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"Techno-Economic Analysis of Solar Calcination for Cement Plants Including Calcium Looping for CO_2-Neutral Operation"

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Title of Master Thesis

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Motivation

One of the world's significant challenges today is the emission of greenhouse gases, such as carbon dioxide and other chemicals that cause global warming. It is more important to find a sustainable fuel source as both the world average temperature and energy demand rise. Long-term prevention of catastrophic climate change is made possible by working toward emission reductions processes from the industries. Being an energy engineering student and environment enthusiast, I have always desired to contribute in the work which processes towards green and sustainable world.

Aim of Master thesis

Cement production is one of the most energy- and CO_2-intensive industrial industries in the world. It contributes to 8% of all global anthropogenic GHG emissions. The calcination process of raw materials is responsible for 60% of the carbon emissions in a cement factory [1]. Thus, efficient decarbonization strategies should be put into practice in order to meet the worldwide targets for lowering global greenhouse gas emissions. This works mainly concentrated on techno-economic evaluation of cement production by using concentrated solar power for calcination and involving calcium looping for the carbon capture. The technical analysis is performed through detailed process modelling and simulation via Aspen Plus V12.1 including mass and energy balances. In the economic study contains capital and operating cost estimations based on technical and financial parameters.

The task list contains the following points:

1. Literature review of conventional cement plant and its solarization
2. Model development of a solarized cement plant in Aspen Plus and annual performance
3. Comparison of costs and CO_2-emissions from solarized process
4. Variation of solarization extent to assess influence on cost and emissions

Literature

[1] Daniele Ferrario, Stefano Stendardo, Vittorio Verda, Andrea Lanzini, "Solar-driven calcium looping system for carbon capture in cement plants: Process modelling and energy analysis", Journal of Cleaner Production, Volume 394, 2023, 136367, ISSN 0959-6526,

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Your sincerely,

Harshavardhan Reddy Tharla

11.09.2023, Magdeburg.

Word of Declaration

I hereby declare that I prepared the work submitted without inadmissible assistance and without the use of any aids others than those indicated. Fact or ideas taken from other sources, either directly or indirectly have been marked as such. Further I have not made payments to third parties either directly or indirectly for any work connected with the contents of the submitted report. The work has not so far submitted either in Germany or abroad in same or similar form as a report and has also not yet been published as a whole.

Harshavardhan Reddy Tharla

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Abbreviations:

ASU	Air separation unit
BAT	Best Available technique
CAC	Carbon avoidance cost
CaL	Calcium Looping Technology
CAPEX	Capital expenditure
CC	Carbon Capture
CCS	Carbon capture and storage
CentRec	Central Receiver
CEPCI	Chemical engineering plant cost index
COC	Cost of cement
CRM	Cement Raw Meal
CSP	Concentrated Solar Power
DCC	Direct contact cooler
EPC	Engineering, Procurement and Construction
GHG	Greenhouse gases
HFLCAL	Heliostat field layout calculations
LFR	Linear Fresnel Reflector
MAL	Membrane Assisted Liquefaction
MEA	Monoethanolamine
OPEX	Operational expenditure
RCC	Regenerative calcium cycle
SM	Solar Multiple

Nomenclature:

C	Carbon
C_2S	Dicalcium silicate
C_3A	Tricalcium aluminate
C_3S	Tricalcium silicate
C_4AF	Tetracalcium aluminoferrite
$CaCO_3$	Calciumcarbonate
CaO	Calcium oxide

Cl	Chlorine
CO_2	Carbon dioxide
CSH_2	Gypsum
H_2	Hydrogen
H_2O	Water
N	Nitrogen
NOx	Nitric oxides
O	Oxygen
S	Sulphur
SOx	Sulphur oxides

Subscripts

t_{clk}	Tonne clinker
t_{cem}	Tonne cement
t_{CO2}	Tonne CO_2
$C_{heliostat}$	Cost of heliostat
$C_{R,\ kiln}$	Cost of Rotary kiln
$C_{transport}$	Cost of transport system
$C_{preheater}$	Cost of preheating system
$C_{carbonator}$	Cost of carbonator
$C_{milling}$	Cost of milling and drying
C_{conv}	Cost of conventional plant
$C_{clinker}$	Cost of Clinker
C_{cement}	Cost of Cement

Abstract

Given the growing worldwide worries about climate change and carbon emissions, the switch to sustainable and environmentally friendly industrial operations is now essential. This report offers a thorough techno-economic analysis for solar calcination as an innovative approach for making cement that incorporates calcium looping technology for enhanced carbon capture. Significant potential exists for lowering energy use and greenhouse gas emissions in the cement manufacturing process by using concentrated solar energy in the calcination process. This work evaluates the technical feasibility, economic viability and environmental benefits of integrating a concentrating solar power system and calcium looping into the cement calcination process. The examination covers a wide range of topics, such as process modelling, different solar multiple cases, concentrating solar power plant modelling and optimization, solar energy collection and conversion, carbon capture efficiency and cost effectiveness. The adoption of solar calcination and calcium looping in cement production is also examined with potential prospects and difficulties. The finding of this study contribute valuable insights in to integrated approach to revolutionize the cement industries, by paving the way for low-carbon, sustainable cement production while addressing the urgent need for carbon reductions. According to the results, CO_2 emissions can be decreased by 79 % with the solar multiple case of 3.75, and the estimated price of the final product and CO_2 avoidance cost will be 116 $\$/t_{cem}$ and 110 $\$/t_{CO2}$ respectively.

1 Introduction

Concrete, the primary building material used to construct homes, bridges, highways, dams and numerous other infrastructures, is produced mostly from cement. Over the past few decades, the demand for the production of cement have accelerated as a result of the ongoing global economic growth. Cement production requires a substantial amount of energy and natural resources, and it is one of the major sources of CO_2 emissions. Cement production accounts for 8 % of global anthropogenic GHG emissions, around 1.4 Gt of CO_2 emissions per year [25]. Hence, to achieve the international targets reducing the global greenhouse gas emissions, effective decarbonization measures should be implemented.

The cement production process consists of mainly three steps, they are (i) the extraction and processing of raw materials; (ii) the manufacturing of clinker, and (iii) the mixing and milling of cement [25]. Among these, the clinker production process is the one that uses the most energy and produces the most carbon. In the clinker manufacturing process pre-calcining technology has been widely used to replace some of the outdated production techniques, such as the shaft kiln process, in response to the continuously rising demand for the cement. The calciner is the one of the key equipment in the process, and mainly undertakes the partial fuel combustion, gas-solid heat exchange, and a large portion of raw material decomposition. The process raw material is a fine powder known as "raw meal" that mostly consist of calcium carbonate ($CaCO_3$) with the inclusion of oxides containing silicon (Si), iron (Fe) and aluminum (Al). The raw meal is burned in a kiln until it reaches the sintering temperature during the clinker production process. When the $CaCO_3$ is calcined, it interacts with SiO_2, Fe_2O_3, and Al_2O_3 to produce clinker, which is the primary component of cement. In the end, cement is produced by milling the clinker along with gypsum and other additives.

During the cement manufacturing process, particularly clinker production stage, CO_2 emissions account 40 % from the fuel combustion and remaining 60 % are being linked with calcination process and thus difficult to abate [45, 61]. The most popular decarbonization techniques currently involved are replacing clinker and raw meal with substitute materials, lowering the clinker to cement ratio, switching from conventional fuel to less carbon-intensive fuels, and improving in energy efficiency [24]. Technologies for Carbon Capture and Storage (CCS) must be used to effectively decarbonize the cement industrial sector. Different CO_2 capture technologies have been investigated to be integrated in a cement production process, including oxy-combustion, post-combustion absorption, membranes and Calcium looping (CaL) [45]. CaL is one of the promising technologies for CO_2 capture in the cement industries. It is based on the high temperature, reversible reaction between CaO and CO_2. In the carbonator reactor operating around 650 °C, the exothermic carbonation reaction takes place when flue gas containing CO_2 is brought into contact with a solid stream containing CaO [45]. Considering that cement factories already have the infrastructure required for processing solid materials, the integration of CC-CaL with cement manufacturing is especially interesting. Since the CO_2 sorbents adsorption capacity declines with the quantity of carbonation and calcination cycles, some of the solid recirculating in the CC-CaL must be purged in order to ensure an adequate level of CO_2 adsorption. The manufacturing of clinker can use this mineral, which primarily consists of CaO, in place of usual raw material, which lowers the calcination processes in the kiln to reduce CO_2 emissions [25]. CC-CaL is already demonstrated in several pilot-projects and attained a lot of attention in the industries for carbon reduction [22, 32].

The combustion of carbon-based fuels provides the reaction heat in conventional procedures. Under these circumstances, combustion contributes to around 40 % of the total CO_2 emissions. Hence, switching to renewables from fossil combustion during the calcination of limestone can reduce CO_2 emissions by 40 % [22]. CaL has also been investigated for use of thermo-chemical energy storage system (TCES) in concentrated solar power plants (CSP) [7]. Innovative solar driven CaL have been proposed by several researchers in the literature for improving carbon capture in the coal power plants. In this instance a heliostat field is used to provide all or some of the energy required for sorbent regeneration [79]. Some authors also proposed hybrid solar and coal-driven clinker production where a solar calciner is used in the raw meal calcination [52].

This work mainly concentrates on the techno-economic analysis of the cement production integrated with solar-driven calcination including CaL system for the carbon capture. The design subject is to reduce the CO_2 emissions by both coal consumption and calcination. The analysis consists of detailed process modelling, CSP plant analysis for yearly operation and economic aspects. The work was carried out for different solar multiple cases targeting the emission and fossil fuel reduction.

2 Literature Review

2.1 Cement Overview

A brief introduction to the properties and manufacturing process of the cement is given at the outset of this section. Followed by the effects of the cement production on environment and variety of solutions that have been used over the years are discussed.

2.1.1 Cement characteristics and Properties

Cement is a commonly utilized building material that is essential to the construction of infrastructure all over the world. Cement is among the most produced material globally due to its broad use in construction activities, low cost, and geographical abundance of its key raw components [35].

Concrete, a building material is basically made up of cement. Cement and water bonded together with aggregate make a paste that combines with sand, rock and hardens to produce concrete [26]. The contribution of cement and other components to the creation of concrete is shown in Figure *1*.

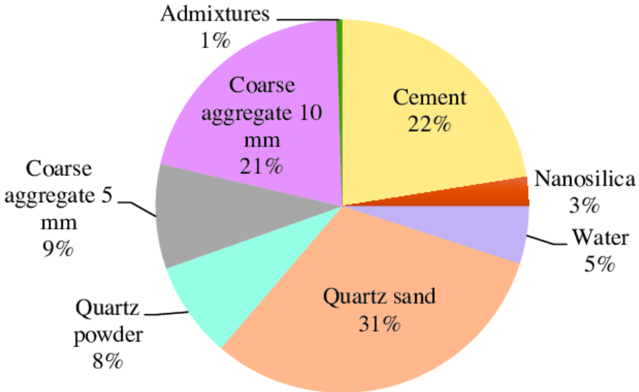

Figure 1. Composition of concrete mix [66]

Cement is made up of calcium silicates, calcium aluminates and calcium aluminoferrite minerals. It is formed from a variety of raw materials, with calcium carbonate serving as a main source of lime which is needed to combine with the cement minerals silica, alumina, and iron oxide [27]. The secondary raw materials used to make the silica, alumina, and iron oxide are aluminium silicate clays and shales, silica sand, bauxite and iron ore [46, 65]. These raw components are combined to create a fine, well blended powder, which is transported to a cement kiln. The materials react with one another in the kiln during the heating process to produce an intermediate clinker, this is then ground with gypsum to produce the finished product [4].

The finished cement product is finely ground, inorganic, non-metallic compound having hydraulic binding capabilities. As previously described when it is combined with water, cement creates a strong, hard paste that holds the sand and rocks together in mortar or concrete due to the formation of calcium silicate and aluminate hydrates. Portland cement is one of the most used cement currently which consists 95 % of clinker and 5 % of gypsum. The gypsum is pulverized along with the cement clinker to regulate the settings of cement and allows mortars to put into molds and place around reinforcements [37].

2.1.2 Cement Clinker

Cement is majorly composed of clinker components which is formed during the intermediate stage of the manufacturing. It is made by sintering clay and other aluminosilicate minerals during the cement kiln stage [9]. The clinker essentially contains four minerals where two of them are calcium silicates, tricalcium silicate known as Alite (C_3S) and Dicalcium silicate called Belite (C_2S) along with tricalcium aluminate (C_3A) and Tetracalcium aluminoferrite (C_4AF) [54, 70]. The weight composition of clinker components and gypsum in cement are listed in *Table 1*.

Table 1. Chemical composition of Cement [54]

Name	Formula	Shorthand	Weight %
Tricalcium silicate	$3CaO.SiO_2$	C_3S	55-60
Dicalcium silicate	$3 CaO.SiO_2$	C_2S	15-20
Tricalcium aluminate	$3 CaO. Al_2O_3$	C_3A	5-10
Tetracalcium aluminoferrite	$4 CaO.Al_2O_3Fe2O_3$	C_4AF	5-8
Gypsum	$CaSO_{4.2}H_2O$	CSH_2	2-6

2.1.3 Cement production

Cement production is key indicator of economic development and construction activity in a country. Global cement production showed consistency level trends in the years before 2021. The demand for cement was primarily driven by reasons such as quick urbanization, rising population, and more infrastructure projects. The global production rate of cement in recent years is shown in *Figure 2*. In the year 2021, almost 4300 Mt of cement was produced and expected to be constant in the upcoming years [38].

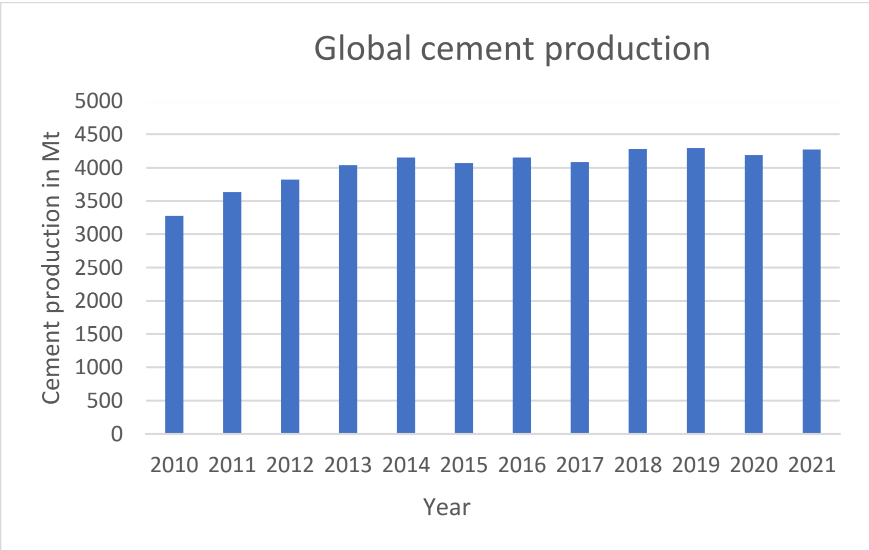

Figure 2. Global cement production [38]

To meet the rising demand for cement while taking the ecological effects into account, technical expertise along with commitment towards the sustainability is essential. Cement industries can build a resilient and green future by embracing the innovation. In the part that follows, we will go through the Best available technique (BAT) used by the cement industries at the moment for cement production.

2.1.4 State-of-the-art cement kiln

The procedure described below has been identified as the BAT for the production of Cement [61]. As shown in *Figure 3* with a capacity of 3000 t_{clk}/d, there are three main steps in the manufacturing of cement. They are **Stage 1**: Raw material preparation, which includes quarrying, crushing, prehomogenization, and grinding raw meal. **Stage 2**: Clinker burning, which comprises preheating, precalcining, clinker generation in the kiln, as well as cooling and storing **Stage 3**: Cement preparation, consists of blending, cement grinding, adding additives to the clinker for cement formation [36]. The primary stages of the process mentioned above goes for several internal steps. The following subchapters provide a clear explanation of these procedures.

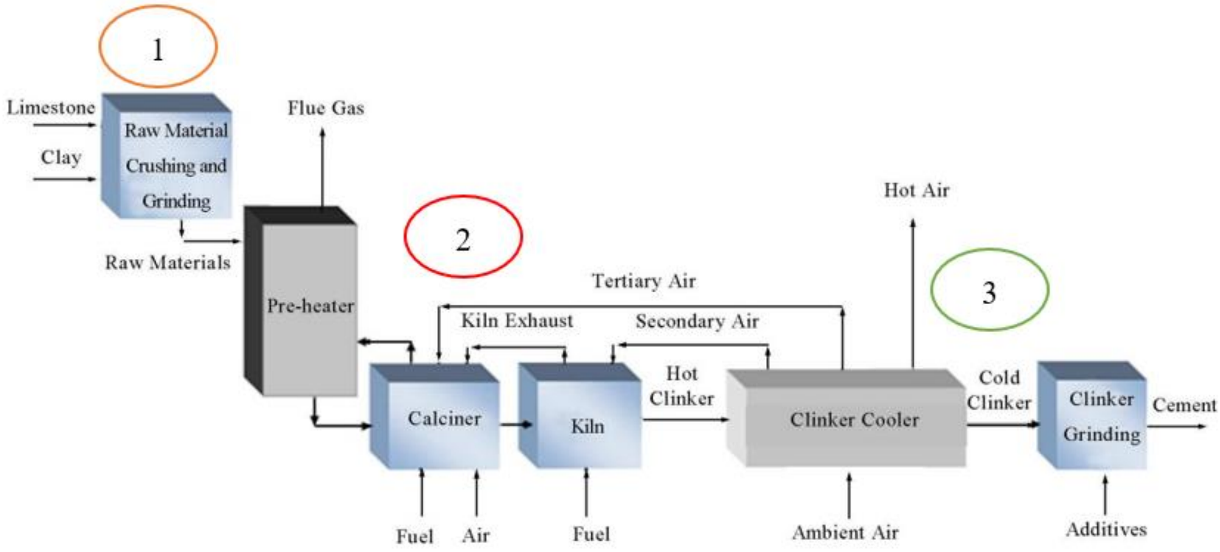

Figure 3. Process block diagram of cement production [36]

2.1.4.1 Raw material preparation

The most common raw materials used for the cement production are limestone, marls and clay as shown in *Table 2*. These materials are extracted out of the quarries, followed by crushing and grinding. Later the raw mix is fed in to the further stage where the process is distinguished by the amount of moisture in the raw feed entering into the kiln stage and are referred to as the following. Wet process, semi-wet process, semi-dry process and dry process. The clinker production process historically transitioned from wet to dry process pathways, in which the raw materials are ground and dried to create a mix in the form of a flowable powder and then fed for the subsequent process. Additionally, it should be emphasized that the dry production method uses less fuel than the wet process because of its less energy demand. The majority of the cement manufacturers are currently operated through the dry process for above mentioned reasons. Approximately, 1.50 t of raw mix is required to produce 1 t of clinker due to calcination [37].

