5 Mt/a of cement, 5.1 Mt/a of clinker and annual thermal energy demand about 18.5 GJ from [7]. The ratio clinker-to-cement was calculated at 68%, the thermal energy demand per ton of clinker was calculated 3.63 GJ/t clinker. The electricity demand of 100 kWh/t cement was taken from literature as present case and 90 kWh/t cement as future case, as a general case for Africa [6] The electricity price was collected in the "globalpetrolprices", 0.172 US$/ kWh (Euro 0.158 / kWh) for the current case [77]. However, the future scenarios consider the use of renewable electricity such as solar energy. The process and electricity emission factors are chosen from the reported values in the following literature. The electricity emission factor estimated 0.563 kg CO_2/kWh [25]. As for the process emission, Cement Sustainability Initiative default value of 525 kgCO_2/t cement was used [2].

Table 3-5: cement plant data for Senegal's cement sector [2],[6],[7],[25],[79]

Strategies	Materials & Technology	Unit	Value	References
Thermal energy demand	New suspension Preheaters/Precalciner kilns	GJ/t clinker	3.68 c	[7]
Electricity demand	Dry kilns	kWh/t clinker	100	[6]
Fuel substitution	Biomass, wastes	%	25	[7]
Clinker substitution	Pozzolans, limestone, calicned clay	%	68 c	[7]
Process emission factor	/	kgCO_2/t clinker	525a	[2]
Electricity emission factor	/	kgCO_2/kWh	0.563b	[25]
Electricity price (2022)	/	EUR/kWh	0.158	[79]
PV Electricity price (2050)	/	EURct/kWh	1.79	[79]

a: CSI recommended default value in absence of data[2]

b: Global average electricity emission factor in 2020[25]

c: Calculated value

Table 3-6: Cost of electricity [64], [79]

COUNTRY	Cost of electricity			Cost of H_2
	PV (EURct/kWh)	**Wind (EURct/kWh)**	**Grid (EURct/kWh)**	**Euro per kg**
China	2.317	5.522653908	2.690035426	2.771
Germany	3.08	4.984672244	4.615649558	3.026
Senegal	1.79	6.31	15.8	1.96

Remark: 1Euro = 100 EURct

3.4 Mathematical calculations

3.4.1 Raw materials

The estimation of the amount of raw material required for production of one clinker are based on a critical comparison of the reported values from literature. The formula below was used to derive the raw materials required for 1 ton of cement.

$$M_{cement(t)} = C/Cr(\%) \times M_{clinker(t)} + (100 - 5 - C/Cr(\%)) \times M_{SCMs} + 5\% \times M_{gypsum}$$

$C/Cr(\%)$: clinker-to-cement ratio

3.4.2 Energy demand

The energy required to produce 1 ton of cement was calculated also with respect to clinker to cement ratio. This method facilitated a quick estimation of the energy demand per ton of cement. The impact of the clinker ratio on the electricity demand was neglected since clinker burning/cooling process represents only about 24% of the total electricity demand [31]. Also, it should be noted that the use of some materials such calcined clay requires more electricity which is difficult to quantify [6]. However due to the waste heat recovery about 37 kWh/t [34], additional electricity demand was offset. Cement kilns can burn up to 100% of waste or biomass fuels as it was reported by Marmier [24].

$$E_{\mathrm{GJ/t\ cement}} = C/Cr(\%) \times E_{th\left(\frac{\mathrm{GJ}}{\mathrm{t}}\mathrm{clinker}\right)} + E_{el\left(\frac{kWh}{t}cement\right)} \times 0.0036$$

Remark: the factor 0.0036 is used for the conversion from kWh/t clinker to GJ/t clinker.

3.4.3 Carbon dioxide emissions

The overall cement plant CO_2 emissions were calculated considering a constant process emission factor per ton of clinker of 538.3 kg, 526 kg and 525 kg per ton of cement literature, and the average was chosen (see Table 3-7). While the variable operational cost was meticulously calculated for each scenario.

- Capital expenditure (CAPEX): which was considered as the investment costs including the cost of equipment, the cost of installations, and others.
- Operational expenditures (OPEX): was separated into Fixed OPEX which take into account the operation and maintenance cost, cost of supervision and other cost, and a variable OPEX which involves the material and fuel costs as well as the cooling costs.

As for cement plant with carbon capture, additional cost of equipment and their installation and maintenance was considered as well as other cost of materials such as MEA solvent of MEA carbon capture and fuel costs or air separation unit (ASU) for oxyfuel, cooling water and others, classified in this work as other variable cost ($OtherVar_{Opex}$), refer to Appendix B-3. The designed routes benefits from waste heat recovery as it was reported in [34], a project of 9 MW with 12 MUSD (Million United State Dollars) of investment and 0.27 MUSD of O&M in a cement plant of 5000 ton per day operating about 300 days. It yielded a saving of 55.242 GWh of electricity annually which corresponded to about 37 kWh/t clinker. [34]. This cost was added to the calculation in order to benefit from a reduction in electricity demand. Table 3-7 presents the calculated costs of cement plants. Formulas below were used to fill the calculate thre corresponding parameters [70].

$$Annualized\ Investment = CAPEX \times \frac{d}{(1-(1+d)^{-t}}$$

$$Var_{OPEX}: OtherVar_{OPEX} + Cost\ of\ energy + cost\ of\ materials$$

$$Cement\ cost = Annualized\ investment + Fixed\ Opex + Var_{OPEX}$$

d: discount rate

t: lifetime

Table 3-7: Calculated cost of cement plant investments with and without carbon capture (refer to Appendix B-1 and B-2)

Cost of cement plant (Euro/t cement)	Plant W/O CCS	Plant with MEA CCS	Plant with Oxyfuel CCS
CAPEX	183.164	330.44	285.56
Fixed OPEX	16.33	19.64	22.8
Annualized Investment cost	17.15857989	30.95521575	26.75091215

Chapter 4: Results & Discussion

The result for the representative processes for potential future cement production process is presented in this section. Initially, section 4.1 gives an overview of cement sector in Senegal and highlight opportunities for cleaner cement production. The section 4.2 shows the interpretation of the previously developed scenario including their application into China, Germany and Senegal cement industries. Section 4.3 discusses a sensitivity analysis of the designed pathways under carbon cost imposition or electricity price changes.

4.1 In depth study of pathways for the cement industry in Senegal

The cement industry in Senegal is dominated by three major companies operating in the sector, Dangote, SOCOCIM (Vicat Group), and Ciment du Sahel. These industries are strategically located in proximity to the capital city, Dakar (see Figure 4-1). With a production capacity reaching up to 7.5 million tons per annum (Mt/a) of cement, it is estimated that around 5.1 million tons of clinker are manufactured each year [7]. Considering the average emission of about 866 kg CO_2 per ton cement as reported by Farfan *et al.* [37], this production could be associated to 6.64 million ton of CO_2 emission per year.
Furthermore, cement production in Senegal could be driven by its "Plan Senegal Emergent," aspires to elevate the country to a middle-income status by 2035 [82]. This ambitious agenda entails comprehensive developmental initiatives encompassing critical infrastructure projects like roads, buildings, railways, and more. Consequently, this strategic plan could generate a substantial demand for cement products, inevitably driving Senegal towards a pronounced reliance on cement imports or necessitating a substantial escalation in domestic cement production capacity.