Table 2. Raw material composition [61]

Components	Mass Fraction (wt.%)
$CaCO_3$	78
SiO_2	13.9
Al_2O_3	3.3
Fe_2O_3	2.0
$MgCO_3$	1.5

2.1.4.2 Preheating System

Preheating systems are the initial approach for allowing part of the clinkering process to take place in a fixed installation outside the kiln. As a result, the rotary kiln became shorter which decreased the heat losses and improved energy efficiency. There are two types of preheaters: (a) Grate preheaters and (b) Suspension preheaters [23]. Currently the grate preheater systems are totally replaced by the suspension model.

Suspension Preheating System

The raw material in the suspension preheater exchange heat with hot gas from the rotary kiln, preheating and even partial calcination of the dry raw meal takes place. Theoretically, the much-increased contact surface allows for nearly maximal heat exchange [44].

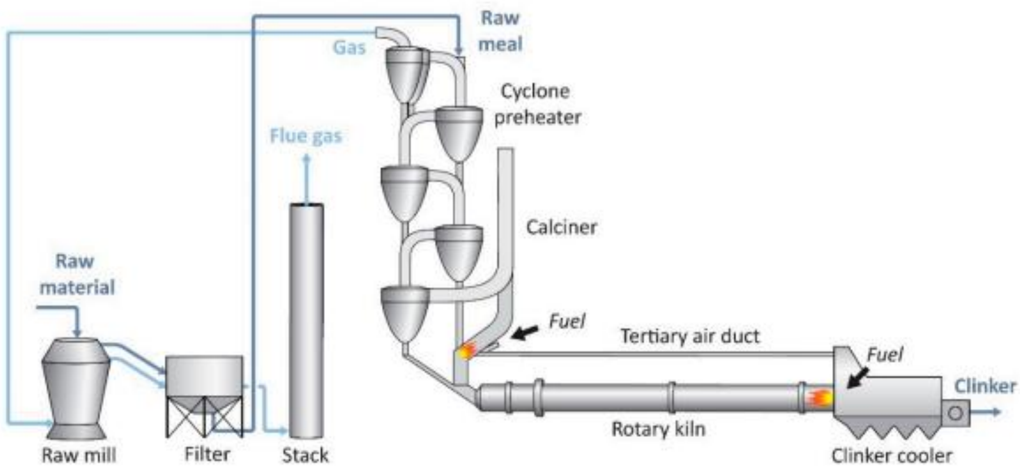

Figure 4. Clinker production process of BAT reference plant [75]

There are many different suspension preheater systems. They typically contain four to six stages, stacked one on the top of the other in a tower that is 50-120 m high as illustrated in *Figure 4* [72]. For new dry process facilities, kiln systems with five cyclone preheaters and one precalciner are considered as a standard technology [78]. Two parallel cyclones in the higher stage are used to separate the dust more effectively. The cyclone stages receive the exhaust gases from the rotary kiln from bottom up. Before reaching to the highest cyclone stage, the exhaust gas is mixed with the dry, powdery raw material mixture. It is separated from the gas in the cyclones and rejoins it before the next cyclone stage. At each level, this process is repeated until the material is finally discharged into the rotary kiln. For the most effective heat transfer, there must be alternate mixing, separation and remixing at higher temperatures [72]. As the number of cyclones increases, the thermal efficiency of the system also increases. The gas risers between the various preheater stages and the cyclones for collecting the heated raw mix powder and passing it to the following stage of the preheater are the essential parts of the gas suspension system [37].

2.1.4.3 Precalciner

The suspension preheater system, which was introduced in the 1970s was later developed in to precalciner system. As seen in *Figure 4*, it comprises a combustion chamber (Calciner) situated between the suspension preheater and the kiln where the preheated raw mix can be almost completely calcined (94%) before entering the kiln [15]. When compared to a kiln with merely a suspension preheater, the use of such a precalciner enables shorter kiln lengths and can reduce energy usage by 5-10 % [23]. A precalciner utilizes 60-70% of the cement plant's total fuel supply to run the reaction (*2*) while the remaining fuel is burned in the rotary kiln [62, 72]. The main reactions mentioned in section 3.3 occurs in precalcination stage.

The precalciner receives the raw meal from the preheating section such as limestone, clay and other elements along with the controlled amount of combustion air. The raw meal is exposed to temperatures between 800 °C to 900 °C. The input is almost fully calcined as a result of this heat producing calcined clinker nodules. The calcined material then goes into the rotary kiln for clinker production process [58]. The cement precalciner considerably increases energy efficiency by heating the partially calcining raw meal using the waste heat from the preheater exhaust gases. Precalcination also lowers the thermal load results in lower fuel consumption and boosts total energy effectiveness [77]. It also enables the regulated partial burning of the fuel. The calciner creates better conditions for the combustion by dividing the fuel combustion into two phases (precalciner and kiln), leading to decrease fuel consumption and fewer emissions of greenhouse gases (GHG), including CO_2 [80]. By separate combustion they offer a fuel type flexibility by providing wider range of fuel options. Alternative fuels including biomass, fuels made from waste, and tires can be added to the cement manufacturing process more simply at calciner. This makes it possible to use a variety of low-carbon and renewable fuel sources, thus decreasing the impact on the environment [3, 67].

2.1.4.4 Rotary Kiln

The rotary kiln is utilized in a variety of solid processes, including drying, incineration, heating, cooling, humidification, calcination and reduction. Its capacity to withstand a range of loads with substantial variations in particle size is one the reason for its extensive use [53].The rotary kiln is a cylindrical steel structure that is slightly inclined and rests on the bearing rollers as indicated in *Figure 4*. It has an internal lining and a rotating motor that creates a turning motion. At the start of the 19th century, a gas/solid contactor of this type was developed for the cement industry [13].

They are vital in the conversion of raw material into clinker, small hard nodules are formed as a result of the chemical reactions that takes place within the kiln high temperatures during the sintering process. Rotating kilns operate at temperature that are typically between 1400 °C to 2000 °C [60].The chemical reactions and physical transformations necessary for the generation of the clinker depend on this extreme heat. Hot gases are produced during the combustion of the fuel such as coal, natural gas or alternative fuels which circulate throughout the kiln. By transferring heat to the raw materials these gases help to accelerate chemical reactions and moisture evaporation [12]. The rotating kiln burner requires around 1/3rd of the fuel used in the facility. The temperature of the gas phase in the rotating kiln can reach 2000 °C, while the solid material reaches 1450 °C. The raw material components undergo intermediate phases while moving through the kiln to eventually generate clinker [61].

The hot clinker is cooled once it exists the kiln in order to maintain its quality and adverse reactions. The desired cooling rates are achieved by using a variety of cooling techniques, such as air quenching or air-grate coolers. The rotary kiln's length, diameter, slope, and internal features contribute to its design, which also effects residence time, heat transfer, material flow, all of which have a big impact on clinker quality and kiln operation [29]. The type of fuel used has an impact on the kiln's energy use, emissions, and general efficiency. To lessen their impact on the environment, cement mills frequently mix fossil fuels with alternative fuels like biomass and fuel obtained from waste [43]. Optimal clinker generation also depends on proper kiln management, which includes managing rotational speed, air flow, and temperature distribution. To guarantee kiln longevity and performance, routine maintenance, and refractory lining replacement are required.

Later, the cement is prepared, going through the steps of mixing, grinding, storing in cement silo, and ultimately being sold as a finished product [38].

2.2 Environmental Impacts and Solutions

The shortage of resources and pollutants emissions are acknowledged as significant environmental challenges facing the cement industry and the high level of GHG emissions are the most frequently addressed environmental impact [30]. Cement is responsible for 36 % of all emissions connected to construction activities [8] and 8 % of all anthropogenic CO_2 emissions [52]. At least 70 % of the GHS emission linked to the production of concrete come from the cement production [50]. The clinker production during the kiln stage is the main source of the GHG emissions in the cement industry, but grinding, raw material sorting and packaging also contribute to the emissions in a negligible way [52]. The global environmental impact of the GHG emissions from the concrete industry cannot be fully addressed by mitigating strategies alone and technological advancements are required to meet global GHG-mitigation goals.

2.2.1 Carbon Dioxide Emission

Fuel combustion and limestone conversion to CaO and CO_2 during the calcination process at high temperature are the two factors that cause emissions from the kiln [25]. Calcination of limestone results in the release of about 0.55 tonnes of CO_2 for every tonne of cement clinker produced [69]. A sizable amount of the CO_2 emissions from cement manufacturing are caused by this process. The energy-intensive nature of cement manufacture results in significant CO_2 emissions in addition to calcination. Coal, oil, and natural gas are the major fossil fuels that are utilized to provide high temperatures needed in the kiln for clinker formation. Increased kiln efficiency and use of the lower carbon fuels can significantly reduce emissions, which are produced by the combustion of energy sources during process and approximately 0.31 kg of CO_2 per kg of cement is exhausted [19]. The inherit material related CO_2 emissions induced by calcination are still present even when the energy supply is decarbonized [25]. As a result, the degradation of limestone during calcination accounts for around 2/3rd of the total GHG emissions [52] when cement is produced by applying a start-of-the-art dry process rotary kiln fitted with a precalciner.

2.2.2 Application of Alternative Raw Materials

The use of alternative raw materials can contribute to the reduction of process and fuel related CO_2 emissions. Because the preceding process that produced the CO_2 emissions can be minimized by employing decarbonated materials. Waste from recycled concrete or fiber cements, as well as other elements like blast furnace slag and ash fly, are examples of alternative materials. The main drawbacks of this method are the lack of readily available substitute materials and the requirement to modify the composition of raw material mixture in order to maintain product quality and kiln operation, both of which are only partially feasible [39].

2.2.3 Energy Efficiency Measures

A crucial technique to lower CO_2 emissions is to increase energy efficiency in the manufacture of the cement. Cement mills can put in place a number of energy efficient solutions. These consists of maximizing the use of process heat, utilizing energy-efficient machinery, putting waste heat recovery systems leading to lower the fuel requirement. Energy efficiency improvements directly cut CO_2 emissions from energy use by lowering the energy demand [76].

2.2.4 Alternative Fuel and Renewable Energy

Utilizing alternative fuels and renewable energy sources to produce cement is another way to reduce CO_2 emissions. It can be accomplished by switching from fossil fuels to biomass, municipal solid waste, or non-recyclable industrial waste [40]. The use of renewable energy sources is one of the most important ways to lower the environmental effects of cement production. Particularly, concentrated solar power (CSP) has demonstrated tremendous potential for supplying the heat and electricity needed in the cement process. In order to produce high temperature heat that can be used for calcination, drying and power generation, CSP technology concentrates sunlight onto a receiver using mirrors or lenses [47]. Through this integration the usage of fossil fuel would be significantly reduced and can lower the GHG emissions.

2.3 CO_2 Capture Technologies for Cement Production

The cement industry can reduce its particular CO_2 emissions through a variety of methods, including improved efficiency, the use of alternative fuels, using alternative raw materials and renewable integration as described before. However, these methods have previously been heavily utilized, and then they are only partially effective at reducing emissions [39, 75]. Since only one-third emissions are caused by fuel, only this share can be avoided by fuel switching. The use of the CO_2 capture and storage (CCS) can dramatically lower emissions from both process and the fuels. It is noted as having the greatest potential for additional overall emission reductions in the cement industry [36, 39].

Typically, cement kilns last between 25-40 years [75]. Even though certain kilns may need to be renovated to satisfy criteria set by governing bodies for pollutant emissions and technical performance, it is unlikely to build many kilns in the near future given that cement production predicted to remain about constant over the ensuing decades [38]. Therefore, it is crucial that CO_2 capture systems may be adapted to existing cement facilities in order to reduce CO_2 emissions from cement manufacturing.

The three primary categories into which the technique to carbon capture has been divided in the literature are pre-combustion, Oxy-combustion, and Post-Combustion as *Figure 5* illustrates [37]. Since the majority of research and this work focus on Calcium-Looping (CaL) technology, thorough explanation of it is provided here and other were given a summary.

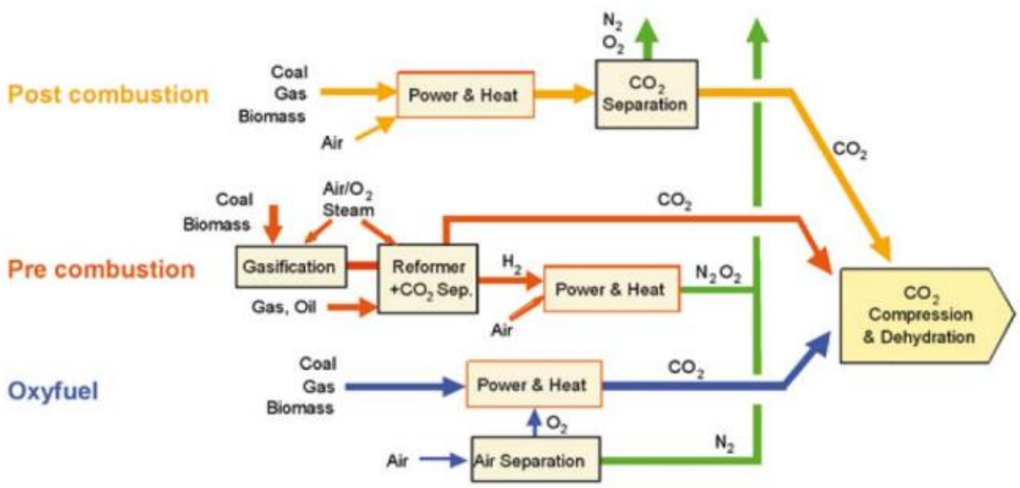

Figure 5. CO_2 Capture processes [5]

2.3.1 Pre-Combustion Capture

Pre-Combustion capture is the process of capturing CO_2 from fossil fuels prior to combustion. For instance, a feedstock (such as coal) is partially oxidized in steam and oxygen/air at high temperatures and pressure to produce syngas on the gasification processes. A mixture of hydrogen (H_2), carbon monoxide (CO), CO_2 and other smaller gases substances are produced. The water-gas shift process can be used on the syngas to change CO and water into H_2 and CO_2, resulting a mixture of gases that is H_2 and CO_2-rich as shown in *Figure 5*. The concentration of CO_2 is in between 15-60 %. The H_2-rich fuel can subsequently be burned while the CO_2 is captured, transported and finally sequestered [5].

Although pre-combustion capture might be used to "de-carbonize the fuel source used in the cement process, " It also has two significant limitations that make its application undesirable. First of all, even with pre-combustion capture, the exit gases from the kiln would still contain significant amounts of CO_2 because of the calcination reaction (*2*) which occurs after the CO_2 associated with the fuel has been separated. Due to decreased CO_2 concentrations, additional and expensive CO_2 removal would be necessary. This would include using one of the various CO_2 reduction technologies. Second, there are few opportunities to include the fuel conversion process into the existing procedure since, unlike power generation facilities, the cement process lacks of an existing steam cycle it can use, which will drive up expenses related to the process. For these two primary reasons pre-combustion is capture is not considered to be very appealing way to reduce CO_2 emissions linked to the cement production [37].

2.3.2 Post-Combustion Capture

In post-combustion capture, the process of cleaning up flue gas is including a CO_2 removal stage. Then it is separated from the flue gas using technologies before being stored and released into the atmosphere, as opposed to being released directly in to the atmosphere (*Figure 5*) [5]. It is anticipated that CO_2 separation methods, which are now widely used in industrial manufacturing, refining and gas processing, might be used for the post-combustion capture process[75]. When compared to other existing and developing capture process, the leading commercial technologies use a chemical process that provides high efficiency, selectivity, and the lowest energy use and cost. So, post combustion capture seems well suited to use at a cement factory given the high CO_2 concentrations in flue gas (30 %).

Mari Voldsund et al. [75] has performed a technical assessments on few of these post-combustion capture techniques used in the cement industries are described below.

2.3.2.1 MEA CO_2 Capture

MEA (Monoethanolamine) absorption process is the most mature technology for capturing CO_2 from the flue gases [61]. There are several modelling studies about the MEA capture process in the literature, with majority of studies concentrating on power plants.

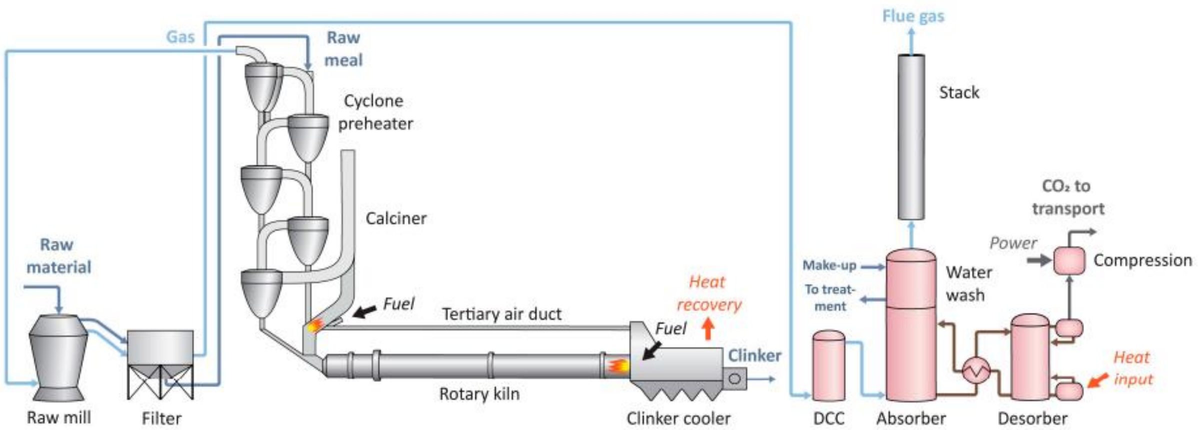

Figure 6. MEA CO_2 Capture for cement kiln [75]

The standard technology MEA absorption is a post-combustion method that uses a solvent called MEA to absorb CO_2 from flue gas before leaving it in to the atmosphere as shown in *Figure 6* [48]. Before the flue gas comes into contact with solvent, the quantity of NO_x and SO_x in the flue gas must be decreased below the authorized emission in order to limit solvent degradation [75]. The flue gas is cooled down in a direct contact cooler (DCC), where water is also removed, and SO_x is eliminated by scrubbing with NaOH. The flue gas can then be transferred to the absorber column after cooling, where CO_2 is removed from the gas by aqueous MEA solution (30 wt. %) [75]. The filtered flue gas is separated from the evaporated MEA in a water wash section at the top of the absorber. A desorber column is used to renew the CO_2 rich MEA solvent, and the resulting high-purity CO_2 is compressed to meet the criteria. In addition to power for the fans and pumps used in the absorption process as well as for the compression of the absorbed CO_2, the process necessitates a significant quantity of heat for the solvent regeneration. A portion of the heat requirement can be satisfied using waste heat [75].