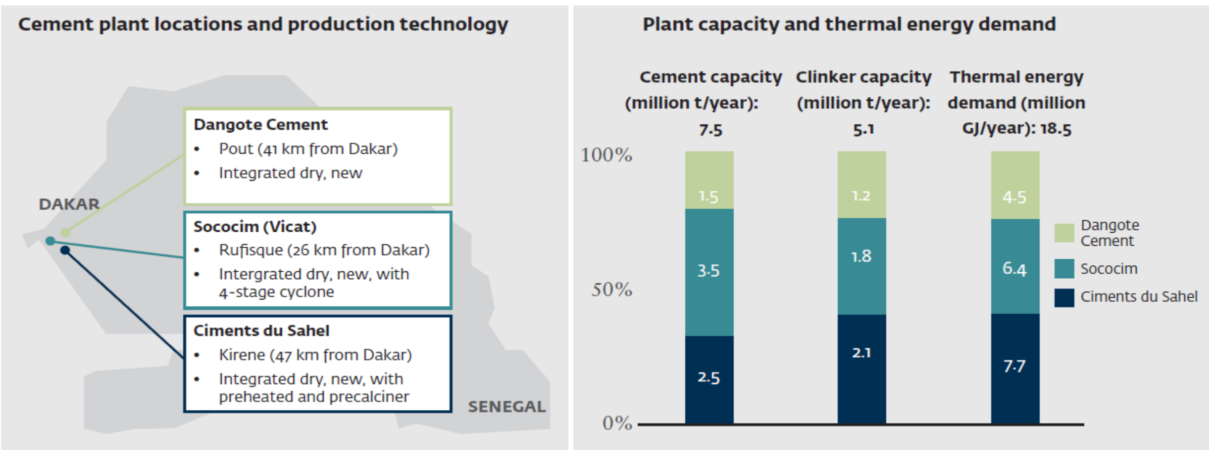


Figure 4-1: Senegal cement plant: location and capacity [7]

4.1.1 Available alternative raw materials

Information regarding potential alternative raw materials in Senegal is rather limited. Nevertheless, reports indicate the presence of significant deposits of Paleocene limestone resources which are situated in the west central section of the sedimentary basin, this emplacement coincides with the location of SOCOCIM [71]. Additionally, other deposits are identified in Bandia, Thiès, and Pout. Notably, these Paleocene limestone deposits are characterized by high-quality calcium carbonate content, reaching as high as 95% $CaCO_3$ [71]. Considering that as much as 50% of clinker can be effectively substituted with ground limestone [49], Senegal's cement sector stands to gain considerable advantages from these extensive deposits. Furthermore, as highlighted in the research conducted by MBAYE *et al.* [80], Senegal possesses abundant clay deposits, thereby presenting an additional potential source of alternative raw materials. Calcined clay emerges as a promising candidate, with the potential to replace approximately 20% of the clinker content in cement production [49]. Additionally, Ndiaye *et al.*'s study delves into another alternative material: volcanic deposits located in Mako within Senegal-Oriental. These volcanic substances have the potential to yield pozzolanic cements, expanding the range of possibilities for sustainable cement production [72].

It is essential to acknowledge that the nation possesses steel and iron factories capable of providing slag waste as a potential resource for the cement industries. Nonetheless, this option has not been explored within the scope of this study due to insufficient information regarding the capacity of steel production and the effective management of the resulting byproduct, slag. Moreover, the steel and iron industry could potentially undergo a transition from its current production process, which employs blast furnaces, to a scrap-based electric arc furnace approach. Such a transition could lead to a reduction in the availability of slag as a supplementary raw material for the cement sector [6].

Therefore, future potential alternative materials for Senegal cement sector could be limestone filler, calcined clay due to abundant quantity located near the production plants.

4.1.2 Alternative fuels

The cement sector in Senegal as many cement sectors around the world relies mainly coal as thermal energy carrier, the energy demand was estimated about 18.5 million GJ per year [7].

Nevertheless, the strategic location of these industries in proximity to Dakar positions them advantageously to tap into the potential of utilizing recycled waste for fuel substitution. Remarkably, an estimated 31% of municipal solid waste is generated in Dakar, further highlighting the city's potential. In 2015, the total waste generation reached about 3.5 million tons, with Dakar contributing 1.1 million tons to this aggregate [7]. An in-depth study conducted by the International Finance Corporation focused on the city of Dakar's 900,000 tons per year of municipal solid waste. Within this context, it was approximated that around 350,000 tons per year of refuse-derived fuel (RDF) could be generated from this waste, equating to a substantial thermal energy potential of 5.5 million GJ [7].

Another promising alternative to coal fuel involves the utilization of agricultural residues. Agriculture holds a substantial economic share, contributing around 17% to the country's gross domestic product (GDP) [74]. Senegal boasts diverse agricultural productions, including crops such as peanuts, maize, rice, sugarcane, and more. The International Finance Corporation has assessed the technical potential of utilizing these residues for cement production, estimating it to be within the range of 3 to 4 million GJ per year of thermal energy [7].

Furthermore, the exploration of wastewater and sewage sludge as potential resources has also been undertaken by the International Finance Corporation in their study of alternative fuels for Senegal's cement plants. In their assessment, they identified a potential output of approximately 18,000 cubic meters per year of dried sludge [7]. Additionally, the country grapples with the generation of millions of waste tires, with Dakar alone accounting for around 100,000 tons per year. The estimated energy potential from this source reaches approximately 2.4 million GJ per year of thermal energy [7]. These alternative resources hold the potential to significantly reduce the reliance on imported coal in the cement sector, thereby yielding substantial reductions in associated carbon dioxide emissions.

4.1.3 Renewable solar, wind, and Green Hydrogen potential

The geographical position of Senegal confers a series of advantages to the country. Situated near the equator and bordered by the Atlantic Ocean, Senegal possesses significant potential for harnessing solar, wind, and hydrogen energy. Benefiting from abundant sunlight year-round, particularly in its northern regions, Senegal is well-suited for the implementation of large-scale solar power projects. Furthermore, the country experiences consistent and robust wind patterns, enhancing its wind energy potential. Indeed, Bilal *et al.* [81] reported an average mean wind speed varies between 4.21 and 5.23 m/s for the dry season and varies between 3.73 and 4.49 m/s for the rainy season at 20 m height. Notably, Senegal has sizeable tracts of land deemed suitable for solar and wind energy development. As assessed by H_2Atlas [79], approximately 21.69% of the country's land area is suitable for solar energy projects, while 18.47% is suitable for wind energy projects. This translates to a formidable potential of 4564.92 TWh/year of solar energy from open field photovoltaic installations and 687.94 TWh/year of wind energy. The average cost of solar and onshore wind electricity is projected (in H_2Atlas Africa [79]) to 1.79 EURct/kWh and 6.31 EURct/kWh, respectively by 2050 [73]. In addition to solar and wind energy, Senegal also possesses a small hydropower potential. The estimated hydropower potential is projected to reach 0.57 TWh/year by the year 2050 [73]. These abundant renewable energy resources position Senegal to significantly diversify its energy mix and potentially reduce its reliance on non-renewable sources.

The least explored energy source in Senegal is biomass energy, despite the fact that agricultural activities contribute significantly to the country's gross domestic product, accounting for 17.2% [74]. However, agricultural activity is widely distributed across the nation, and the residues generated are frequently utilized as fodder for livestock or left on farms. Surprisingly, a substantial portion of these residues, estimated at 50%, is either burned or otherwise utilized on-site, as reported by the International Finance Corporation [7].

Senegal sets a goal for universal electrification by 2025 [62], the country has recently received support from partners including United States Agency for International Development (USAID), the European Union, the World Bank, African Development Bank (ADB) and other European countries [75]. This total electrification which is based mainly on 30% penetration of renewable energy such as wind and solar by 2030, may not be reached by 2025 since in 2020 level of access in the rural area was around 50% versus 78% as target; but, in the far future between 2030 – 2050, this could be achievable. The deployment of renewable may therefore be assisted by the hydrogen production infrastructure as storage option when there will be excess of electricity since the country has in particular a large potential for hydrogen generation due its position in regard to the oceans and existing underground water for electrolysis. The hydrogen produced may be used in some other sectors such as transport and industrial sectors like cement production to replace coal or be reconverted into electricity during peak demands.