2.3.2.2 Membrane-Assisted CO_2 Liquefaction

The CO_2 liquefaction process is combined with polymeric membranes in the membrane-assisted CO_2 liquefaction (MAL) technology as shown in *Figure 7*. The bulk separation process uses polymeric membranes to produce moderately pure CO_2 as the end product. This product undergoes additional processing in the CO_2 liquefaction method, in which CO_2 is liquefied to create high purity CO_2, and the partially decarbonized tail gas is recycled into the membrane feed gas [75].

In a DCC, water is first removed from the flue gas before it is compressed and transferred to the membrane module. Both the flue gas compression on the membrane's feed side and the pumps on its permeate side produce the pressure differential and pressure ratio over the membrane module [75]. The kind of polymer affects polymeric membrane's chemical stability, and it is frequently noted that these membranes tolerance to SO_X and NO_X is questionable [6]. The technology is post-combustion and does not further integrate with or provide feedback to the cement plant. Comparatively to MEA absorption, which has higher energy consumption and operational difficulties, membrane-based CO2 capture offers energy-efficient and scalable separation [37].

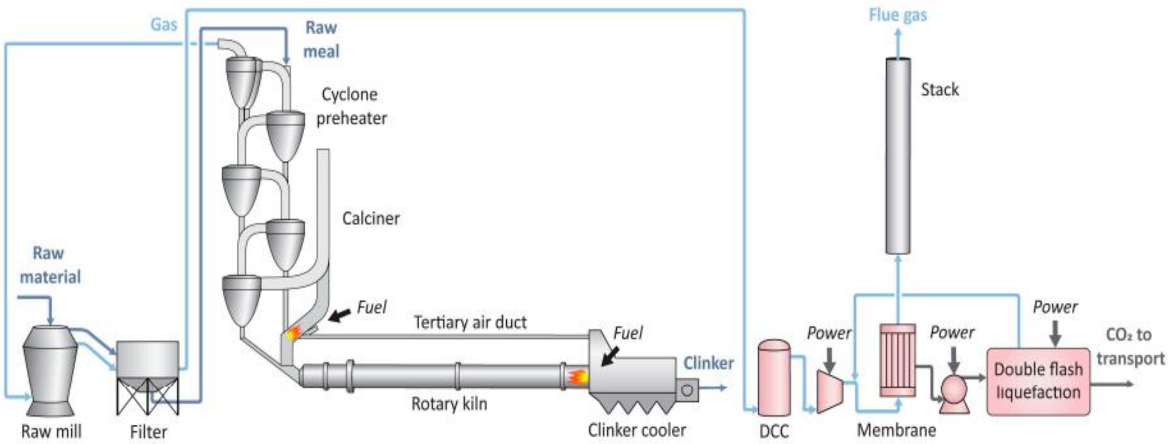

Figure 7. Membrane-assisted CO_2 Liquefaction [75]

2.3.3 Oxyfuel Combustion Capture

Oxy-Combustion is the burning of fuel in practically pure oxygen as compared to air. An air separation unit (ASU) removes the nitrogen from the air, which normally contains 78 % nitrogen by weight, in order to produce oxygen needed for burning. According to the fuel and particular oxy-combustion method, the flue gas is cooled after combustion to condense water vapor, and the resulting flue gas has a high percentage of CO_2 (80-95 %). In addition, to these products, the flue gas will also include diluents in the oxygen feed such as NOx, SOx, inert gases from the fuel or leaks into the system at fuel combustion stage. Stoichiometric combustion temperature for fuel in an atmosphere with oxygen is extremely high (3500 °C) [37]. A part of the flue gas can be recycled back to the burner as a diluent to manage this by lowering the temperature. Remaining CO_2 gas containing goes for compression and storage [75].

2.3.4 Calcium-Looping Technology

In the cement industry, the calcium looping process (CaL) offers a possible route for carbon capture. It is viable option for lowering CO_2 emissions due to its high capture efficiency, affordability, and capacity to use already-existing calcium rich feedstocks [73]. The calcium looping process, also known as regenerative calcium cycle (RCC) is a second-generation carbon capture technology [21]. It uses calcium-based sorbents to remove CO_2 from the flue gases. Calcination and Carbonation are the two primary phases in the process as shown in *Figure 8*.

- Carbonation is the first stage of the CaL process, where flue gas is sent into the reactor named carbonator. In this stage, CO_2 in the flue gas interacts with the calcium sorbent (CaO), causing the reaction to produce calcium carbonate ($CaCO_3$) [17]. This occurs typically around 650-700 °C making it suitable for high temperature production process. This process is exothermic and releases heat that can be used for other plant operations like drying raw materials or producing steam [2].

$$\mathrm{CaO} + \mathrm{CO_2} \rightarrow \mathrm{CaCO_3}\,,\Delta\mathrm{H_R} = -178\ \mathrm{kJ/mol} \qquad (1)$$

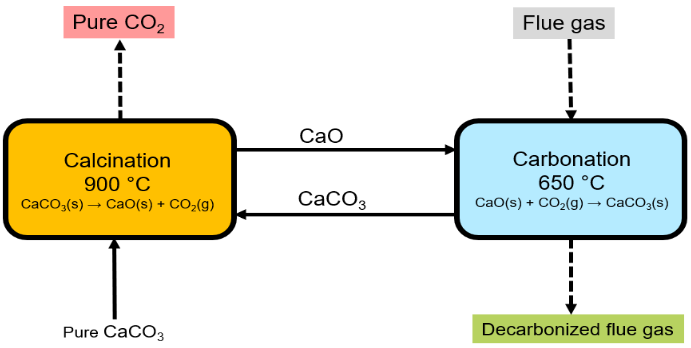

Figure 8. Calcium Looping Process

- The second stage in CaL is calcination, take account in decomposing the $CaCO_3$ produced in the carbonation stage to extremely high temperatures, usually between 850-950 °C. The reaction (*2*) explains how this heat causes $CaCO_3$ to decompose, releasing the captured CO_2 and regenerating the CaO sorbent [2]. The process is endothermic and heat is supplied through various ways. The emitted CO_2 can subsequently be collected, compressed and stored for usage of processes like chemical synthesis, oil recovery etc. The continuous cycle of carbon capture and release can be completed by recirculating the regenerated CaO back to the carbonation stage to capture more CO_2 [18].

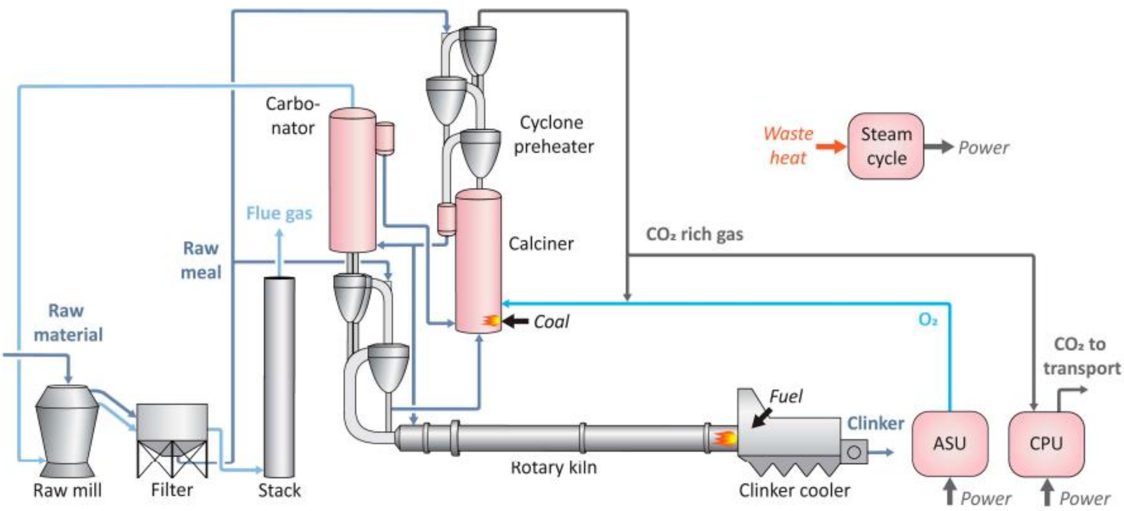

Figure 9. CaL integration with cement plant [75]

Given its high CO_2 emissions and access to calcium-rich resources like limestone as feedstock, the cement industry makes a suitable option for the calcium looping process. CO_2 emissions can be greatly decreased by implementing the CaL during the cement production. The compatibility of calcium looping technology with the current cement plant infrastructure is one of its key benefits. The incorporation of this technique does not necessitate significant changes or new machinery because the carbonation and calcination stages can be incorporated to the cement manufacturing process as shown in *Figure 9*. Calcium looping is a desirable alternative for cement producers seeking to lower their carbon footprint without sacrificing production efficiency[31].

The sorbent is also a cost-effective choice for large-scale deployment because it can be produced from readily available and affordable raw materials like limestone or dolomite [1]. Research has also been done on CaL technology's commercial viability. The economic viability of applying CaL in cement factories has been assessed by cost analysis studies [75]. These assessments have taken into account things like the price for sorbent preparation, energy needs, plant integration, potential revenue from CO_2 storage use. The findings show that calcium looping, especially when integrated with ongoing operations and using inexpensive sorbent materials, can be a financially viable solution for CO_2 capture in cement plants [11].

2.4 Solar Energy

Our most abundant and accessible source of energy, the sun, provides a sustainable answer to our expanding energy needs. The quantity of solar energy that reaches earth in single hour is equal to the amount of energy used by all humanity combined in a single year [55]. By 2050, solar energy is predicted to make up 16% of all worldwide electricity production according to International Energy Agency [41]. The solar energy sector has been expanding rapidly as the amount has been installed worldwide as of 2020 exceeded 760 GW, a substantial rise from just 5.5 GW in 2005 [42].

Solar energy has many different applications. Solar Photovoltaic systems (PV) and solar thermal systems are two of them that are extremely in utilization. Residential, commercial, and utility-scale applications all frequently use solar PV systems. Rooftop solar panels, and other structures can produce electricity for individual use or can send extra power back in to the grid.

On the other hand, solar thermal technology uses the heat from the sun to generate high temperature for power production such as concentrated solar power. In concentrated solar power (CSP) plants, sunlight is focused through mirrors and lens that reflects the light to a targeted area to that produces heat to run high temperature reactions, steam generation that powers turbines to produce energy on a bigger scale. More details of CSP plants are discussed in section 2.4.1.

By tackling the issues of climate change, energy security and economic growth, solar energy is essential for building a sustainable future.

2.4.1 Concentrated Solar Power (CSP)

Concentrating solar power (CSP) technologies may play a crucial role in the rich and diversified portfolio of renewable energy source in view of some distinctive features. CSP entails concentrating solar radiation onto a solar receiver using optical sun tracking mirrors (heliostats), from which it can be used to fuel power cycles, provide process heat, or support solar-powered chemical process [71]. CSP is distinguished by a few noteworthy and distinctive characteristics that make it a viable solution for particular applications. (a) CSP has the potential to achieve substantially better thermal efficiency because it can utilize the entire solar spectrum as opposed to just a few spectral regions, (b) CSP becomes a dispatchable energy source on an hour-to-day time scale when coupled with cheap thermal energy storage (TES) systems (c) CSP might be a source of useful high-temperature thermal energy that can be used as process heat or in hybrid plants where CSP is combined with endothermal physical or chemical processes [28].

CSP technologies that are frequently used in industry are mainly four types: Linear Fresnel reflector (LFR), Parabolic dish, Parabolic trough, and Solar tower Central receiver as shown in *Figure 10* [63]. These technologies can broadly classify according to their optical design, receiver form, heat transfer characteristics and heat storage capacity. Among the four technologies the central receiver has an advantage to achieve higher operating temperature than other systems, which allows more efficient power conversion and energy storage options [40]. Central receiver system is the only option for cement production at large scale since it requires very high temperature to drive the process. So, a CSP plant with solar tower model is designed in this study for the calcination process.

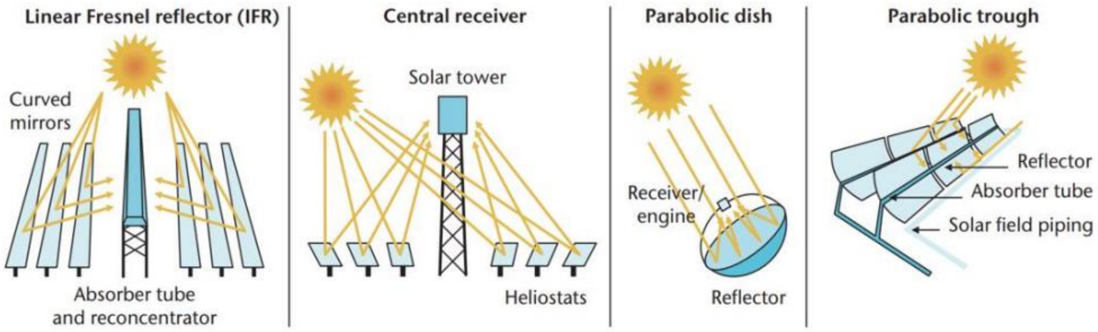

Figure 10. Types of Concentrated Solar Power technologies [56]

Solar Tower System

Solar power tower also known as central receiver system, includes employing a field of mirrors called heliostats to concentrate sunlight onto central receiver situated on the top of the tower as shown in *Figure 11*. Concentrated sunlight is absorbed by the receiver, which acts as a thermal source for the various high temperature processes such as desalination, mineral processing and cement production. The temperature reaches more than 1000 °C depending on the material used in the receiver [56].

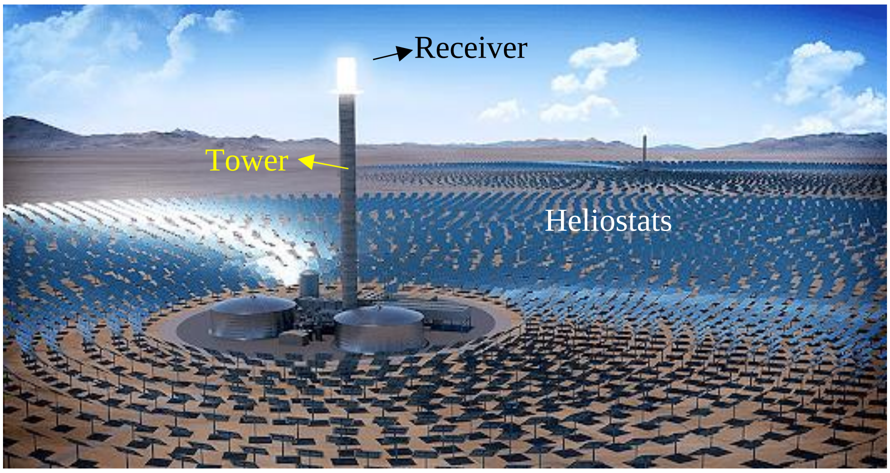

Figure 11. Central tower Receiver CSP Plant [33]

The design of the towers are finalized by the multiple factors depending on the number of receivers, the dimensions of the fields and its orientation. Heliostats, which plays a crucial role are also designed in various shapes and sizes with surface areas ranging from 1 to 160 m^2 [10]. Based on the total area needed, the number of heliostats is determined. Additionally, the placements should be optimized to prevent the shadowing and obstructing problems [56].

There are already 142 CSP plants active and under construction worldwide, according to a research by Solar Paces mentioning the progressive increase in CSP utilization. Among these more than 30 projects are using solar tower-based technology. NOOR III, the largest concentrated solar tower plant in the world is located in Morocco with an investment of 877 million USD delivering 500 MW total capacity [56].

As a high energy process, cement production integrating with CSP offers an attractive solution to lower carbon emissions, increase energy efficiency, and encourage sustainable practices in the cement industries. CSP also ensures the availability of reasonably priced and reliable energy while assisting the transformation of cement manufacturing into a cleaner, more environmentally friendly process.

3 Modelling of CSP-CaL Cement Plant

The reference cement plant taken into consideration in this work is a conventionally run facility that has been classified as BAT. It is specified and modelled by CEMCAP, an EU-project that aimed at CO_2 capturing technologies for cement production [61]. It is based on the dry kiln method and consists of a rotary kiln, grate cooler and five step preheater cyclones with a precalciner. The clinker production capacity of the referred cement plant is about 3000 t/d and represents an average cement plant in Europe.

In this work, initially a conventional model taken from the reference document is modelled and later it is developed with solar and CC technology for the integration.

3.1 Aspen Plus Setup

The process modelling and simulation is performed in the Aspen Plus V12.1 software. The cement process is complex, including several chemical reactions and heat transfer phenomena. Accurately describing the qualities of the solids involved in the process is one of the crucial aspects. Solids like limestone and clay are important in the cement production, and their properties plays a major role in the efficiency and product quality. Aspen Plus provides a property method called “Solids” that allows for precise modelling of solids and their interactions in the system.

To precisely represent the behavior of solid materials, Aspen Plus’s solid property considers a number of parameters, including particle size distribution, particle density, and specific capacity. These characteristics are essential for simulating solid-phase chemical processes, mass transport, and heat transmissions. Along with Solid property method a stream class of MIXCINC is chosen based on the component’s sub streams involved in the process. Where gases are considered as mixed (MIX), solids are CISOLIDS (CI), Coal and Ash are non-conventional (NC). The HCOALGEN and DCOALIGT models, respectively are used to compute the characteristics of the non-conventional components.

3.2 Solarized Process Description

The conceptual design, as seen in *Figure 12* primarily comprises of two operations: Solar and Conventional. In contrast to the conventional portion, which only contains one preheating system, a combustion chamber and a calciner, the solar part includes a splitter, three preheating systems and a solar calciner. The entire solar system is run by CSP from the heliostats, while the conventional is powered by coal burning. Due to its operational period (8 hours per day depending on sun availability), the capacity of solar operation should be approximately three times bigger than the conventional part where it operates 24 hours a day continuously. In terms of feeding cement raw meal (CRM), 90 % of it goes in to the solar section and remaining 10 % fed in to the conventional part to maintain the conventional calciner operation and system temperature. A major goal of this work is to limit the use of coal and its emissions in calciner, so major part of the calcination takes place in solar operation.

In Splitter1, the feed entering the solar system is first divided in half and transferred to preheating system 1 and 2. In order to transfer the heat, the solid raw meal goes through the cyclones and gets into contact with the hot gases originating from the calciner. The preheated CRM enters the solar calciner, which is positioned on top of the solar tower and heated using CSP heat to perform the calcination procedure. The hot CO_2 that is emitted during the calcination process enters the preheating process into system-1 and leaves on top of the cyclone where it is collected and stored (CO_2-Out). The calcined hot solid material then moves to the preheating cyclone system-3 where it exchanges heat with incoming ambient air (Air-in) before cooling in Cooler 2 and stored for continuous operation during non-solar hours. The heated air sent into cyclone system-2 for preheating before being released into the atmosphere (Air Out).