This study will incorporate the utilization of solar and wind electricity as potential energy sources to supply the cement industry. These options are particularly attractive due to their lower cost per kilowatt-hour (kWh) compared to conventional sources. Furthermore, the potential of hydrogen will also be explored as a viable pathway for achieving green cement production. Notably, the average cost per kilogram (kg) of hydrogen has been estimated at 1.96 Euros, rendering it a noteworthy consideration for enhancing the sustainability of cement production processes [73].

4.2 Interpretation of the results

What should be noted from the designed scenarios is that clinker replacement plays a very crucial role in cement sector decarbonization, especially in countries where carbon capture technologies would be expensive. The electricity prices will also impact on the decarbonization pathways since, the new routes such as calcined clay uses to replace in some countries, or carbon capture technologies deployment will require substantial amount of electricity, therefore in order to insure a full decarbonization of the cement sector and meet the Paris agreement, sustainable and cost-effective renewable sources would be needed to fulfill the electricity requirement in cement plant.

4.2.1 Current situation

4.2.1.1 Material demand

The designed model has considered the same amount of raw material required for producing a ton of cement in all the three countries. Approximately 1.7 tons of raw materials, with approximately limestone (84.84%), clay (8.56%), sand (4.23%), and iron ore (2.34%) as the major constituents, were utilized for manufacturing one ton of clinker. The composition of cement was derived specifically from each country (adding country's available supplementary cementitious materials). Subsequently, the clinker-to-cement ratio distinct to each country was applied, incorporating additives such as gypsum (5%) and other materials like fly ash, slag, and limestone, among others. The clinker to cement ratio of China, Germany, and Senegal has been provided in Table 3 -3, Table 3-4, and Table 3-5, respectively in the methodology section.

4.2.1.2 Energy demand

A comparison of all the selected countries in terms of energy demand in Figure 4 -2.

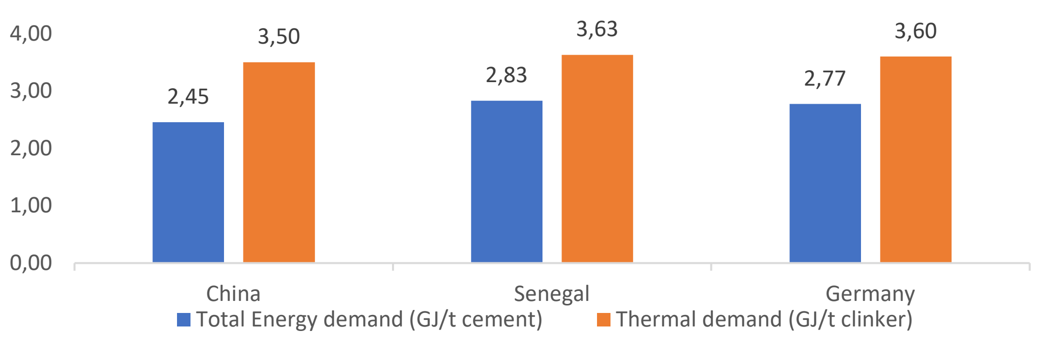


Figure 4-2 : Thermal energy and total energy demand for China, Germany and Senegal in the current situation

The designed model facilitated the estimation of the total energy needed to produce one ton of cement. As depicted in Figure 4-2, the results indicate a comparable thermal energy requirement for manufacturing one ton of clinker across the three countries: approximately 3.5 GJ for China, 3.63 GJ for Senegal, and 3.6 GJ for the German cement sector. However, when considering the total energy demand per ton of cement, the Chinese cement sector emerges as the frontrunner in terms of efficiency. This performance can be attributed to China's low clinker-to-cement ratio of 60.88 and its electricity demand of 90 kWh per ton of cement (refer to Table 3-3). Furthermore, as highlighted by Wei *et al.* [20], the increased utilization of new suspension preheaters and precalciner (NSP) dry kilns in China's cement sector has also contributed to enhanced thermal energy efficiency and improved clinker quality. Notably, Schneider *et al.* [28] reported a widespread implementation of waste heat recovery systems in China's cement industry, leading to a reduction in electrical energy requirements to 90 kWh per ton of cement, compared to 100 kWh per ton for both Germany and Senegal. Germany and Senegal exhibit approximately similar energy consumption levels per ton of cement due to their comparable electricity demands, nearly identical thermal energy requirements per ton of clinker, and approximately equal clinker ratios. Germany's ratio is 67%, whereas Senegal's is 68.5% (see Table 3-4 and Table 3-5).

4.2.1.3 Carbon dioxide emission

The results of the cement sector's carbon dioxide emission are illustrated in Figure 4-3. Country-specific average carbon emissions per ton of cement are depicted, signifying the total emissions in the Figure 4-3. In the current situation, the lowest CO_2 emissions are observed in Germany, approximately 524 kg CO_2 per ton of cement, showcasing a saving of about 90 kg CO_2 per ton of cement compared to China and Senegal’ s cement sectors. China's cement industry emits 609.3 kg of CO_2 per ton of cement, while Senegal emits 612.2 kg per ton of cement, as indicated in Figure 4-3.

These disparities are attributed to distinct clinker-to-cement ratios, emission factors per ton of cement, and notably, the utilization of more environmentally friendly fuels, such as waste-derived fuels and biomass, as alternatives to conventional fuels like coal, petcock, and oil. It is noteworthy that both electricity and process emission factors were taken into consideration. In Figure 4-3, it is evident that process emissions are relatively similar for Senegal and Germany, with 357.0 kg and 352.4 kg of CO_2 per ton of cement, respectively. This consistency aligns with approximately similar clinker ratios observed in these two countries, but also the process emission factor of 526 kg and 525 kg of CO_2 per ton of clinker respectively for Germany and

Senegal (refer to Table 3-4 and Table 3-5). In contrast, China exhibits the lowest process emissions, at 327.7 kg of CO_2 per ton of cement, attributable to its high clinker substitution rate, averaging 60.88% clinker-to-cement ratio, meaning that approximately 39.12% was substituted by cementitious materials, in comparison to Senegal and Germany, with substitution rates of 31.5% and 33%, respectively.

Regarding the energy emission, despite China's significant progress in its cement sector, its energy emission is slightly higher than that of Senegal, at 202 kg per ton of cement compared to 198.9 kg of CO_2, respectively. This discrepancy arises due to China's reported electricity emission factor being about 57% higher than that of Senegal, 0.8834 kg per kWh and 0.563 kg per kWh, respectively (see Table 3-3 and Table 3-5). Both China and Senegal exhibit energy emissions around 70 kg CO_2 higher than those of the German cement industry. This contrast can be attributed not only to the low electricity emission factor but also, more crucially, to Germany's high thermal substitution rate of 68.5%, compared to Senegal's 25% and China's mere 2% (see Table 3-3, Table 3-4, and Table 3-5).

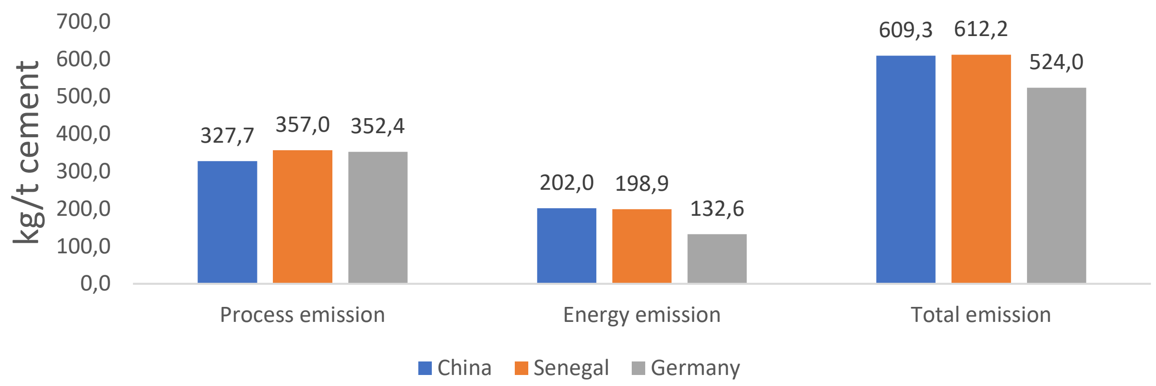


Figure 4-3: Carbon dioxide emission from cement industries

The conclusion that can be derived from this section is that the overall emissions in cement production are intricately tied to two primary factors: the clinker-to-cement ratio and the specific type of energy carrier employed, along with its associated emissions factor.

4.2.1.4 Cost of cement production

The cost of cement production for the three selected countries has been calculated and is presented in Figure 4-4.

The investments and the fixed operational cost were maintained as consistent values across all selected countries, totaling 33.44 Euros per ton of cement. This amount is slightly higher than the one reported by Roussanaly *et al.* [69], which stood at 28.32 Euros per ton of cement.

However, this cost is notably lower compared to the figures reported by Wilhelmsson [48] and Barker [70], which were 39.2 and 38.9 Euros per ton of cement, respectively.

Since the countries share the same CAPEX (Capital Expenditures) and Fixed costs, the variable costs, involving raw materials and energy carriers, are computed and compared. Figure 4-4 illustrates that the overall cost of cement production is notably higher in the Senegal cement sector, at 64.81 Euros per ton of cement, compared to Germany and China, which stand at 55.77 Euros and 53.7 Euros per ton, respectively. These disparities primarily stem from significant differences in electricity prices among the countries. Senegal's electricity price, at 15.8 EURct/kWh, is approximately 3 to 4 times higher than that of Germany and China, at 4.6 EURct/kWh and 4.61 EURct/kWh, respectively (refer to Table 3-6). Additionally, these differences are influenced by the proportions of clinker used. In this study, the costs of alternative raw materials and fuels were slightly lower than those of traditional counterparts, varying between 3 Euros per ton of limestone and 50 Euros per ton of sand or clay, and about 2 Euros per ton of slag to 3 Euros per ton of limestone or calcined clay (refer to Appendix B-4). Therefore, the lower the clinker ratio, the more cost-effective the materials become. Lastly, these variations are also linked to the cost of thermal energy, which ranges from 3 to 4 Euros per gigajoule for coal or natural gas thermal energy, compared to an average of 1.5 Euros per Gigajoule for alternative fuels (refer to Appendix B-4). Consequently, higher substitution of fuels results in reduced energy costs.

However, what is interesting to note is that the cost of production per ton of cement of all the countries falls within the range reported in the literature, ranging between 45.3 Euro [69] to 65 Euro [70] per ton of cement for cement plant without carbon capture.

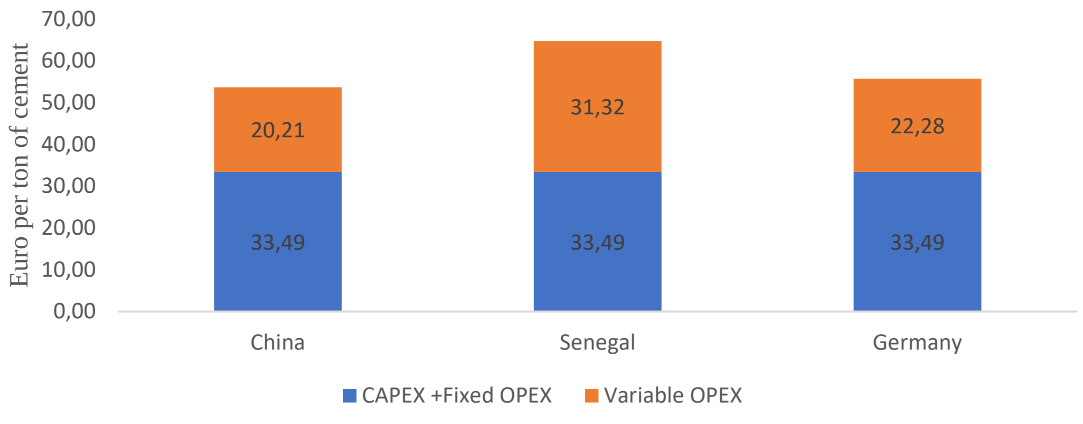


Figure 4-4: cost of cement production in the three selected country

4.2.2 Future representative process routes

In this section, the scenarios for sustainable cement production are interpreted and compared. The scenarios previously defined are applied to the selected countries and compared to one another.

4.2.2.1 Comparison of the scenarios and technologies

As outlined in the methodology section, the assessment and comparison of carbon dioxide abatement and the cost of cement production for the five scenarios are conducted. Alongside the scenario comparison, an evaluation of the three distinct technologies, monoethanolamine, oxyfuel, and plasma technologies is also performed.

4.2.2.1.1 Carbon dioxide emission abatement

In terms of emission reduction, the model reveals that all scenarios (pathways) show promising potential for emission reduction across all selected countries and for any technology of carbon capture used.

Since renewable energy was utilized, scenario 4 employing plasma technology with 100% capture rate displaced zero (0) carbon emission per ton of cement for all the countries (refer to Figure 4-5, Figure 4-6, and Figure 4-7). The emissions resulting from the implementation of these pathways in cement production range from 0 to 33.6 kg of carbon dioxide per ton of cement for Senegal, 0 to 31 kg for China's cement sector, and 0 to 28 kg for the German cement industry. The slight differences in emission ranges across the countries stem from scenario 0, which maintains the current share of alternative materials and fuels, as well as energy consumption, unchanged.

Across the scenarios, minor discrepancies in emissions arise due to variations in energy sources, transitioning from fossil fuels to alternative waste, renewable electricity, or hydrogen. Among the technologies, these differences are attributed to variations in efficiency. Monoethanolamine and oxyfuel carbon capture efficiencies are assumed to be 95% by 2050 ECRA [25], while plasma technology is assumed to have 100% efficiency (as per the study conducted in [48])

Importantly, it should be noted that the captured carbon quantity is higher than the avoided carbon dioxide emissions. This discrepancy is also related to the efficiency of the employed technologies. When carbon capture is integrated into cement industries, additional energy is required to operate the capture units either for the regeneration of solvents in post-combustion technologies or for oxygen purification in oxyfuel carbon capture processes.