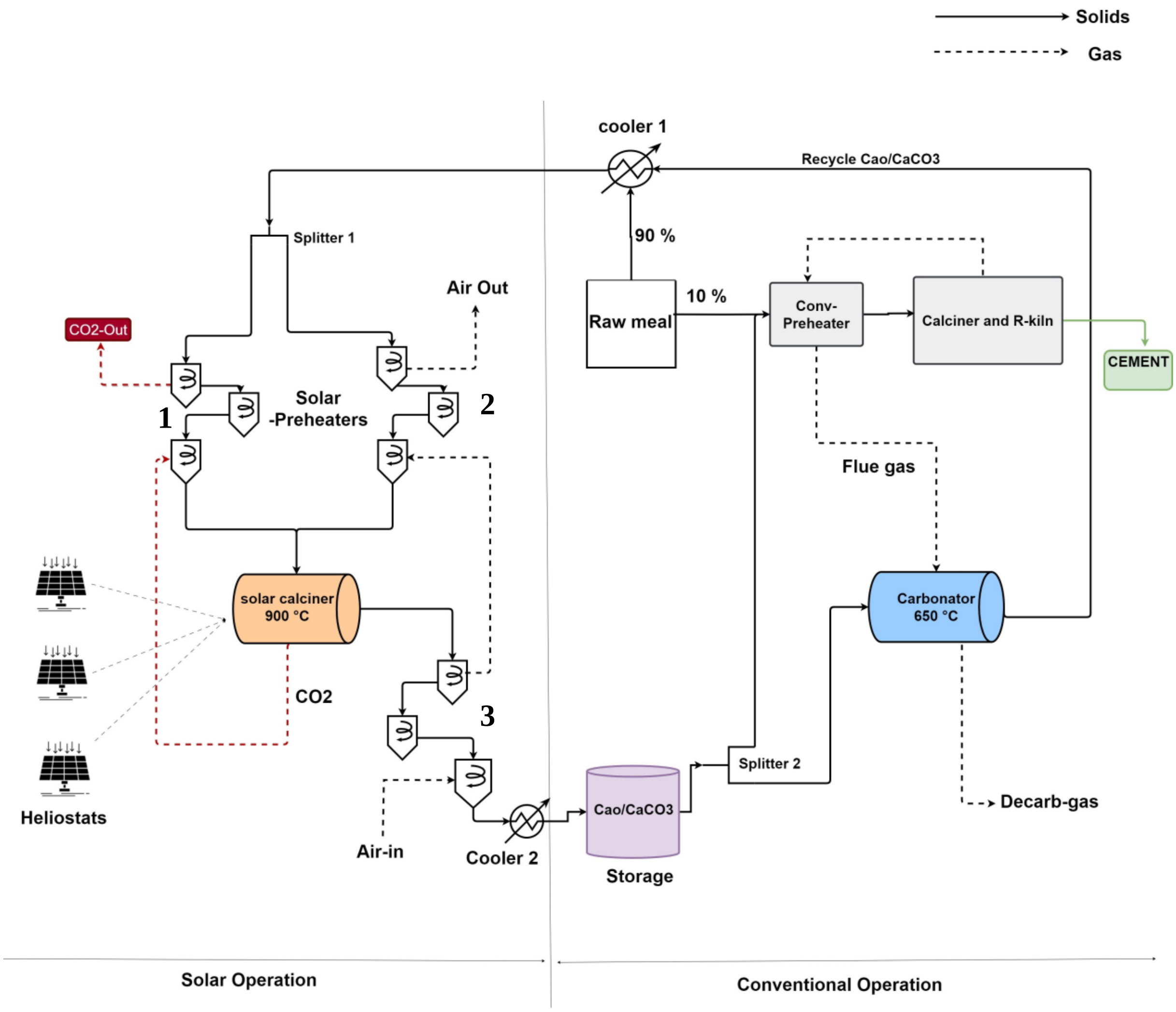

Figure 12. Schematic representation of CSP-Cement Production

The calcined material from storage is separated into two streams in Splitter 2, where one is directed towards the carbonator containing the amount required for carbonation. The remaining amount mixed with 10 % of raw meal enters into the preheating system. This material travels through each cyclone to exchange the heat with hot gases originating from the rotary kiln and precalciner and leaving the preheating system as flue gas. Later, the preheated material goes into the calciner, where heat from the coal is used to calcine the raw material. Almost completely calcined material enters in to the rotary kiln for the sintering process, which is the stage where clinker formation takes place. The produced clinker is sent into a cooling system for cooling and later stored for usage as explained in section 2.1.4.

The conventional plant's flue gas and a stream of calcined material from Splitter 2 are fed into the carbonator. Here, the CO_2 in the flue gas is absorbed by CaO to form $CaCO_3$ as shown in reaction (*1*). $CaCO_3$ that has been renewed is recycled back in to the solar calciner as feed to remove and store the CO_2. To capture the CO_2 from the combustion plant, this procedure will be carried out continuously.

The next section contains further technical information regarding the modelling approach.

3.3 Process Modelling

Here, the model contains preheater cyclones, coal combustion, calcination (*Figure* **12**-grey boxes) and carbonation but the rotary kiln has been neglected. In consideration of the model's progress, only the pre-calciner is being solarized, and the kiln is not modified, since the goal is to keep the feed properties (temperature, mass and composition) the same as the CEMCAP case. Hence, the rotary kiln outputs are determined in accordance with the CEMCAP report 4.2 [61] for the calcination modelling. The model needs input parameters such as cyclone efficiency, extent of reaction in the calciner and heat losses etc.

Figure 13 shows an overview of the Aspen Plus flowsheet used to simulate a cement plant with stream representation from the CEMCAP Model [61].

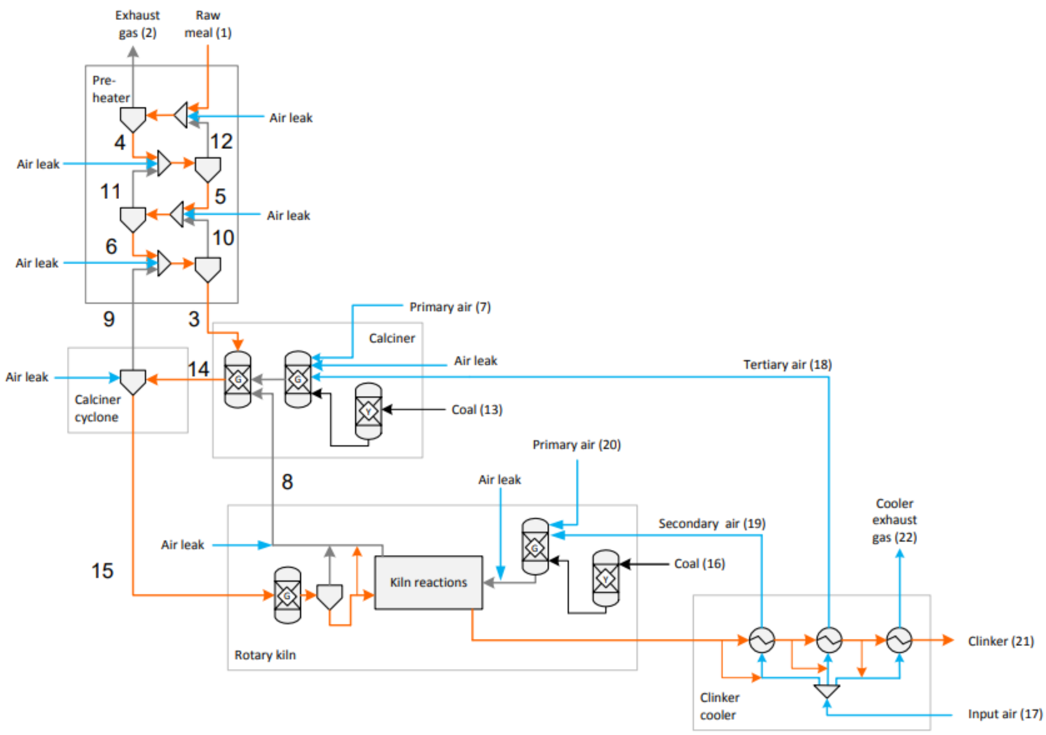

Figure 13. Aspen Plus simulation set-up of the reference cement kiln [61]

3.3.1 Preheating systems

A set of mixture, Gibbs reactor and SEP unit operations together form a cyclone. Totally five cyclones are designed similarly to represent the complete preheating system as designed in *Figure 14.* It combines raw meal solids from above with the gas from below. After passing through the reactor the mixture is sent to SEP block which separates the mixture. The gas and solid temperatures in each stage are considered to be constant. Each cyclones efficiency is set and certain amount of heat losses is considered as per the CEMCAP report. The specific operating conditions are listed in *Table 4*. In solar operation, the same preheating method is employed, but there are only three cyclones in each system as opposed to five in the conventional section. In contrast to the single preheating system in the conventional section, the solar part has three as shown in *Figure 12*.

3.3.2 Coal Combustion

The combustion of coal is simulated using the RGibbs model. By reducing the Gibbs free energy, RGibbs simulates a chemical equilibrium. Yet, because coal is a non-conventional component, it is not directly possible to compute the Gibbs free energy of the coal. Decomposing of coal has to be performed before feeding it into the RGibbs block. This is carried out in the DECOMP block of RYield. During the coal burning, the heat of reaction is related to coal degradation must be taken into account. So, a heat stream is used to carry this of reaction from the RYield block to RGibbs block as we see in *Figure 14.*

The *Table 3* contains the characteristics of the coal burned in the precalcination process.

Table 3. Key values for coal combustion

Parameter		Value	Unit
Fuel Composition			
	C	69	wt. %
	H	4	wt. %
	S	0.5	wt. %
	N	0.48	wt. %
	O	9	wt. %
	H_2O	0.5	wt. %
	Cl	0.02	wt. %
	Ash	16.5	wt. %
Fuel lower heating value		27	MJ/kg

When compared to a completely conventional plant, the solarized model's conventional calciner is set just 10 % of the coal, as 90 % of the material is calcined in the solar calciner. The primary air supplied here for the combustion is also reduced in same ratio as the coal supply.

3.3.1 Conventional Calciner

The calciner receives the heated raw meal from the cyclones. Heat is produced by the combustion of coal and hot flue gasses from the kiln. The reactions involved in the calciner are endothermic. The calciners primary chemical reactions are as follows:

$$CaCO_3 \rightarrow CaO + CO_2 \quad \Delta H_R = +178 \text{ kJ/mol} \tag{2}$$

$$MgCO_3 \rightarrow MgO + CO_2 \tag{3}$$

A RGibbs reactor is used to model reactions (*1*) and (*2*) . According to the CEMCAP report, a heat loss of 11.3 GJ/h was considered. Due to the absence of certain components in Aspen Plus, some reactions are not considered in the calciner. The ignored reactions are listed below.

$$CaO + Al_2O_3 \rightarrow CA \tag{4}$$

$$2CaO + Fe_2O_3 \rightarrow C_2F \tag{5}$$

$$2CaO + SiO_2 \rightarrow C_2S \tag{6}$$

$$C_2S + CaO \rightarrow C_3S \tag{7}$$

Additionally, tricalcium Silicate (C_3S) known as Alite (*7*), was considered as clinker for the total process simulation. These reactions will have an impact on the calciner's composition (increased concentration of CaO) and temperature (reactions are exothermic). As a result of these consideration and exclusions, equilibrium of reaction (*2*) is impacted. Due to the aforementioned factor, temperature approach to equilibrium was tuned to achieve a good agreement considering the outlet temperature and calciner efficiency with the CEMCAP report.

General technical details required for the modelling are tabulated below.

Table 4. General data for Aspen Modelling

General data	**Conventional Part [61]**	**Solar part**
Raw meal inlet temperature, °C	60	60
Fuel inlet temperature, °C	50	-
Preheater		
Number of preheating systems	1	3
Number of stages in each system	5	3
Cyclones efficiency (1-5 stages)	96/86/86/86/76	96/86/86
Heat loss in each stage, kW	625	625
Calciner		
Calciner temperature, °C	865	900
Fuel consumption, kg/s (stream 13)	0.24	-
Calcination degree, %	92	90
Primary air mass flow rate, kg/s (stream 7)	0.07	-
Tertiary air mass flow rate, kg/s (stream 18)	16.2	-
Tertiary air temperature, °C (stream 18)	1050	-
Heat loss, kW	3138	-
Carbonator		
Temperature, °C	650	-
CO_2 Capture rate, %	90	-
Carbonation, %	50	-

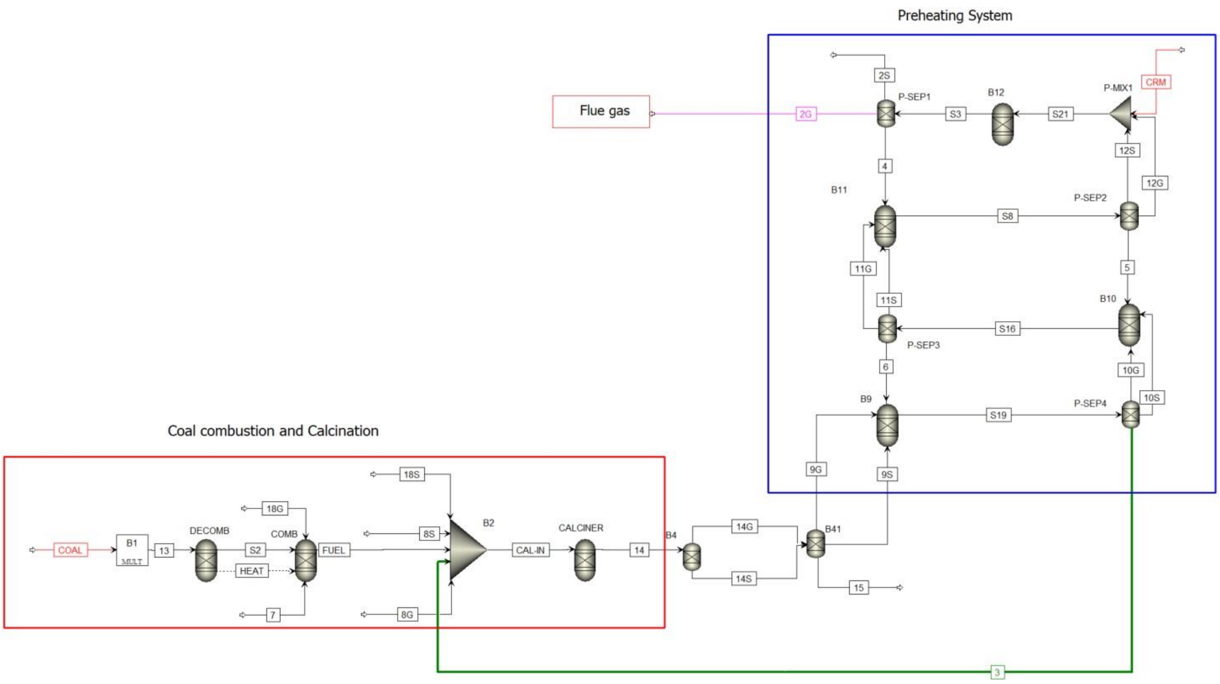

Figure 14. Aspen Plus model for conventional operation

(Red box: Coal combustion and calcination, Blue box: Preheating system, Green line: Recycle stream)

3.3.2 Solar Calciner

A working temperature of 900 °C is set for the breakdown of $CaCO_3$ with a high CO_2 concentration compared to the conventional operation of 860 °C low CO_2 concentration release. The RStoic model is chosen to model the calcination. The functioning of RStoic reactor unit is adaptable in terms of operating conditions, reaction type and rate of conversion. In this level of our simulation, only the reaction (*2*) is considered with conversion of 90 % rate (*Table 4*). All other reactions are neglected at this particular stage. This calcination is purely driven by CSP as the reaction is endothermic. A rotary kiln is considered for the solar calcination which is currently being developed at DLR.

3.3.3 Carbonator

Similar to the solar calciner, the carbonator is modeled using an RStoic reactor. However, the reaction is reversible to calcination. So, the operating conditions are set as mentioned in *Table* ***4***. Only a single reaction is considered in the carbonator as capturing of the CO_2 is the major target. With the conceptual data several carbonation criteria are set, with a carbonation rate of

50 % (*i.e.*, 50 % of CaO reacts) is selected in order to remove 90 % of the CO_2 from the flue gas (*i.e.*, 90 % CO_2 reacts) in the reaction. Later, the generated product ($CaCO_3$) and unreacted solids goes for the recycling into solar process and hot CO_2-lean flue gas is released into the further process such as drying before going into the atmosphere.

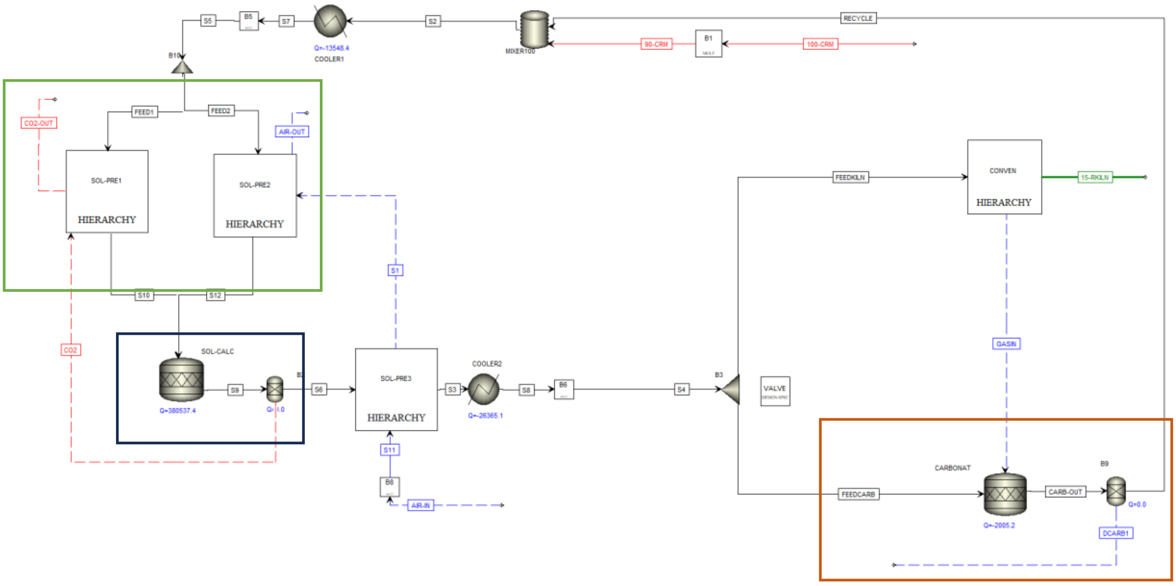

Figure 15. Solarized Aspen Plus model of cement production

(Green box: solar preheating system, Black box: Solar calciner, Red box: Carbonator)

3.4 Solar System Dimensioning

CSP serves as the major source of thermal energy in this designed case. A sizable CSP plant with a solar tower, heliostats and receiver should be designed. As the heliostats plays a major role in overall performance and capital in the CSP plant consequently, it is crucial to build the plant with best possible dimensions. Regarding this goal, DLR developed the HFLCAL (Heliostat Field Layout Calculator) software that focuses especially on the CSP field layout and its optimization has been used here. To design the solar field another parameter is important called 'Solar multiple'.