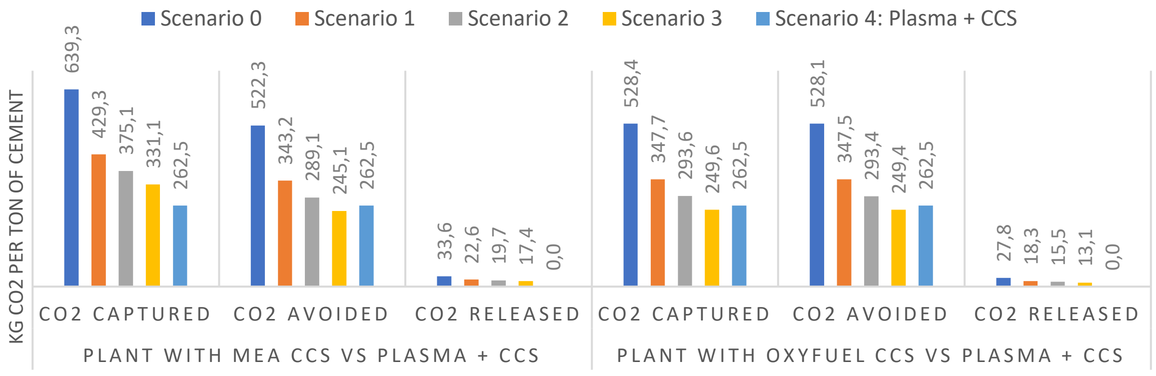


Figure 4-5: Scenario application to Senegal cement industry

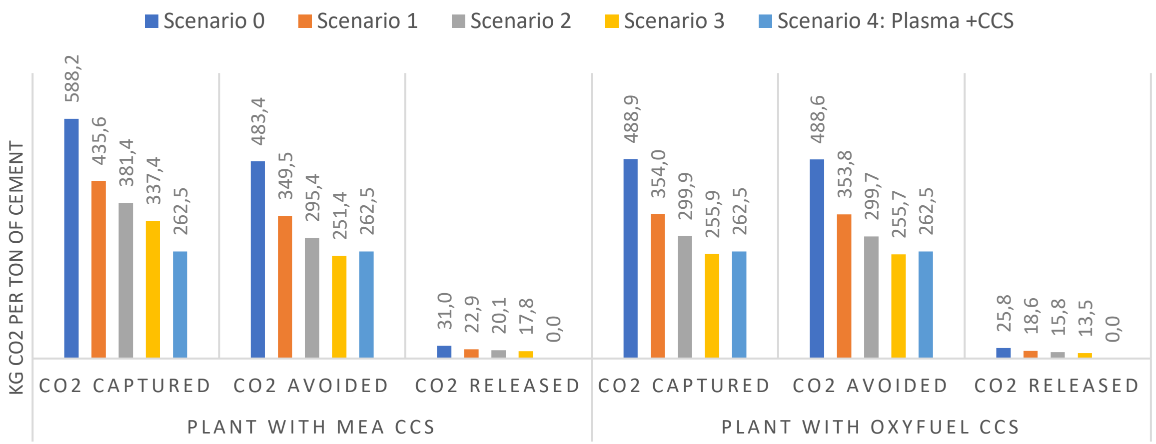


Figure 4-6: Scenario application to China's cement industry

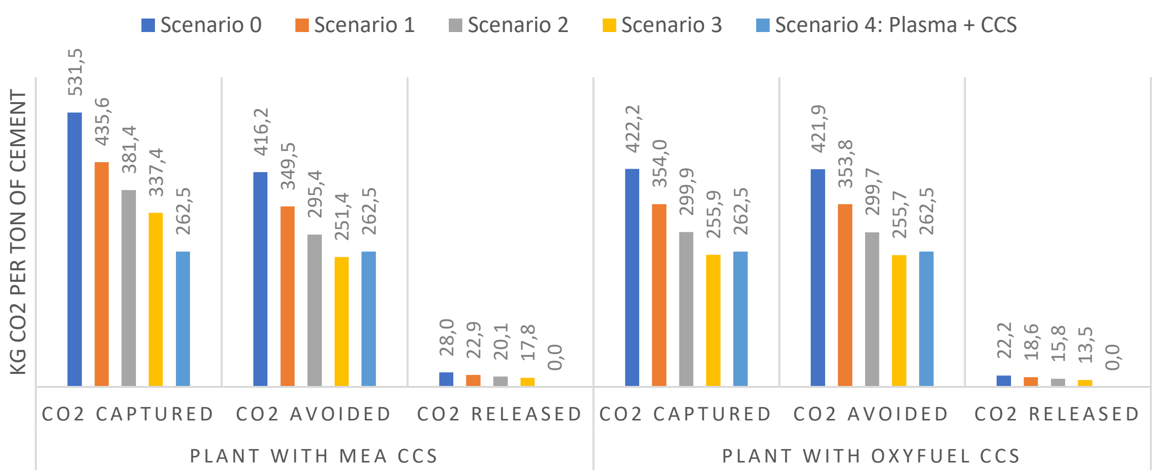


Figure 4-7: Scenario application to Germany's cement industry

4.2.2.1.2 Cost of cement production of the 5 scenarios

As shown in the previous section, there are slight differences across the countries in terms of emission avoidance when the scenarios are applied. The same observation was made in this section as well.

Figure 4-8 illustrates that the cost of cement production under the developed pathways is high compared to the current case. Across the technologies, the cost of cement production varies from 67.2 Euro to 106.9 Euro per ton of cement for MEA technology, while for oxyfuel technology, this amount is slightly lower and ranges between 62 to 100.9 Euro per ton of cement. This is in accord with values found in the literature, which consistently show lower costs for oxyfuel compared to MEA carbon capture. For instance, Barker[70] reported 81.6 Euro for oxyfuel and 129.4 Euro per ton of cement for MEA technology, and Gardarsdottir[68] also reported lower clinker production costs for oxyfuel carbon capture.

However, it can be noted that these prices are lower than that found in the literature, between 80.7 Euro [69] to 129.4 Euro [70] for MEA carbon capture. The difference in these ranges can be attributed to the price of renewable solar electricity used to meet the electricity needs in all the scenarios. In this study, the electricity price is low compared to that in the literature, ranging from 0.0179 to 0.0308 EUR per kWh, whereas the literature reports 0.0581 Euro per kWh [68]. It is also important to indicate that the present work used less amount of clinker, lower energy per ton of cement and high share of alternative fuels with low cost.

Across the selected countries, scenario 0 and scenario 1 favors the Germany cement industry for both technologies used. Meanwhile, Senegal benefits from the designed pathways, particularly scenario 4, due to two key factors: lower electricity prices at 1.79 EURct per kWh, compared to 2.317 EURct and 3.08 EURct for China and Germany respectively. Additionally, in scenario 3, the hydrogen price in the selected countries is 1.96 Euro, 2.771 Euro, and 3.026 Euro per kg of H_2, respectively for Senegal, China, and Germany (refer to Table 3-6).

Across the scenario, the most expensive scenario is scenario 3 where hydrogen was used to meet fully the thermal energy needed to carry out the production of one ton of cement. Future projected hydrogen price, 1.96 Euro, 2.771 and 3.026 Euro per kg were used, therefore, scenario seems to be unlikely unless the cost of hydrogen decreases further, to be able to compete with the other pathways. Even electrified kilns with plasma technology appeared to be affordable for all the countries, this is due to reduced prices of electricity in the three countries because of cheap solar electricity by 2050 (refer to Table 3-6).

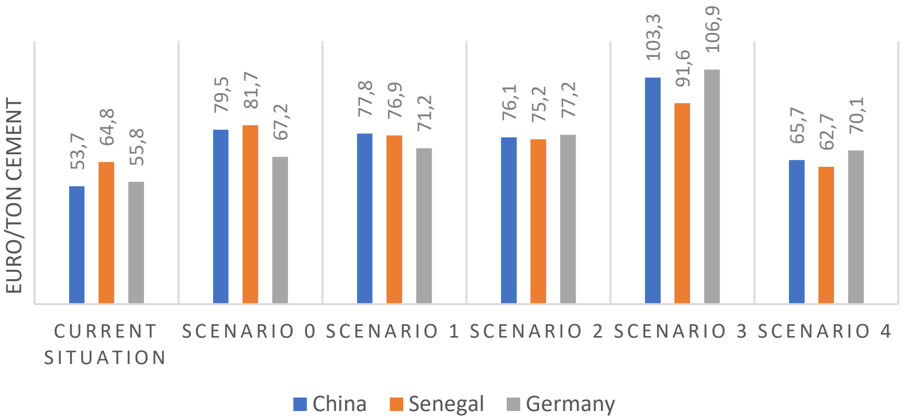


Figure 4-8: Cost comparison between the business-as-usual and the designed pathways with MEA carbon capture technologies

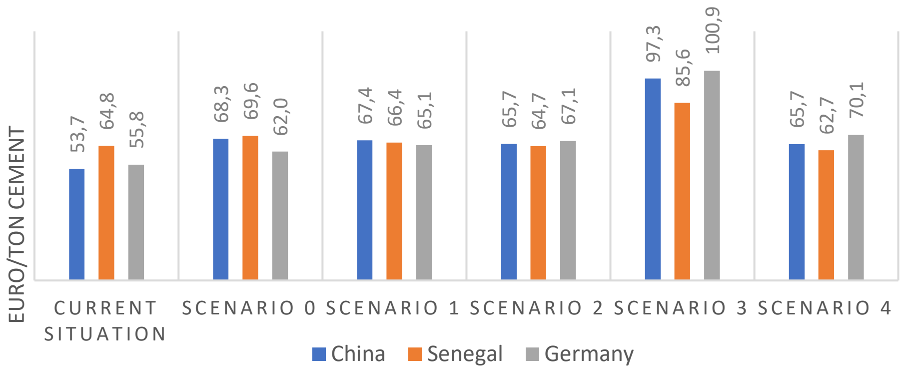


Figure 4-9: Cost comparison between the business-as-usual and the designed pathways with oxyfuel carbon capture technologies

4.2.3 Application process rout in Senegal cement sector

4.2.3.1 Comparison between current scenario and the designed scenarios

The designed model shows in Figure 4-10 that, the current cement production process in Senegal releases about 612.2 kg per ton of cement, where 357 kg is process related and 198.9 kg is energy related. However, for the design scenarios the emissions vary between 0 to 33.6 kg per ton of cement produced. In these pathways, emission related to the process, or the energy utilized, are captured by carbon capture technologies. Therefore, all the scenarios are good option of Senegal cement sector to reduce or neutralize its carbon dioxide emissions.