Solar Multiple

Solar multiple (SM) is defined as the ratio between the thermal energy produced by the solar field at the design point during sun availability to the thermal power required to operate the plant continuously [51]. A higher solar multiple would imply a greater proportion of solar thermal energy used in the cement manufacturing process, as well as potentially greater energy cost savings and lower greenhouse gas emissions. It also results in more calcination of more raw meal and storage for the continuous conventional operation. Based on the capacity, the nominal power required for the 24/7 operation in our case is 127 MW (*i.e.*, SM = 1).

$$\mathrm{SM} = \frac{\text{power produced by solar field at design point}}{\text{power required for } 24/7} \tag{8}$$

For solar tower plants with a specific energy output capacity, the HFLCAL is primarily used for planning and optimizing the heliostat field. The design characteristics of heliostats, such as size and shape must be specified in HFLCAL. For optimization of the field, it also needs additional design criteria, such as site location, tower height, Direct Normal irradiance (DNI), aperture shape and size, design time point and design power. The Aspen Plus simulation result is used to determine the receiver design power, which is a key factor for field layout dimensioning. The settings needed to start the HFLCAL field optimization for solar multiple 3.75 are listed in *Table 5*.

Table 5. HFLCAL required input for SM =3.75

Parameter	**Value**	**Unit**
Latitude	31.4	°
Height above sea level	999	m
Design time	21. March 12:00	
Design DNI	945.0	W/m^2
Aperture type	circular	
Design flux	1250	kW/m^2
Receiver power at design point	238.5	MW
Receiver efficiency (η_{rec})	0.85	

In this study, the location for plant operation was selected as Odessa, USA. The yearly irradiation of Odessa is approximately 2400 $\frac{\mathrm{kWh}}{\mathrm{m}^2}$. The latitude and height above the sea level are obtained from the meteorological data for the picked location. The design date of 21. March is chosen, because it is in between the solar solstices and thus representing average conditions.

The Odessa’s meteorological data at the time of design is used to determine the DNI design. The receiver efficiency is selection is made through equation (*10*) explained in section 3.5. The tower height is fixed in this work considering the stable position of the receiver and preheater placement on top, totally limiting the height to 240 m approximately. This is one of the reasons for decrease in the field efficiency.

Based on the capacity and construction feasibility, a two tower CSP system is considered. The two towers share the power demand and operation equally. The inputs and calculations performed in this work are for a single tower and later adapted to the other in every aspect.

The current study evaluated the operation of different solar multiples as mentioned in *Table 6* and conducted the analysis for all cases. The results mentioned in the below table are generated by the HFLCAL for each case at appropriate design power for single tower.

Table 6. HFLCAL Results

Solar Multiple	**2.5**	**2.75**	**3**	**3.25**	**3.5**	**3.75**
Energy required for two towers (MW)	318	350	380	412	444	478
Energy required single tower (MW)	159	175	190	206	222	238
Tower height (m)	199	199	199	199	199	199
Mirror area (m^2)	285123	318099	351986	387246	423033	458756
Annual field Efficiency (%)	58.79	58.29	57.85	57.39	57.25	56.5

Here, in *Figure 16*, we can see the optimized filed placement of the heliostats and their efficiency for the SM 3.75 at design time. The black dot in the middle refer to the tower and the red dots defines the shadow of the tower. The heliostats are bound to be on the north direction as per the location and suns altitude. The colored dots scattered across the field are heliostats, and the color determines the efficiency of each heliostat. The color red represents least efficient and, the color green indicates the most efficient as showing on the left side scale of the figure in percentage.

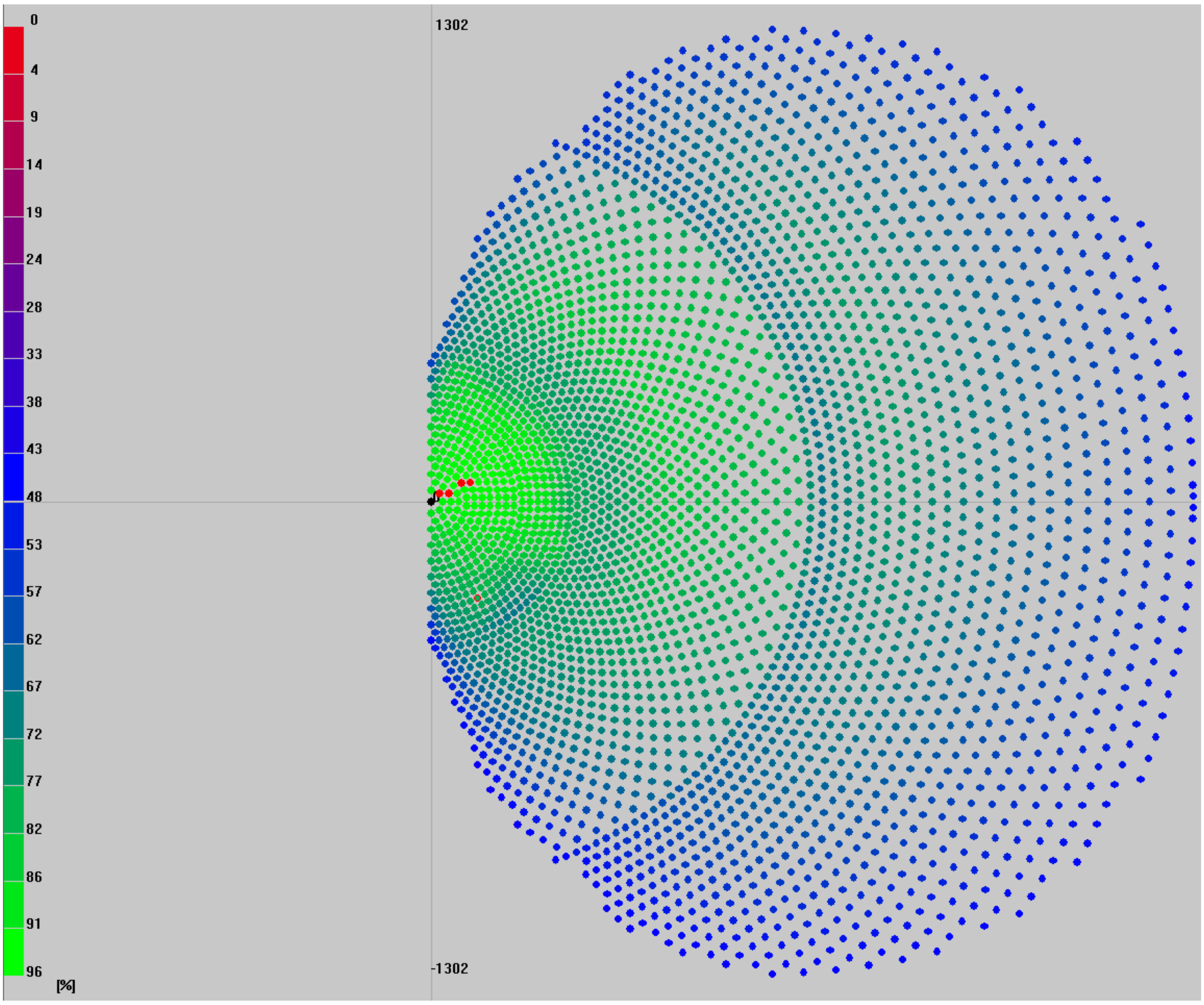

Figure 16. HFLCAL field placement of heliostats

3.5 Energy Analysis

This section describes the method for estimating annual power production of the modelled CSP plant based on the solar irradiation available in each hour of the year. Using the raw meteorological data, the overall power production is calculated as shown in equation (*9*).

$$\text{Energy (W)} = \text{DNI (W/m}^2) * \text{Mirror Area (m}^2) * \eta_{field} * \eta_{rec} \quad (9)$$

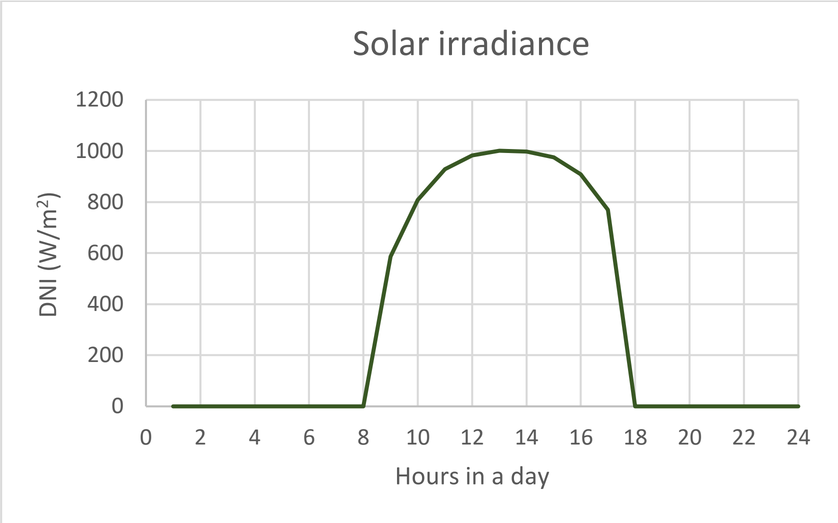

Figure 17. DNI distribution on 01. January 2022

Initially, the DNI from meteorological data is obtained for each hour of the year using Meteonorm software for the year 2022. It considers seasonal variations in atmospheric conditions such as particulate matter, fogginess, and cloudiness at the desired location. The area required for the total heliostat field is taken from the HFLCAL results shown in *Table 6*. HFLCAL also provides the total field efficiency (η_{field}) related to the sun's position taking elevation and azimuth angle into account. The Epsilon software is used to extract the position of the sun for every hour of the year and matched it to the field efficiency. The receiver specific parameters are obtained from Buck's explanation of the connection between receiver efficiency (η_{rec}) and design flux for the CentRec through the equation (*10*), which has a similar geometry as the solar calciner [14].

$$\eta_{rec} = \beta - \left(\mathcal{E} \cdot \sigma_r \cdot T_{rec,out}^4 + h \cdot \left(T_{rec,out} - T_{amb} \right) \right) \cdot \frac{1}{P_{ap}} \tag{10}$$

Thus, $\beta = 0.95$ is the effective solar absorptivity, $\mathcal{E} = 0.9$ effective thermal emissivity, $\sigma_r = 5.67E-08 \frac{W}{m^2k^4}$ is the Stefan-Boltzmann constant, $T_{rec,out} = 900\ °C$ is the receiver particle outlet temperature, $h = 30 \frac{W}{m^2K}$ is the heat loss coefficient to the ambient and $T_{amb} = 30\ °C$ is the ambient temperature. $P_{ap} = 1250 \frac{kW}{m^2}$ is the solar flux density on the aperture. *Figure 18* explains the efficiency of both field and receiver on a January 1st 2022. It shows that the solar operation begins around 8:00 and reaches its maximum around 13:00 and then stops at 18:00 depending on the sun setting point.

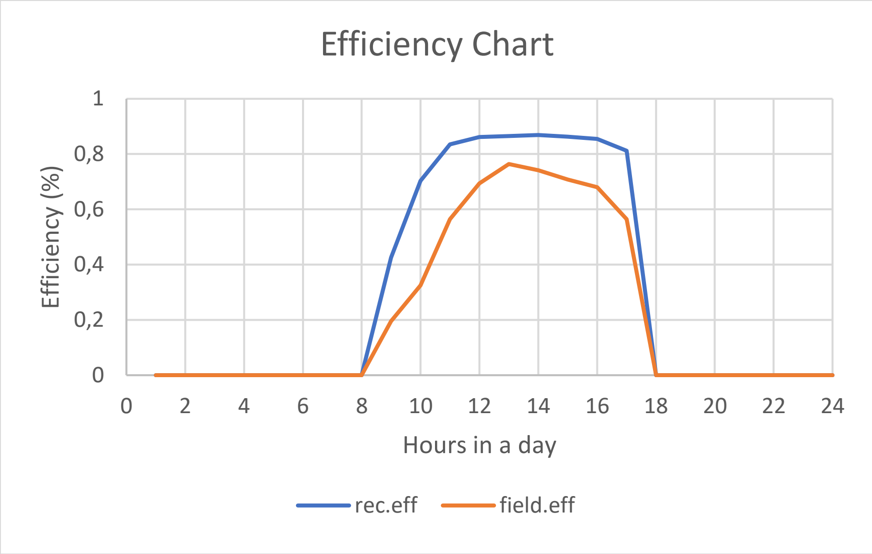

Figure 18. Field and receiver efficiency on 01. January 2022 for SM 3.75

Other necessary considerations were also made in order to calculate the total power output over the course of the year. The plant should go for shut down and maintenance for a few days in order to exercise the plant's safe operation. Generally, production plants require 30 days for this maintenance and there will be no power generation from the plant during this period. The 30 days continuously with the lowest power output over the course of the year should be eliminated. The lowest cumulative power generation is found to be in between January 02nd and February 2nd of the every year. Therefore, the entire month of January is taken into account for the shutdown and maintenance. Additionally, the total power generation from the CSP plant is limited to 110 % to avoid the excess energy and unnecessary equipment usage. The calcination receiver must also be heated for the operation at the start of the day, so the first solar hour power of the day is also ignored for this purpose. Following all limitations, the total power production of each hour of the year is shown in *Figure 19* The total power produced with these limitations will be 867,602 MWh where total power required would be 1,019,636 MWh, which makes 85 % of solarization.

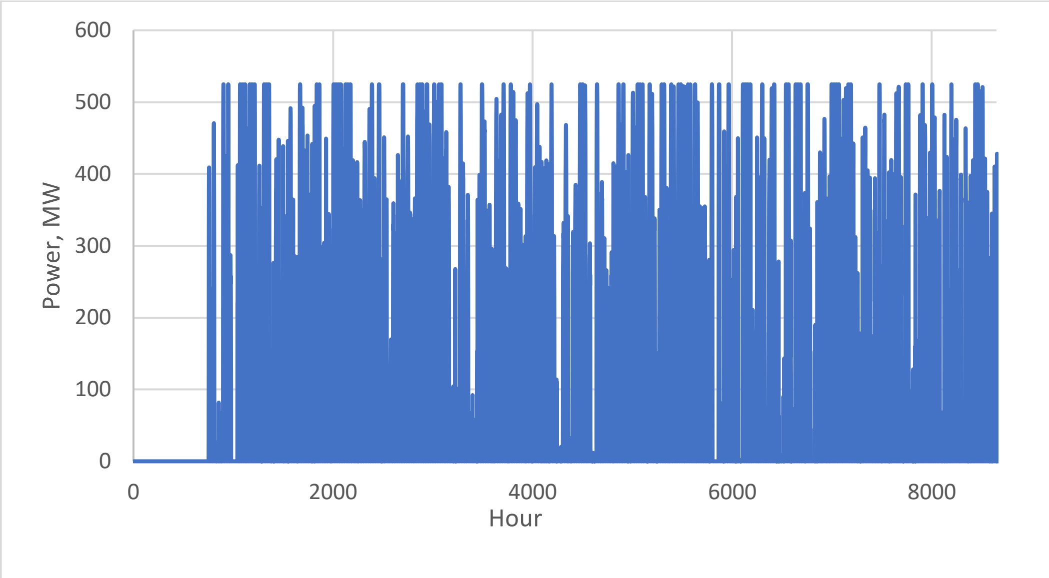

Figure 19. Power production for every hour

4 Economic Analysis

4.1 Cost Estimation Methodology

In determining the viability and profitability of the projects, economic evaluation is essential. Economic evaluation entails a thorough review of numerous important aspects, some of them are considered here are Capital Expenditure (CAPEX), Operational Expenditure (OPEX), CO_2 avoidance cost (CAC) and cost of cement and clinker (COC).

Some general factors important for the economic assessment are listed below in the *Table 7*.

Table 7. General factors for economic evaluation

Parameter	Value	Units
Operational years	25	years
Clinker production	1	Mt_{clk} / year
Cement production	1.36	Mt_{cem} / year

Cost Index and Lang factor

Among all aspects, the process equipment cost plays a major role in the investments. The estimation of equipment costs is done through the cost estimated in previous years by using the cost index approach. Most cost data available for making a preliminary or predesign estimate is only valid at the time it was created. Because prices may have changed significantly over time due to changes in economic conditions, some method for updating cost data applicable at a previous date to costs representative of conditions at a later time must be used. This can be accomplished by employing the chemical engineering plant cost indexes (CEPCI) [49] for the month of July 2022 [34].

A cost index is an index value for a specific time that shows the cost at that time in relation to a specific base time. This method is used for the majority of the process equipment cost estimation in this work. The current value of the specific equipment can be estimated by using the equation (*11*).

$$\text{Present cost} = \text{past cost}\ (\text{CEPCI}) \quad (11)$$

$$\text{CEPCI} = \frac{\text{index value at present year}}{\text{index value at the past year cost estimation}} \quad (12)$$

Lang factor refer to a multiplier used to estimate the total cost of a project or equipment when the purchase costs of the equipment are known. The Lang factor can range from 2 to 6, depending on the complexity and scale of the project [49].

4.2 Capital Expenditure

The initial expenditure needed to build or improve an industry is referred as CAPEX. This covers expenses related to purchasing the equipment, their installation cost and contingency factor along with the property and other infrastructure. The total plant system is divided into two main categories based on their operation in order to accurately estimate the total investment needed, 1) Solar site and 2) Conventional site. The precise cost of all equipment has been evaluated using correlations from research articles and widely used techniques mentioned in project economics-based literature in order to accurately estimate the necessary investment.

4.2.1 Solar Site

The cost estimation for the solar site is done based on the capacity distributed into five major categories: 1) Solar tower, 2) Heliostats, 3) Solar Rotary Kiln, 4) Transport System, 5) Preheaters.