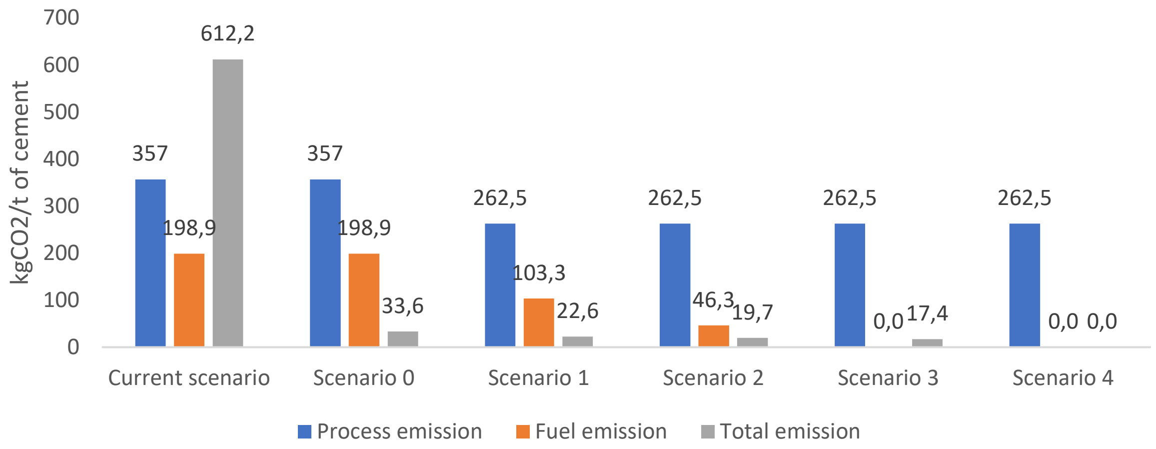


Figure 4-10: Carbon dioxide emission from cement sector in Senegal: current state vs Future potential state of CO_2 emission per ton of cement.

4.2.3.2 Projection of Senegal cement sector and the associated carbon dioxide emission

The population of Senegal is estimated to reach 18,449,572 people at the end of 2023, with a growth rate which has increase from 2.76% to 3.1% between 2020 and 2023 [78], and a GDP growth at 6.1% per year. Furthermore, the urbanization rate was estimated at 3.59% per year. This trend is likely to drive an increase in cement demand, necessary for the construction of essential infrastructure, roads, and railway systems, among other projects. Historically, the cement demand has exhibited significant growth, with an 8% increase observed between 2010 and 2015 [7]. This section aimed at protecting the cement demand by 2050 compared to the trend in 2016. Additionally, the greenhouse emissions associated to cement production was established and compared: business-as-usual, in which there is no change in current cement production process and NetZero emission scenario where the previously developed pathways for sustainable cement production were applied. The growth rate was taken as 3% per year until 2050 with regards to the GDP and urbanization growth. The formula below was used to determine the amount of cement in 2050. This method was also used by Roche in her study for Nigerian's cement sector [67].

$$Demand_{2050} = Capacity_{2016} \times (1 + growth\ rate)^{(2050-2016)}$$

The results are displaced in the Figure 4-11.

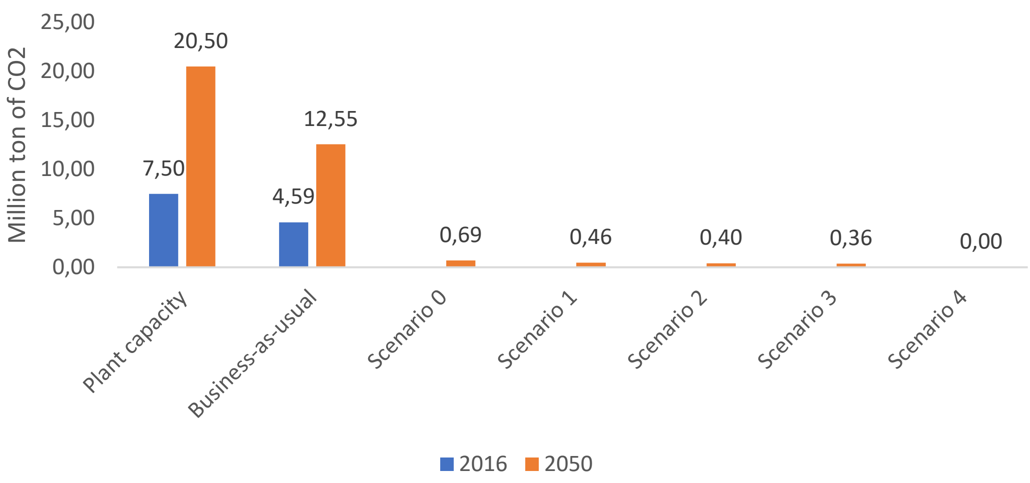


Figure 4-11: Future projection of Senegal cement sector: capacity and CO_2 emissions

The figure shows that Senegal's cement factories could potentially produce 20.5 million tons of cement by the year 2050. Consequently, if there is no alteration in the measures aimed at reducing carbon dioxide emissions, the emissions are projected to increase roughly 4.6-fold, escalating from 4.59 million tons of CO_2 in 2016 to 12.55 million tons of CO_2 in 2050. However, in the scenario where carbon dioxide reduction strategies including clinker and fuel substitution, hydrogen utilization, process electrification and carbon capture technology, are implemented within the cement sector, the cement industry could achieve a state of approximate carbon neutrality. As displaced in Figure 4-11, the cement sector would release between 0 to 0.69 million de ton of CO_2 per year.

4.3 Sensitivity Analysis

In this section, various analyses were conducted with a focus on cost variations. It is crucial to note that there are several methodologies to pursue this, encompassing factors such as capital costs, operational expenses, plant lifespan, fuel costs, and more [23], [68]. The objective is twofold: to validate the developed model and to identify the most cost-effective pathways.

For this study, two specific scenarios were chosen: first, the imposition of a carbon cost amounting to 60 Euros per ton of carbon dioxide, and second, an exploration of the influence of electricity prices on the overall cost of cement production. To facilitate this investigation, the Senegal cement sector was exclusively selected. The ensuing results of this analysis are presented below. Only the case of Senegal’s cement sector was chosen to conduct this analysis.

4.3.1 Cost of carbon of 60 €/t CO_2

The developed model facilitated a comprehensive comparison of the cost of cement production between the existing scenario and the envisioned future process routes. It is crucial to acknowledge that the current scenario employs distinct parameters with varying costs from those of the future scenario outlined in Chapter 3. The current scenario is characterized by a 68% clinker ratio, 3.68 GJ/t clinker, 100 kWh/t of cement, and 75% coal usage. In contrast, the future scenarios assume improvements in all these parameters (detailed in Table 3-2 and Table 3-5).

The outcomes obtained from this evaluation are graphically represented in Figure 4-12. These results illustrate that, without the inclusion of carbon costs, the cost of cement production exceeds that of the current context across all scenarios employing monoethanolamine carbon capture (from scenario 0 to scenario 3) as well as in cement plants integrating oxyfuel technology. The disparities range from 10.5 Euros for Scenario 2 utilizing 100% alternative fuels to 34.6 Euro for Scenario 3 employing 100% hydrogen. Conversely, when plasma technology is implemented within the pathways, the production cost approximates the cost of the current cement production due to lower electricity cost, 0.0176 Euro compares to 0.158 Euro per kWh.

However, across all scenarios encompassing MEA, oxyfuels, or plasma technologies, the introduction of a carbon price of 60 Euros per ton of emitted carbon significantly enhances cost-effectiveness compared to current cement production. The cost of cement production in the current scenario increases to 98.2 Euros per ton of cement, for which even the most expensive scenario (scenario 3 with MEA carbon capture) can compete. Therefore, carbon price can play an important role in accelerating the industry's transition and making zero-carbon cement cost advantageous.

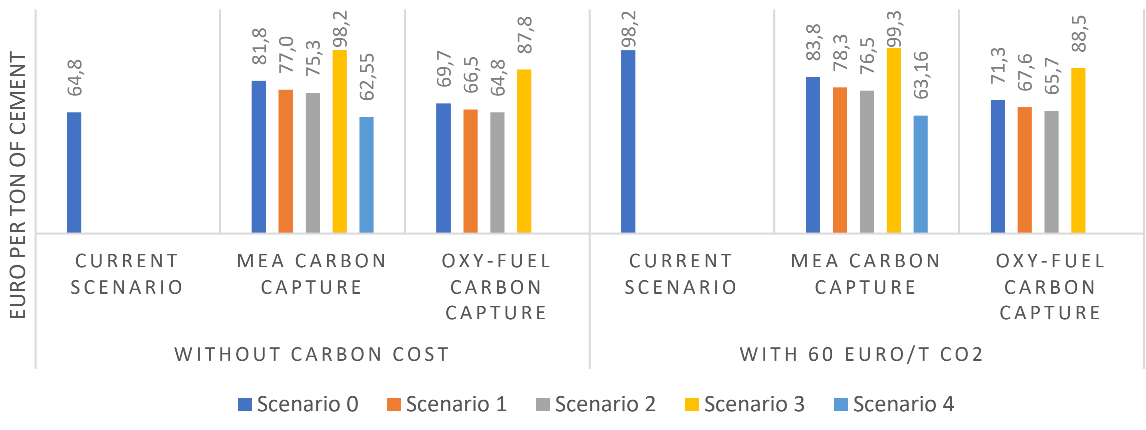


Figure 4-12: Impact of carbon cost of the cement production in Senegal cement factory

4.3.2 Impact of electricity cost on the process routes

This was accomplished by considering various electricity sources, which encompass grid electricity, solar energy, and wind energy. Given the considerable cost discrepancies between these sources – grid electricity at 0.158 Euros/kWh, photovoltaic energy at 0.0176 Euros/kWh, and wind energy at 0.0631 Euros/kWh, this approach was employed to assess the influence of electricity prices on representative process routes.

The result is presented below in the Figure 4-12

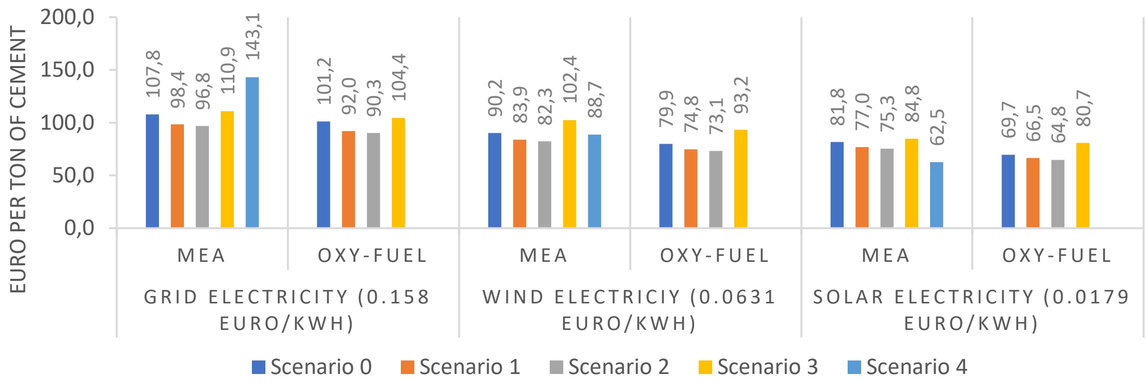


Figure 4-13: Impact of electricity prices on the design pathways for sustainable cement production

Figure 4-13 illustrates that grid electricity does not support any of the formulated pathways, a concern that amplifies when considering the potential indirect emissions associated with electricity importation. This issue is particularly pronounced in scenario 4, where the exclusive use of electricity is employed by plasma technology. Furthermore, in all scenarios, a rise in electricity prices (progressing from solar to grid electricity) results in an increase in the cost of cement production.

Scenario 3 is still in high cost even when the cheapest pathway is considered, however this is due to the cost of hydrogen, projected to be 1.96 Euros per kg in Senegal by 2050 (as per H_2 Atlas [79]).

Consequently, the overarching conclusion is that the lower the cost, the more economically effective and encouraging the implementation of these pathways becomes within Senegal's forthcoming cement production landscape. As previously highlighted, the nation boasts substantial potential in solar and wind energy, and capitalizing on this potential can play a pivotal role in the decarbonization endeavors of sectors emitting carbon dioxide, such as the cement industry.

Chapter 5: Conclusion and Recommendations

5.1 Conclusion

Cement is one of the most consumed materials around the globe. Despite the associated CO_2 emission, countries worldwide continue to produce million tons of cement every day for the construction of new roads, bridges, buildings, dams, and others. The cement sector contributes to approximately 8% of global carbon dioxide emissions.

All sectors worldwide must achieve NetZero greenhouse gas emission to stay in line with the Paris climate agreement. While it looks easier to decarbonize sectors like power generation or transportation in which the emissions are related to energy carriers. Decarbonizing cement industry is complex since energy-related emission only represents about 40% of the total and the rest is due to the calcination process. This research has proposed important measures aimed at transforming the cement production to a more environmentally friendly process, not only within Senegal but also on a global scale.

The investigations have shown a combination of strategic approaches, including clinker and fuel substitutions, electric processes, and carbon capture, constitutes a promising pathway towards a substantial reduction in carbon dioxide emissions. This pathway could potentially lead to a reduction ranging from 0 to 33.6 kg per ton of cement, in contrast to the current emissions range of 524 kg to 612.2 kg per ton of cement within the selected countries. The adoption of alternative fuels like biomass and hydrogen, along with the implementation of electrification processes hold the potential to effectively eliminate or substantially reduce carbon dioxide emissions originating from energy consumption. While the process-related emission could be reduced by reducing clinker-to-cement ratio, for 50% clinker ratio about 50% of the process emission could be eliminated. However, achieving low carbon dioxide emissions from cement production requires the integration of carbon capture technology. However, it is worth noting that technologies like MEA carbon capture demand 3.07 GJ/t of clinker in thermal energy, compared to conventional cement plants without carbon capture [54].

Furthermore, the analysis of both present and future process routes has provided insights into the potential pathways for the cement sector in Senegal. Thorough exploration of alternative materials, fuels, and renewable energy sources highlights the Senegalese cement industry's capacity to significantly reduce its carbon footprint. By integrating carbon capture technologies, emissions can even be reduced to zero.

Senegal cement production capacity was projected by 2050 at 20.5 million ton of cement which will require carbon dioxide reduction strategies, otherwise carbon dioxide emission from the cement sector will rise from 4.59 to 12.55 million ton per year.