I. Solar Tower

The tower is one of the CSP system's most important components. Using the correlation described by Weinrebe [68] depending on the tower height considered as expressed in the equation (*13*) is used to estimate the cost of the tower. The tower height is taken from the HFLCAL setup, which is fixed to be 199 m. This correlation estimates the cost for the year 2014 ($Tower_{cost,old}$), so that the CEPCI is used to obtain the present cost of the tower as mentioned in equation (*14*). A lang factor of two is used for the additional expenses. The tower consumes 2/3rd of the total cost where remained 1/3rd goes for piping and installation [68]. The tower cost is calculated in euros as per the source and converted to dollar at current rate.

$$\mathrm{Tower_{cost,old}} = 0.0003034 \cdot \left(\mathrm{t_{height}^2}\right) - 0.0490 \cdot \mathrm{t_{height}} + 6.48 \qquad (13)$$

$$\mathrm{Tower_{cost,present}} = \mathrm{Tower_{cost,old}} \cdot \mathrm{CEPCI} \cdot \mathrm{Lang\ fact} \qquad (14)$$

II. Heliostats

The largest portion of the overall investment needed for the CSP system is represented by heliostats. The mirror area needed is directly correlated to the cost of the heliostats. The projects required area is determined from the results of HFLCAL based on the thermal energy output. As a result, the heliostat lowest marginal installed cost of 96 $\$/m^2$ is considered from the literature [59].

$$\mathrm{C_{heliostat}} = 96 \left(\frac{\$}{\mathrm{m}^2}\right) \cdot \mathrm{Mirror\ Area\ (m^2)} \qquad (15)$$

III. Rotary Kiln

In the CSP system, rotary kilns would be utilized for the calcination process. Since, the solar rotary kiln would differ from a conventional kiln, an existing solar receiver (CentRec) with similar geometry is considered as reference. In literature [16] the calculated the cost of the CentRec based on its power demand where mentioned charges are 38 $/kW. The consideration involved in the final calculation of rotary kiln cost ($C_{R.Kiln}$) is explained in below equation (*16*). CentRec is used for other operation so a higher lang factor of 3 is considered to estimate the cost for rotary kiln.

$$C_{R.Kiln} = \text{power demand (kW)} \cdot 38 \left(\frac{\$}{kW}\right) \cdot \text{CEPCI} \cdot \text{Lang fact} \tag{16}$$

IV. Transport system

The raw material should be fed from the bottom storage units to the top of the tower's preheaters and calciner, and then the calcined material should be transported back to the ground by a transporting system. Initially, it is estimated that 500 t/h (Capacity A) of the material is transported for the solar operation with an investment of 1.7 M$. It is adapted to the final mass flow resulted in the Aspen Plus simulation of 1184 t/h (Capacity B) with a scaling factor of 0.8 and lang factor of 3 as mentioned in equation *(17)*.

$$C_{transport} = 1.7 \cdot \left(\frac{\text{Capacity B}}{\text{Capacity A}}\right)^{0.8} \cdot 10^{-6} \cdot \text{Lang fact} \tag{17}$$

V. Preheating system

The size or mass flow capacity of the system can be used to estimate the cost of the preheating system. Through the systems mass inlet flow, IEA [20] estimated the cost of five-stage preheating system with a flow rate of 51.6 kg/sec (Case A), and it claims that costs are roughly 3.8 M$. Due to the operational capacity shown in *Table 8*, it is modified in this project to use two preheating systems with three stages each and a higher mass flow rate of 164.5 kg/sec (Case B). The initial cost consideration for the two systems according to IEA report would be 7.5 M$ along with the CEPCI. Equation *(18)* was used to calculate while taking the scaling factor of 0.7 and lang factor of 2 into consideration.

$$C_{preheater} = 7.5 \cdot \left(\frac{\text{Case B}}{\text{Case A}}\right)^{0.7} \cdot \text{Lang fact} \tag{18}$$

Table 8. Capex with two tower system (SM 3.75)

Component	Capacity	Equip.cost (M$)	Lang fact	Final cost (M$)
Solar Site		**(1 tower)**		**(2 tower)**
Tower	200 m	9.2	2	36.7
Heliostat	458756 m^2	44.0	1	88.1
Rotary Kiln(s)	238.5 MW	11.4	3	68.6
Transport System, solar	1184 t/h	3.5	3	20.7
Pre-Heaters, solar	164.5 kg/sec	27.9	2	111.8
Conventional site				
Carbonator	2	3.8	2	7.6
Milling and drying, solar	1	64.8	1	64.8
Cement plant	3000 t/d	303.3	1	303.3
EPC (25 %)				175
Land (2 %)				8
Total CAPEX				894 M$

4.2.2 Conventional site

It primarily falls under three categories: 1) carbonator 2) the milling and drying section 3) conventional plant. The detailed cost estimates are made using references from previous studies and correlations, much like the solar site.

i. Carbonator

Numerous research works estimated the carbonators in several processes based on their volume or thermal power. This evaluation is based on the heat transfer of the carbonator and adapts the estimation method used by Ortiz et al [57] for a fluidized bed reactor.

The heat release in the carbonator for our process is approximately 2 MW (Q_{th}) as obtained from Aspen Plus simulation results. The calculation is carried out with below mentioned equation *(19)* by Ortiz et al.

$$C_{Carbonator} = \left(16591 \cdot Q_{th}^{0.67}\right) \cdot 10^{-6} \text{ [M\$]} \quad (19)$$

ii. Milling and drying

The IEA's estimate is used to determine the reference costs for milling and drying [20]. The grinding and drying sections works in stages with various machinery like raw mill drive, raw mill fan, raw mill ancillaries, raw mill bag filter and bag filter fan. IEA lists every equipment and summing it to the final cost of the milling and drying section. The literature stated that the investments cost 30.6 M$ for a plant with a capacity of about 1 Mt_{cem} per annum (Case A). The capacity of current model would be around 1.3 Mt_{cem} per annum (Case B).

$$C_{milling} = 30.6 \cdot \left(\frac{Case\ B}{Case\ A}\right)^{0.8} \text{ [M\$]} \quad (20)$$

iii. Conventional Plant

The CEMCAP project deliverable 4.2 has already estimated the CAPEX of the conventionally operated site. It primarily consists of the calciner, rotary kiln, preheating system and clinker cooling system. Here, the cost of increasing current project capacity from 2896 t_{clk}/d (Case A) to 3000 t_{clk}/d (case B) is taken into consideration, and its value for current year is done through CEPCI. The previous CAPEX for the CEMCAP conventional model was 200 M$ for the conventional plant.

$$C_{conv} = 200 \cdot \left(\frac{Case\ B}{Case\ A}\right)^{0.8} \text{ [M\$]} \quad (21)$$

iv. EPC and Land

Large infrastructure projects, including those in the energy and construction sectors, often use a type of contract known as EPC (Engineering, procurement, and construction). It is a comprehensive contract that covers the design, acquisition of tools and materials, and construction services need to compete the project. Around 25 % of the total CAPEX was considered according to the report made by Peters et al. [49] on plant design and economics. Land calculations involve assessing the cost and value of the land that will be used for the project. It is considered the total land cost would be 2 % of the total CAPEX as per above mentioned literature.

4.3 Operational Expenditure

All recurring costs incurred during the plant operation are included in OPEX. This covers the purchase of raw materials, the use of energy, the cost labor, maintenance etc. The data for the OPEX calculations are considered from the CEMCAP report that listed all the factors for cement factory.

1. **Raw materials**

In the cement manufacturing process, operating expenses for raw materials refer to ongoing costs related to obtaining and utilizing the raw materials required for clinker production. It requires 1.66 t of raw meal to produce 1 t of clinker. Using CEPCI, current cost of the raw meal is around 4.5 $/t as mentioned in the CEMCAP. Based on the calculations for the analyzed process a total 1.6 Mt of the raw meal is required for the clinker production capacity. Final spendings on the raw meal yearly basis would be 7.5 M$. This amount represents the annual operating cost of continuously acquiring and using the necessary raw meal to produce specified clinker rate over the course of year.

2. Utilities

Coal and electricity will be the main source of utilities for the cement production. Based on the amount of solarization, the usage of coal would be reduced compared with the fully conventional plant. For the SM 3.75 the fuel consumption would be 1.57 MJ/kg while the electricity consumption stays constant at 0.457 MJ/kg due to the absence of solar power. In areas that are operated through electricity and the additional crushing needed for solar system is considered as an intermediate crushing in conventional part. These numbers translated into annual fuel and electricity consumption of 440582 MWh and 132889 MW, respectively. According to CEMCAP, the price for the coal was considered as 16 $/MWh and 85 $/MWh for electricity.

3. Maintenance

The costs associated with daily maintenance of the cement plant's smooth operation and dependability are referred to as maintenance costs. Costs for consumables and spare parts required for machinery maintenance are also included. According to the CEMCAP, the maintenance of the plant consumes close to 2.5 % of the total CAPEX. In this study it is set to 3 %, and the increase was made as a result of the CSP plant upgrade, that results 26.3 M$/a totally.

4. Labor costs

The wages, salaries and benefits that are paid to the work force assisting in production are included in labor costs. This includes skilled workers, technicians, engineers and support personnel to operate and maintain the equipment, manage production, quality control, logistics, and administration. Wage rates, labor laws, over time and work productivity will have an impact on the labor costs. As per the analysis done on the US labor laws and method mentioned by Peters et al. [49] it is valued as 5.5 M$/t in an operational year considering 62 workers.

Other elements that must be taken into account include insurance and the cost of replacing specific equipment based on their operational life (Rotary kiln). The replacement will be for 15 years with an interest of 2 % while the insurance will take up 2 % of the total capital [49]. The total operational costs are added up to obtain the OPEX, which will be incurred over the course of the plants' operational life.

Table 9. Opex for the CemSol

Parameter	Cost (M$/a)
Raw meal	7.5
Fuel	7.1
Electricity	11.2
Labor	5.5
Insurance	17.5
Maintenance	26.3
Replacements	1.6
Total OPEX	76.9

4.4 CO_2 Avoidance Cost

The cost of avoiding or reducing the CO_2 emissions is referred to the CO_2 avoidance cost (CAC) [64]. It determines the expenses for carrying out the plans or initiatives to slow down climate change by reducing the CO_2 emissions. CAC is generally measured in the budget spent to avoid one tonne CO_2 ($/$t_{CO2}$). Simon et al. [64] explains a number of methods that can be used to calculate the CAC. The equation *(22)* mentioned below is used for the current work. This includes the yearly capital expenditures for carbon reductions, yearly operating expenditure for carbon reductions and the annual amount of carbon reduced through the CC application. The annual CAPEX is calculated here with an interest of 8 % results in annuity of 9.4 %.

$$\mathrm{CAC} = \frac{\text{Annual CAPEX for CO}_2\text{ reduction} + \text{ Annual OPEX for CO}_2\text{ reduction}}{\text{Annual amount of CO}_2\text{ emissions reduced}} \qquad (22)$$

4.5 Cost of Clinker and Cement

Similar to the CEMCAP methodology, the price of the cement and clinker is estimated. The product cost is the sum of all investments made to produce one tonne of clinker. The CEMCAP report states that clinker cost is 1.36 times higher than the cost of the tonne cement because the cement is a mixture of clinker and other additives such as gypsum which is less expensive than clinker.

$$C_{\text{Clinker}} = \frac{\text{Annual CAPEX} + \text{Annual OPEX}}{\text{Annual amount clinker produced}} \quad (23)$$

$$C_{\text{cement}} = 1.36 \cdot C_{\text{clinker}} \quad (24)$$

5 Results and Discussion

In this section, the techno-economic results for the CSP-CaL cement plant are presented. The effect of the solar multiple on the solarization rate is first explained in section 5.1. The reductions of CO_2 emissions for each solar multiple and their distribution are described in section 5.2. The economic results are explained in the section 5.3 along with cost breakdown for product cost, CO_2 avoidance cost, and cost distribution. The techno-economic result comparison of all factors is described in section 5.4.

5.1 Solarization

Solarization of the plant depends upon the power production to the power required for the process. The plants annual operational hours would be 8016 when all restrictions for the maintenance are taken into consideration. With 127 MW thermal energy needed in hour, the power requirement will be 1, 019, 636 MWh for the considered plant capacity. Due to the limitation in sunlight and receiver efficiency a 100 % solar operation is not possible. *Table 10* lists the energy production of the examined solar multiples based on the above considerations for the system.

Table 10. Total solar power production and solarization in the plant

Solar multiple	Overall production (GWh)	Deficient (GWh)	Solarization (%)
2.5	572.6	-446.9	56
2.75	630.6	-388.9	61
3.0	689.6	-330.0	67
3.25	748.8	-270.7	73
3.5	810.5	-209.0	79
3.75	867.6	-152.4	85

According to *Table 10* and as expected, the rate of solarization increases as the solar multiple increases. Among the solar multiples under considerations, 85 % of maximum and 56 % minimum solarization can be attained through the solar operation while losing remaining of the required demand for maintenance, receiver efficiency and sunlight availability. The variation of solar output is also greatly influenced by the design power as well. The solarization based on the design power of a single tower in each SM are presented in *Figure 20.*

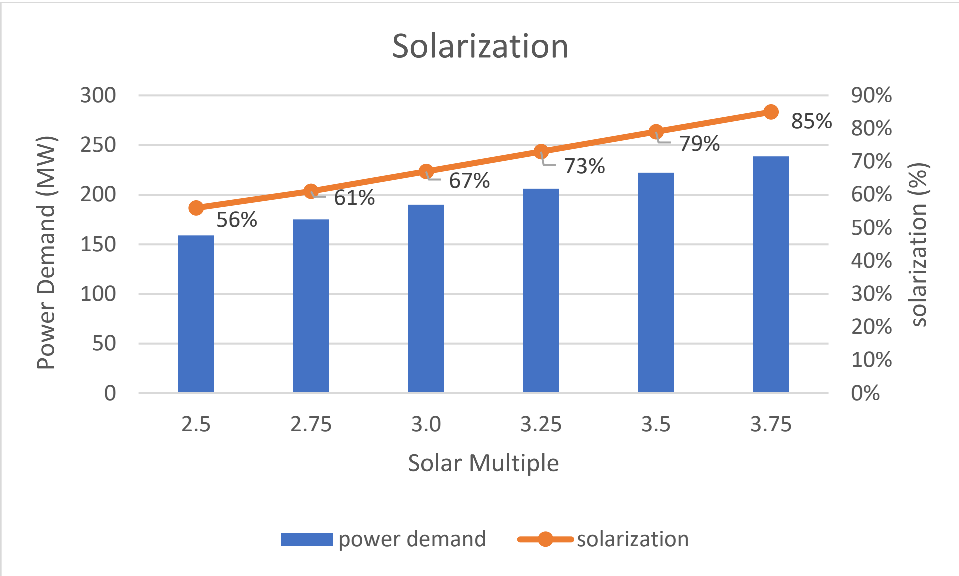

Figure 20. Solarization rate vs Design power

5.2 CO_2 Emission Reductions

In the cement industry, calcination reaction (65 %) and coal combustion (30-35 %) account for the majority of CO_2 emissions. The use of coal and its emissions are significantly impacted by the solar calcination. *Table 11* illustrates the SM impact on the coal utilization in the conventional part.

Table 11. Change in thermal energy (Coal) demand with SM

Solar Multiple	Conv	2.5	2.75	3.0	3.25	3.5	3.75
Thermal energy demand (MJ/kg)	3.135	2.1	2.0	1.89	1.76	1.67	1.57

In additions to the fuel emissions from the conventional calciner, the calcination reaction, rotary kiln and electricity emissions are also to considered. The *Figure 21* shows the total CO_2 emission reductions from the solarized cement plant for various solar multiples. Of all the SM being studied, the CO_2 reduction starts at 52 % by the SM 2.5 and can be neglected up to 79 % maximum by emitting 151 kg_{CO2}/t_{clk} with SM 3.75 comparing to the conventional plants 720 kg_{CO2}/t_{clk}.

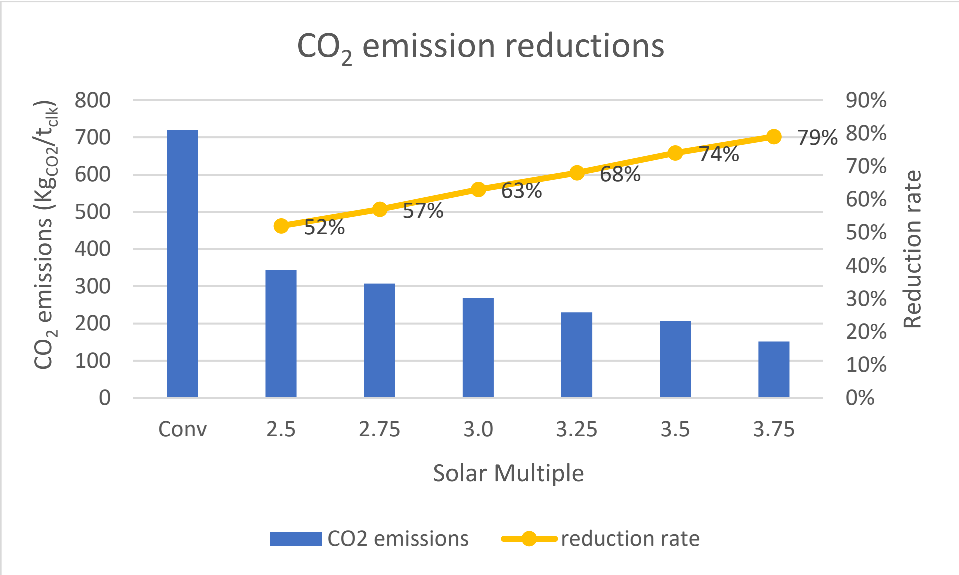

Figure 21. CO_2 Emission Reductions

5.2.1 Emissions Distribution

This section explains the CO_2 emission distribution of the operation for the case with SM 3.75. The explanation includes four process schemes, to show step-by-step how the emissions are distributed for a solar operation with carbon capture and are illustrated in *Figure 22.*

- **Solar calciner only, 100 % of raw meal, 100 % operation in the year, no capture**
  Process scheme 1 is a theoretical case to assess the maximum reduction with solar calcination only (no calcium looping, *i.e.*, capture). The overall emissions of a conventional cement plant's calciner are 65 % due to reaction and 16 % from the coal combustion. The rotary kiln for clinker production, its reactions and the electricity are the reasons for the remaining emissions. Therefore, in case of full raw meal fed into the solar operation along with 100 % solarization, the emissions (83 %) due to calcination

reaction and fuel can be avoided. The remaining emissions from conventional plant would be due to fuel (8 %), reaction (4 %) and electricity (5 %).

- **Solar calciner only, 90 % of raw meal, 100 % operation in the year, no capture**
  In process scheme 2, 10 % of the fine raw meal particles are supplied to the conventional section, to keep the conventional calciner running at part-load, and remaining sent to the solar operation with 90 % calcination rate. This resulted in fuel rise for conventional part. Fuel emissions grow from 8 % to 10 % and reaction emissions rise from 4 % to 10 % as raw meal and fuel increment in conventional operation. As a result, the overall emissions from the plant reduces from 83 % to 75 % due to lower solar operation compared to the process scheme 1.

- **Solar calciner only, 90 % of raw meal, 85 % operation in the year, no capture**
  In scheme 3, the effect of having 85 % of solarization is depicted, thus, considering the real meteorological conditions onsite. As a result the emissions in the conventional part increase as the non-calcined material in solar part is fed into the conventionally operated section. The increased emissions are reported as non-solar with a share of 11 %. So, the overall reduction rate after this scenario is 64 %.

- **Solar calciner and carbonator, 90 % of raw meal, 85 % operation in the year, 90 % capture**
  Finally in scheme 4, a capture system is added where 90 % of the emissions from the conventional part are being captured. As a result, the fuel and reaction emissions from the conventional plant largely decrease (15 %) due to the capturing. As a consequence, the total reduction rate increases from 64 % to 79 % with fulfilling all the considerations of the developed model compared to the existing conventional plant.