It is important to also highlight the cost of electricity as well as the cost of carbon emission which could also play an important role in the deployment of the developed scenarios. The lower the cost of electricity the lower the cost of cement production for the designed pathways. Also, for carbon cost of 60 euro per ton, the prospect pathways are more cost effective. Low hydrogen cost will furthermore make the scenario 3 viable option.

The pathways illuminated by this study can serve as comprehensive plan for modelers, policymakers, industry leaders, stakeholders to collaboratively design a future where the cement industry plays a role in achieving the Paris agreement.

5.2 Recommendations

Based on the comprehensive analysis of the present and potential future process routes for the global cement sector, including pathways for Senegal, Germany and China cement sector, the recommendation that can be drawn from the results of this study are the following:

1. Governments, academic institutions, and industry leaders around the world in general and regions like China, Germany, and Senegal in particular should invest in research and development.
2. Improved, efficient and low-cost technologies of carbon capture, waste heat recovery and renewable electricity sources need to be implemented.
3. Industry associations and educational institutions should offer training programs that equip professionals with the skills and knowledge required for sustainable cement production.
4. Policymakers in Senegal and all across the globe should actively collaborate with industry experts and environmental scientists to develop policies that promote and encourage.
    - The use of alternative fuels,
    - The substitution of clinker,
    - Kiln electrification
    - Carbon capture integration.

These regulations could contribute to sustainable cement production.

5. Cement producers should set their emission reduction targets, therefore investing in clean technologies and reporting continuously the impacts of their operation.

By implementing these recommendations, Senegal cement sector can transition towards more sustainable cement production.

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Appendix A: Generic Calculation

Appendix A-1: Generic table for Material demand calculation

Material demand	Share (%)	Unit	Weight
Raw materials	/	t/ton of cement	1.58
Raw materials	/	t/ton of clinker	1.7
Main raw materials			
Limestone	80	kg	1360
Clay	12.4	kg	210.8
Sand	3.7	kg	62.9
Iron ore	3.9	kg	66.3
Clinker Material	/	ton	1
Clinker ratio	95	kg / ton of cement	950
Supplementary cementitious materials	0	kg / ton of cement	0
Fly ash	0	kg	0
GGBFS	0	kg	0
Pozzolans	0	kg	0
Limestone	0	kg	0
Calcined clay	0	kg	0
Others	0	kg	0
Gypsum	5	kg/ ton of cement	50
Cement	/	ton	1

Appendix A-2: Generic table for Energy demand calculation

Energy demand	Share (%)	Unit	Value
Wet process	/	GJ/t clinker	6.1
Thermal energy	/	GJ/t cement	5.795
Fossil fuels	80	GJ/t cement	4.636
Coal	40	GJ	2.318
Gas	30	GJ	1.7385
Oil	/	GJ	/
Petcock	/	GJ	/
Alternative fuels	15	GJ/t cement	0.86925
Tires	/	GJ	0
Refused derived fuel	/	GJ	0
Plastics	/	GJ	0

Mixed industrial waste	/	GJ	0
impregnated saw dust	/	GJ	0
Waste oil and solvent	/	GJ	0
Biomass	5	GJ/t cement	0.28975
Dried sewage sludge	2	GJ	0.1159
Agricultural Waste	8	GJ	0.4636
Animal Meal	/	GJ	0
Wood, non-impregnated saw dust	/	GJ	0
Paper, cardboard	/	GJ	0
Electricity	/	kWh/t cement	100
Total energy demand	/	GJ/t cement	6.155

Appendix A-3: Generic table for carbon dioxide emission calculation

Carbon dioxide emission	**Emission factor**	CO_2 **emission (kg)**
Process emission	525 kg/t of clinker	498.75
Fuel emission	/	319.884
Fossil fuels	$kgCO_2/GJ$	319.884
Coal	96	222.528
Gas	56	97.356
Oil	/	/
Petcock	/	/
Alternative fuels	/	/
Tyres	62	/
Refused derived fuel	36.6	/
Plastics	75	/
Mixed industrial waste	/	/
impregnated saw dust	39.4	/
Waste oil and solvent	74	/
Biomass	0	/
Dried sewage sludge	0	/
Agricultural Waste	0	/
Animal Meal	0	/
Wood, non-impregnated saw dust	0	/
Paper, cardboard	0	/
Electricity emission	0.5	50

Total CO_2 emission (kg/t cement)		868.634

Appendix B: Cost of technologies, energy carriers and materials

Average exchange rate in 2023: 1.0862 USD.

Appendix B-1: CAPEX

Plant W/O CCS	Investment (M€)	Capacity (Mt of cement)	Plant lifetime (year)	discount rate(%)	CAPEX (M€)
Roussanaly	202.13	1.36	25	8	148.6
Barker	263	1	25	10	263.0
Gardarsdottir	204	1.36	25	8	150.0
Plasma	231	1.35	25	8	171.1
Average					183.2

Plant with MEA CCS	Investment (M€)	Capacity (Mt of cement)	Plant lifetime(year)	discount rate (%)	CAPEX (M€)
Roussanaly	309.3	1.36	25	8	227.43
Barker	558	1	25	10	558.00
Gardarsdottir	280	1.36	25	8	205.88
Average					330.44

Plant with Oxyfuel CCS	Investment (M€)	Capacity (Mt of cement)	Plant lifetime(year)	discount rate(%)	CAPEX(M€)
Barker	327	1	25	10	327.00
Gardarsdottir	332	1.36	25	8	244.12
Average					285.56

Appendix B-2: Fixed OPEX

Cost of cement plant (Eur/t cement)	Plant W/o CCS	Plant with MEA CCS	Plant with Oxyfuel CCS
Fixed OPEX	16.33	19.64	22.8

Appendix B-3: Other Variable Cost

Plant W/O CCS	Cost (M€)	Capacity (Mt)	Cost (€)
Millaceous material	0.72	1	0.72
Cooling water	0.02	1	0.02
Cement plant Other OPEX	/	/	0.74
ORC invest cost	0.48	1.55	0.309677419
O & M of ORC	0.27	1.55	0.174193548
Other Variable cost	/	/	1.223870968

Plant with MEA CCS	Cost (M€)	Capacity (Mt)	Extra Cost (€)
MEA	2.47	1	2.47
Ammonia	0.37	1	0.37
Additive Inhibitor	0.49	1	0.49
Catalyst for SRC	1.19	1	1.19
Limestone	0.04	1.36	0.029411765
Cooling water	1.02	1.36	0.75
Other Variable cost	36.3235	/	5.299411765

Oxyfuel CCS	Extra Cost (€)
Limestone	0.032
Sea water	0.23
Water Cooling	0.04
Others	0.02
Total	0.322

Appendix B-4: cost of materials and energy carriers

Cement plant inputs	Unit	Cost	Reference
Materials	/	/	
Limestone	€/t	3	IEAGHG
Shale/clay	€/t	1.5	IEAGHG
Sand	€/t	50	IEAGHG
Iron Ore	€/t	50	IEAGHG
Gypsum	£/t	6	Driver

Alternative raw materials			
Fly ash	£/t	2	(a)
Slag	£/t	2	Driver
Limestone	€/t	3	IEAGHG
Calcined clay	€/t	3	Double of clay price (b)
Pozzolans	€/t	2	(a)
Fuels	/	/	/
electricity	€/MWh	58.1	Roussanaly *et al.*
Coal	€/GJ	3	Roussanaly *et al.*
NG	€/GJ	4.4 / 3.6 / 3.2	ECRA
Alternative Fuels	**€/GJ**	**1.5 / 1.5 / 1**	**ECRA**
RDF	$/GJ	2.5	IFC
Tires	$/GJ	2.1	IFC
Peanut shells	$/GJ	1.5	IFC
Agri-residue	$/GJ	4	IFC
Hydrogen	€/GJ	3.2 / 2.2 / 1.5	ECRA

a: assumed similar to the price of slag.

b: assumed due to clay process cost requirements