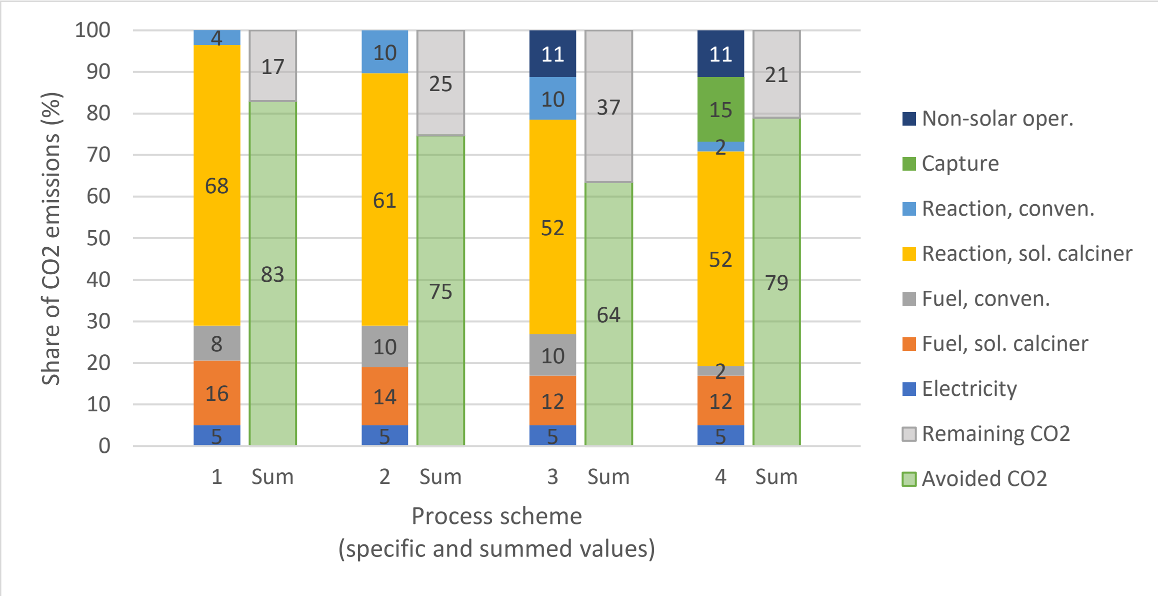

Figure 22. CO_2 Emission Distribution

5.3 Economic Results

This section outlines the overall costs associated with each solar multiple according to the method described section 4. Each SM's CAPEX and OPEX listed in the table shows that a higher level carbon reduction necessitates more capital, as evidenced by the rising costs with increase in solar multiple.

Table 12. CAPEX and OPEX of all solar multiples

SM	CAPEX (M$)	OPEX (M$/a)
2.5	779	73.1
2.75	802	73.8
3.0	825	74.6
3.25	848	75.3
3.5	871	76
3.75	894	76.9

The next section shows a breakdown of CAPEX and OPEX for solar multiple 3.75. The total investment is divided into two portions, where 52 % is shared by capital covering upfront infrastructure and equipment costs, and 48 % is designated for operational costs covering the ongoing maintenance and operations as seen in *Figure 23.*

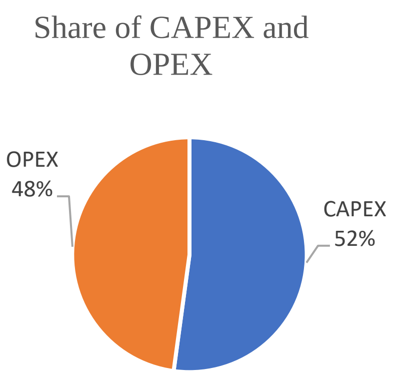

Figure 23. Share of CAPEX and OPEX on the production cost for SM 3.75

The total plant CAPEX lies around 894 M$ and is divided in different compositions as shown in Figure *24*. The building and setup of the conventional plant infrastructure, which includes all necessary facilities for raw material processing and clinker production is assigned the largest component accounting for 43 % of the total. Preheating system, which increase energy efficiency by heating raw materials before they reach the rotary kiln, receive a considerable 16 % of the budget. The 13 % is shared by heliostats represents a financial commitment to solar thermal technology. 10 % of the CAPEX goes into the rotary kiln, a crucial component in the solar system. The remaining portion of 18 % is distributed among important components that individually contribute to sustainable and efficient operations including the carbonator for carbon capture, material transporting system, milling and drying procedures.

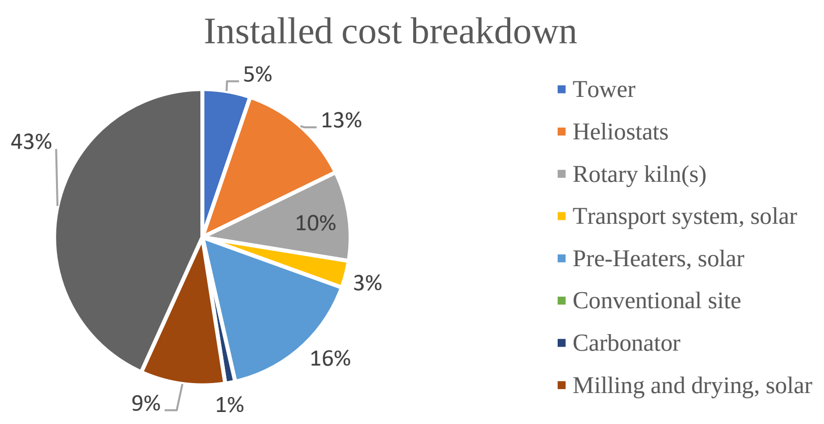

Figure 24. CAPEX composition of SM 3.75

The Operational expenditure of 77 M$ annually, is split among many crucial operations. The largest portion, constituting 34 %, is shared by maintenance activities to ensure the continuous and efficient operation of the plant. Following closely is 23 % allocated to insurance protection, securing the plant against potential hazards and unforeseeable occurrences. The considerable power needs for the plant's operation are reflected in the 15 % contribution of electricity consumption to OPEX and fuel takes 9 % for the necessary high temperature procedures. The procurement of raw materials needs 10 % of the costs, while labor costs takes up to 7 %. Additionally, 2 % is set aside for the replacement of rotary kiln considering 15 years of operation, a vital unit in the process. A schematic view of the OPEX breakdown can be seen in *Figure 25*.

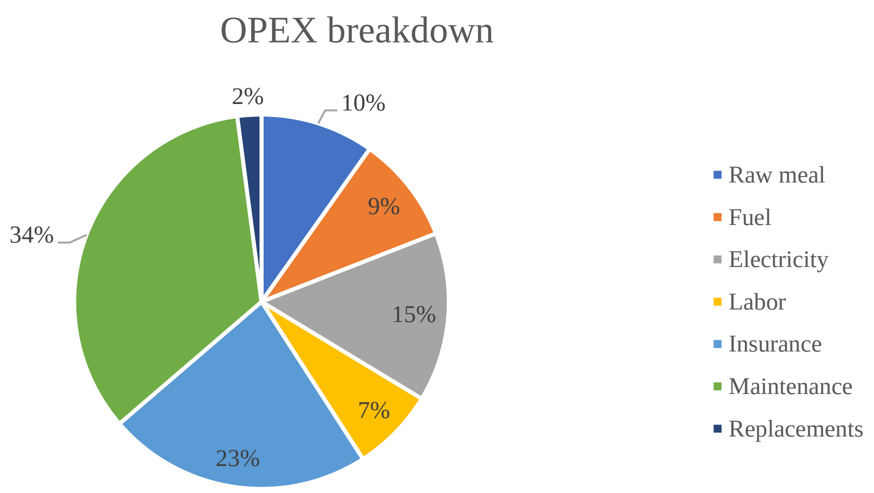

Figure 25. OPEX breakdown of SM 3.75

5.3.1 Cost of Clinker and Cement

The cost of clinker is significantly influenced by the solar multiple chosen for the process. Higher solar multiple require bigger expenditures in solarization and energy efficient technologies, which drives up the clinker cost. *Table 12* shows the rise of clinker costs with increase in the solarization rate. The basic cost of clinker starts at 143.5 $/t for solar multiple 2.5 and reaches its maximum at 157.8 $/t for solar multiple 3.75 among the examined solar multiple cases.

It is crucial to note that, despite being inextricably related to clinker production, the cost of cement benefits from the addition on additives that lower its overall cost. As a result the price of cement is 1.36 times less expensive than the price of clinker. This price disparity emphasizes the economic benefit of using additives in cement preparation, effectively lowering the entire cost per ton. A direct comparison to the costs of the reference cement plant, where cement costs 71 $/t and clinker costs 96 $ per ton, demonstrates that the current developed model costs are significantly higher. However, both products have highly different carbon footprints making a direct comparison difficult. It is essential to note, that these costs were calculated without considering CO_2 taxes. As market dynamics and environmental regulations change, the economic environment for the cement and clinker cost may experience considerable changes that have an impact on the entire cost structure.

Table 12. Cost of clinker and cement

SM	Cost of Clinker ($/$t_{clk}$)	Cost of Cement ($/$t_{cem}$)
2.5	143.55	105.55
2.75	146.40	107.65
3.0	149.27	109.76
3.25	152.02	111.78
3.5	154.85	113.86
3.75	157.82	116.05

5.3.2 Cost breakdown for clinker

A shown in *Figure 26*, the breakdown of the product costs for clinker production at SM of 3.75 shows an investment contribution of 81.5 $/t for capital installation, followed by maintenance spending of 26 $/t and insurance costs 17.4 $/t for ongoing facility operations and risk protections. Additionally, 7.1 $/t and 11.1 $//t go into fuel and electricity respectively. The labor related payment share is 5.5 $/t and the equipment replacement portion is 1.6 $/t.

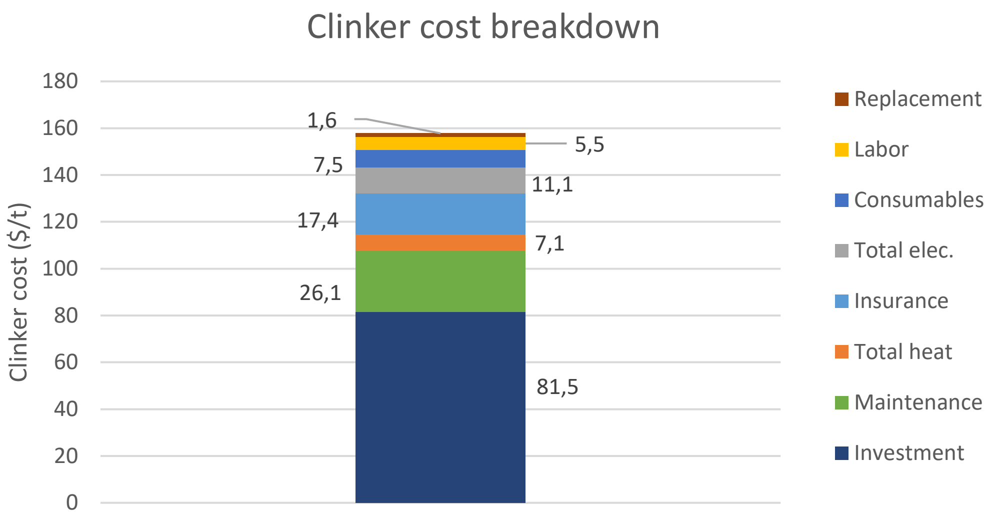

Figure 26. Cost breakdown of clinker for SM 3.75

5.3.3 Cost Comparison

The *Figure 27* explains the variation of the product cost and CO_2 avoidance cost in relation to the examined solar multiples. The cost of clinker, cost of cement, the value of solar multiple and the associated costs of CO_2 avoidance are the main factors that were analyzed.

Firstly, the prices of cement and clinker both exhibit a consistent upward trend as the solar multiple values rise. This pattern can be explained by the fact that higher solar multiple values call for greater investments in solar enhanced calcination process (*Table 12*). Secondly, a trend can be seen in the CO_2 avoidance cost, which is the expense incurred per unit CO_2 reduction. The CO_2 avoidance cost constantly falls at the rate of 3 % up to a solar multiple of 3.5. This decrease shows that the initial investment made in carbon reduction system produces higher reduction in CO_2 emissions, resulting in more cost effective carbon avoidance as solar multiple rise. But in between the solar multiple 3.5 and 3.75, there is a noticeable shift in the trend. Costs associated with avoiding CO_2 fall at a slower rate of 1.9 %. The implication of transition is that, even though more investments in carbon reduction system continue to lower the emissions, the benefits start to wane. The increase in the investment necessary to capture additional carbon becomes relatively higher than the reduction achieved, thus, nearing an optimum.

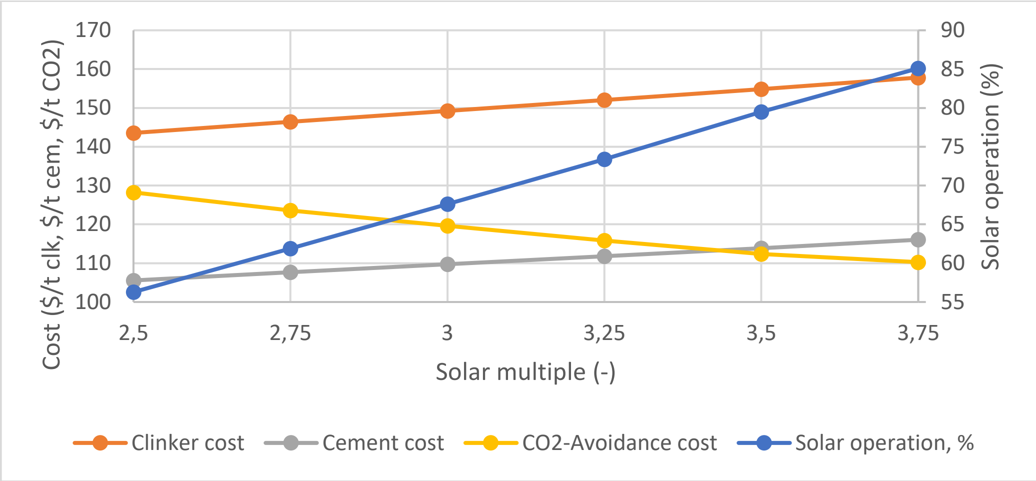

Figure 27. Cost results of all solar multiples

A comparison analysis of CO_2 avoidance costs across various CC technologies mentioned in section 2.3 has been done thoroughly by Verein Deutscher Zementwerke (VDZ) [74]. The results shows various approaches have considerable cost differences. The costs of post-combustion capture, which aims to absorb CO_2 after combustion, range from 87-98 $/t_{CO2}$. Oxyfuel technology, an alternative technique depending on combustion with pure oxygen to permit simpler CO_2 extraction, exhibits a considerably lower cost range of 43-65 $/t_{CO2}$. The avoidance cost for the this CSP-CaL project, considerably higher at 110 $/t_{CO2}$. The higher costs of the CSP-CaL system, which sets apart from other capture technologies are related to the increased complexity brought on by solar integration. Although more expensive, this system is a ground breaking innovation that has the potential to reduce CO_2 emissions by opening up a promising new path for long term emission reductions.

5.3.4 Cement Cost and CO_2 Tax

The *Figure 28* shows the relation between the price of cement and CO_2 tax, with a black line denoting the current CO_2 tax rate of 87 $/t_{CO2}$ under the EU ETS (European Union Emission Trading Scheme). The figure illustrates that while CO_2 taxes climb, the cost of making solar cement increases slightly, whereas the cost of making conventional cement substantially increases. A noteworthy point made by the graph in that once the CO_2 tax reaches the threshold of 110 $/t_{CO2}$, Solar cement becomes economically viable compared to conventional cement. Under the influence of rising CO_2 taxes, this threshold marks a pivotal point at which the economic advantage of solar cement becomes pronounced, placing it as a more affordable substitute for conventional cement.

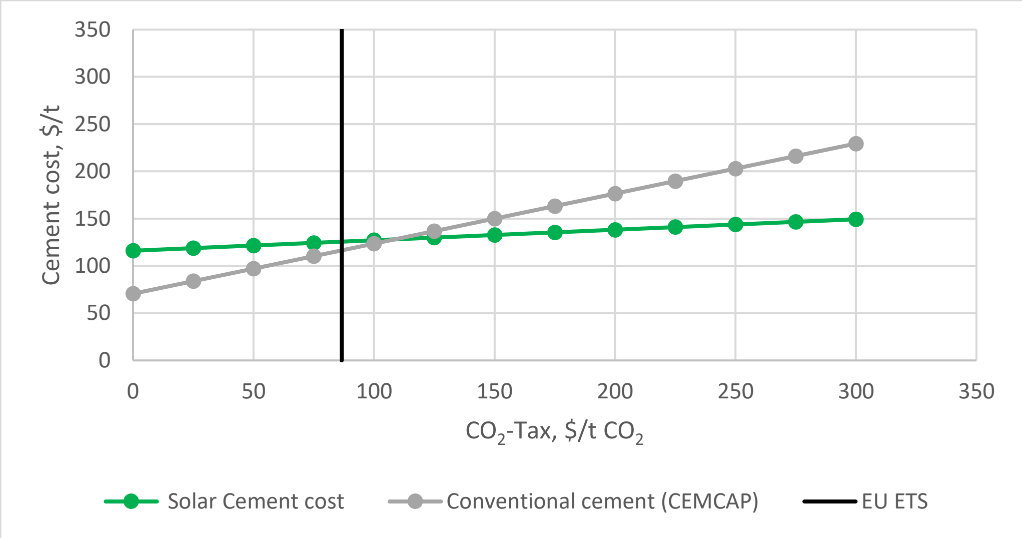

Figure 28. Cement Cost Vs CO_2 tax

5.4 Sensitivity Analysis

Sensitivity is a crucial technique used for assess in the robustness and reliability of the results obtained from a particular economic model or evaluation. It is employed to understand how sensitive the outcomes are to change in key variables, assumptions or parameters within the model for SM 3.75.

5.4.1 Cement Cost variations

Figure *29* presents a thorough sensitivity analysis of cement costs, show casing the impact of different cost for key components - heliostats, rotary kilns, fuel and electricity across a range of -50 % to +100 % changes. The analysis provides insightful information on how changes in the cost factors affect the overall cost of the cement.

With initial capital expenditures of 88 M$ and 68 M$ respectively, heliostats and rotary kiln have noticeable impact on the cement price. The overall cost of cement increases in direct proportions to the capital of these two expenses. In operating investments, fluctuations in fuel and electricity costs also impact the cost of cement as they are important costs for the production. A decrease in the price of fuel will not have a significant impact on the cement price due to the limited usage and low price of coal compared to the other parameters.

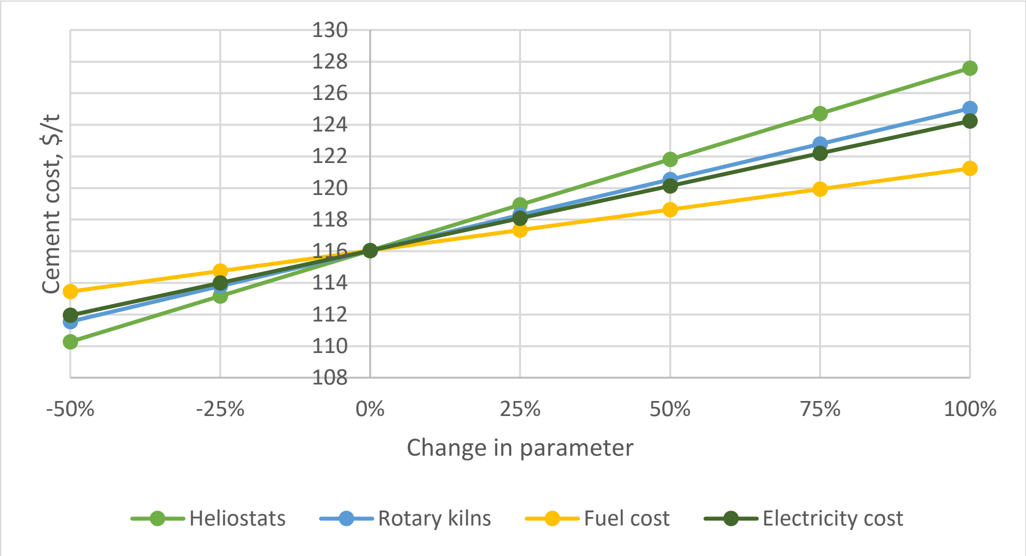

Figure 29. Sensitivity analysis for cement cost

The sensitivity analysis of the graph demonstrates the complex relation between the price of essential pars and how those effect the manufacturing costs. With their significant capital investment needs, heliostats and rotary kilns have a greater impact on the cost structure. Even if operating investments in fuel and electricity have a more gradual impact, variation in these factors are nevertheless quite important in determining total cement cost. This analysis serves as a valuable tool for the decision makers in understanding the financial implications of cost fluctuations in crucial elements of cement production.

5.4.2 CO_2 Avoidance Cost Variations

The sensitivity analysis for CO_2 avoidance costs shows a progressive rise that is correlated with increasing costs for the heliostats and rotary kiln. This tendency is mostly attributable to the fact that investments in heliostats and rotary kilns have a significant impact on CO_2 reduction rate attained in cement process *Figure 24*. The overall costs spent for the carbon capture and

CO_2 reduction initiatives increases as the price of these essential components rise, which also drives up the price of CO_2 avoidance.

Notably, the change in electricity prices has no appreciable effect on the expenses associated with CO_2 avoidance as seen in *Figure 30*. This is due to the fact that no more electricity is being consumed for the carbon reduction compared to the conventional operation. In contrast, there is an indirect proportionality between fuel consumption and cost of avoiding CO_2. The conventional plant is more impacted by the rise in fuel prices than the solar part since the fuel demand in the solar process is significantly lower.

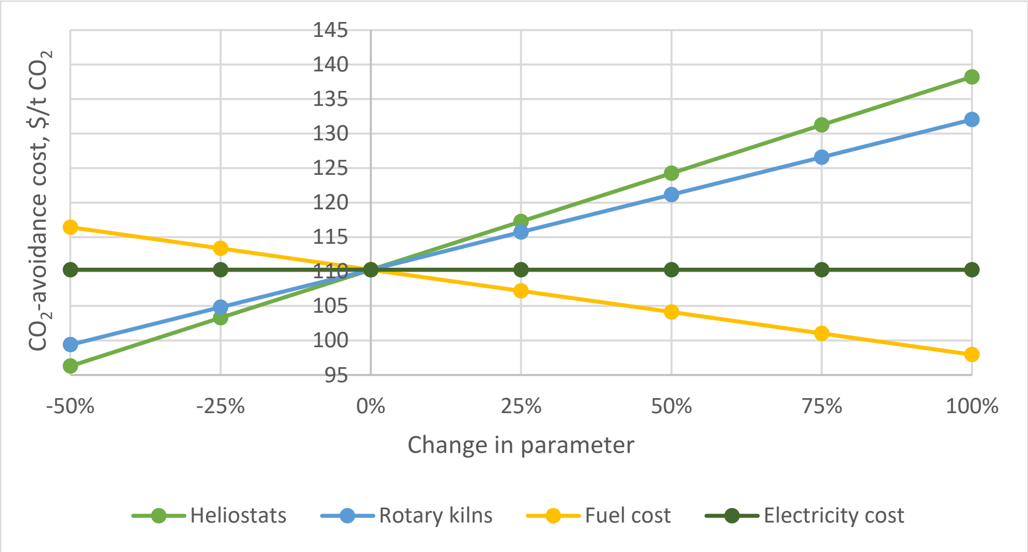

Figure 30. Change in CO2-avoidance cost

6 Conclusion and Futurework

6.1 Conclusion

In conclusion, research work on integrating the solar calcination and calcium looping technologies for the carbon capture and fossil fuel usage reduction in the context of decarbonization of cement industries has given promising findings. The solar multiple of 3.75 stands out as the most interesting viable option among the numerous solar multiples evaluated, considering a fixed tower height. Despite the fact that costs typically increase gradually as the solar multiple rises, it is important to emphasize that, after solar multiple 3.5 the CO_2 reduction rate encounters a declination. This would be a breaking point for attaining the significance balance between the affordability and effective CO_2 reduction.

The economic effects deploying this technology are illustrated by the predicted ultimate cost of cement and clinker as 116 $/t and 158 $/t respectively. Where conventionally produced cement and clinker costs 70 $/t and 96 $/t . It is clear that the 3.75 solar multiple was selected since it not only maximizes financial factors but also results in outstanding solarization and reduction rates in the presence of the several limitations, where 85 % of solarization and 79 % of CO_2 reduction rate are achieved. Moving to cleaner cement production this will demand a significant financial commitment, as seen by the estimated 894 M$ of capital expenditure and 77 M$ annual operational expenditure.

In essence, the findings highlight the potential of solar calcination and calcium looping technology to spreadhead the decarbonization of cement industries. The chosen SM 3.75 indicates its potency in achieving a compromise between cost, CO_2 reduction rate, solarization and technical feasibility. Adopting such solutions becomes necessary as the global movement towards carbon neutrality gathers steam, but it is also a proactive step towards a green and more resilient future for the cement industry and beyond.

6.2 Future Work

Future work on creating a thorough heat recovery system from the coolers and gases leaving the solar preheaters and carbonation process offers an enormous promise for improving the overall energy efficiency and sustainability of the CSP-CaL system. Utilizing this untapped thermal energy, which has a total heat potential of over 110 MW. An assessment is needed for the utilization of this energy in the cement production.

Additionally, considering the high sensitivity and degree of uncertainty, heliostat and solar rotary kiln costs must be thoroughly evaluated, with special attention paid to the innovative solar rotary kiln's unexplored potential. Therefore, more research and innovation are needed in these particular fields. Continued research is necessary to improve and advance these crucial components, assuring the viability and competitiveness of the total process, even if the current study has shown the potential for obtaining economically reasonable costs for commercial application.

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8 Appendix

8.1 Economic Results

The CAPEX, OPEX and cost breakdown of the each solar multiple are presented in this section. The description of the each figure can be found in similar with the section 5.3 with change in percentage.

8.1.1 Solar Multiple 2.5

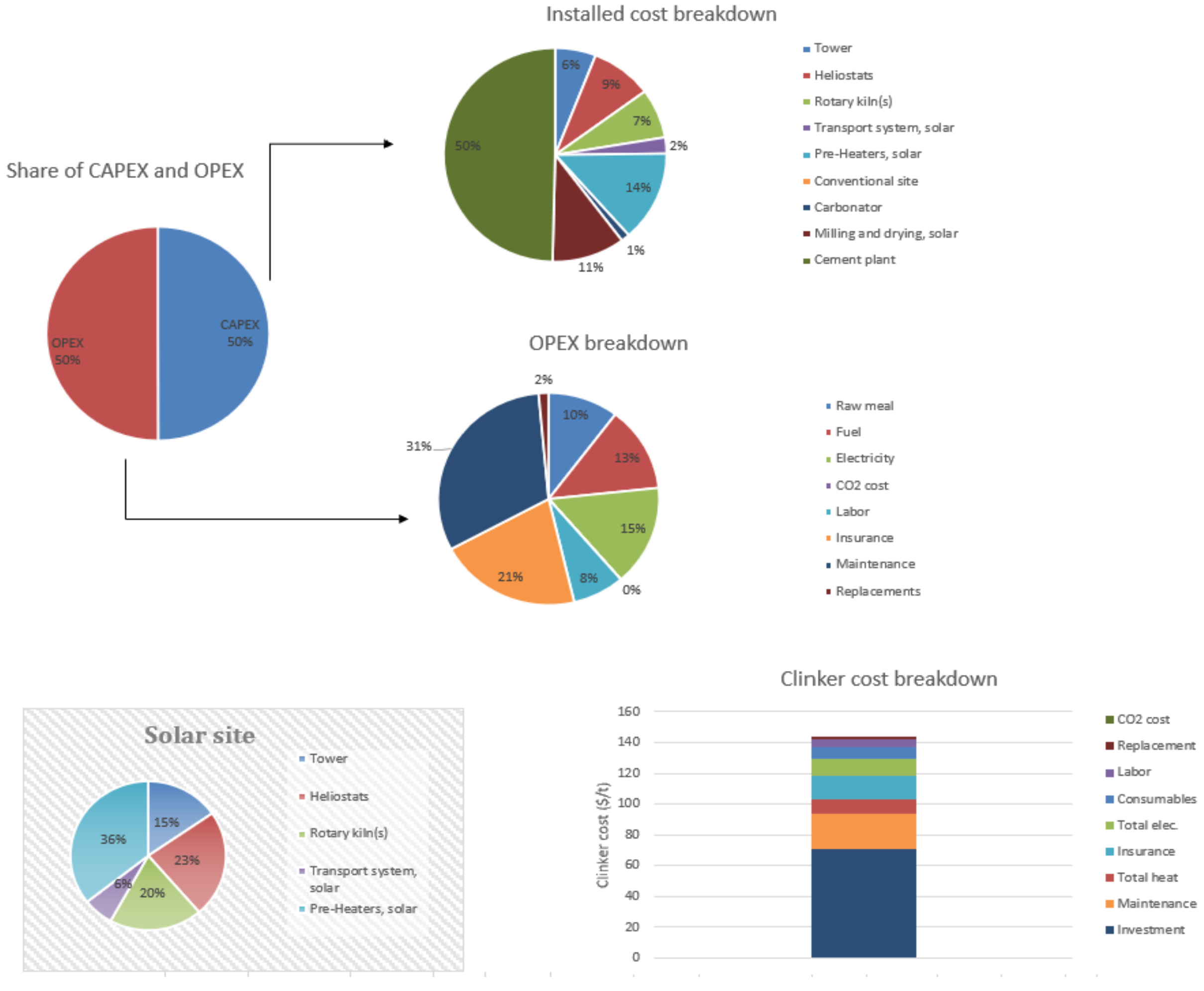

Figure 31. Capex and Opex for SM 2.5

8.1.2 Solar Multiple 2.75

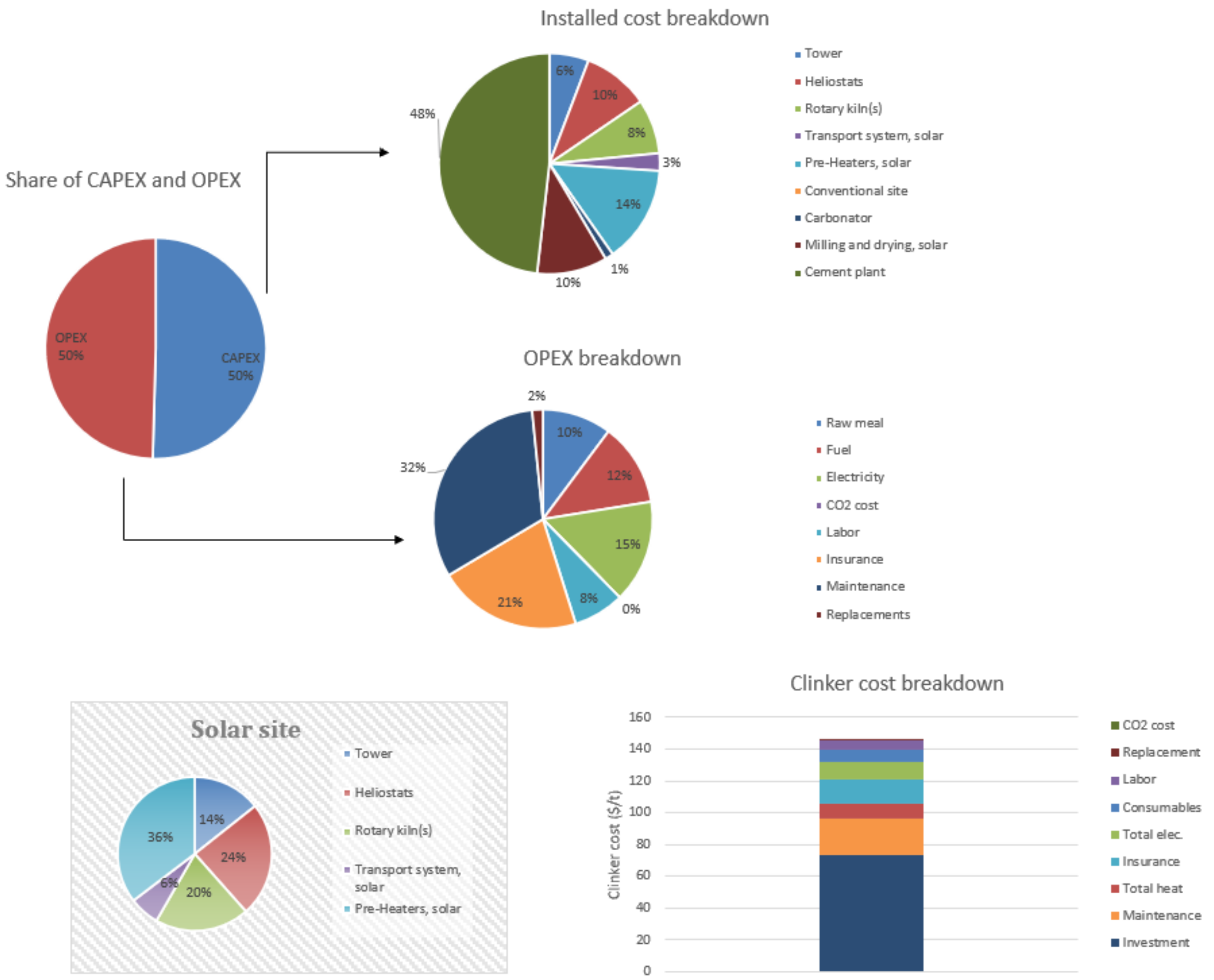

Figure 32. Capex and Opex of SM 2.75

8.1.3 Solar Multiple 3.0

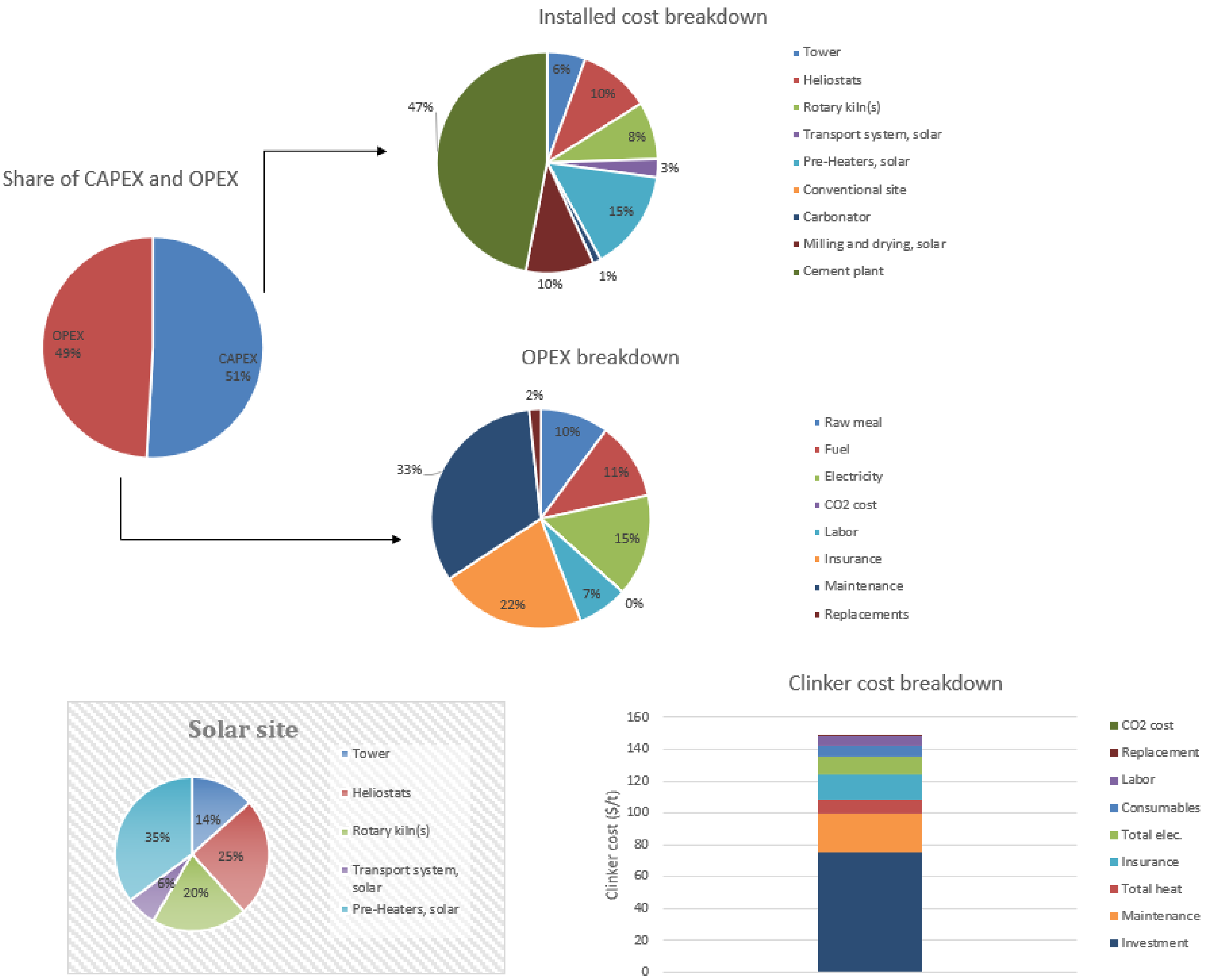

Figure 33. Capex and Opex of SM 3.0

8.1.4 Solar Multiple 3.25

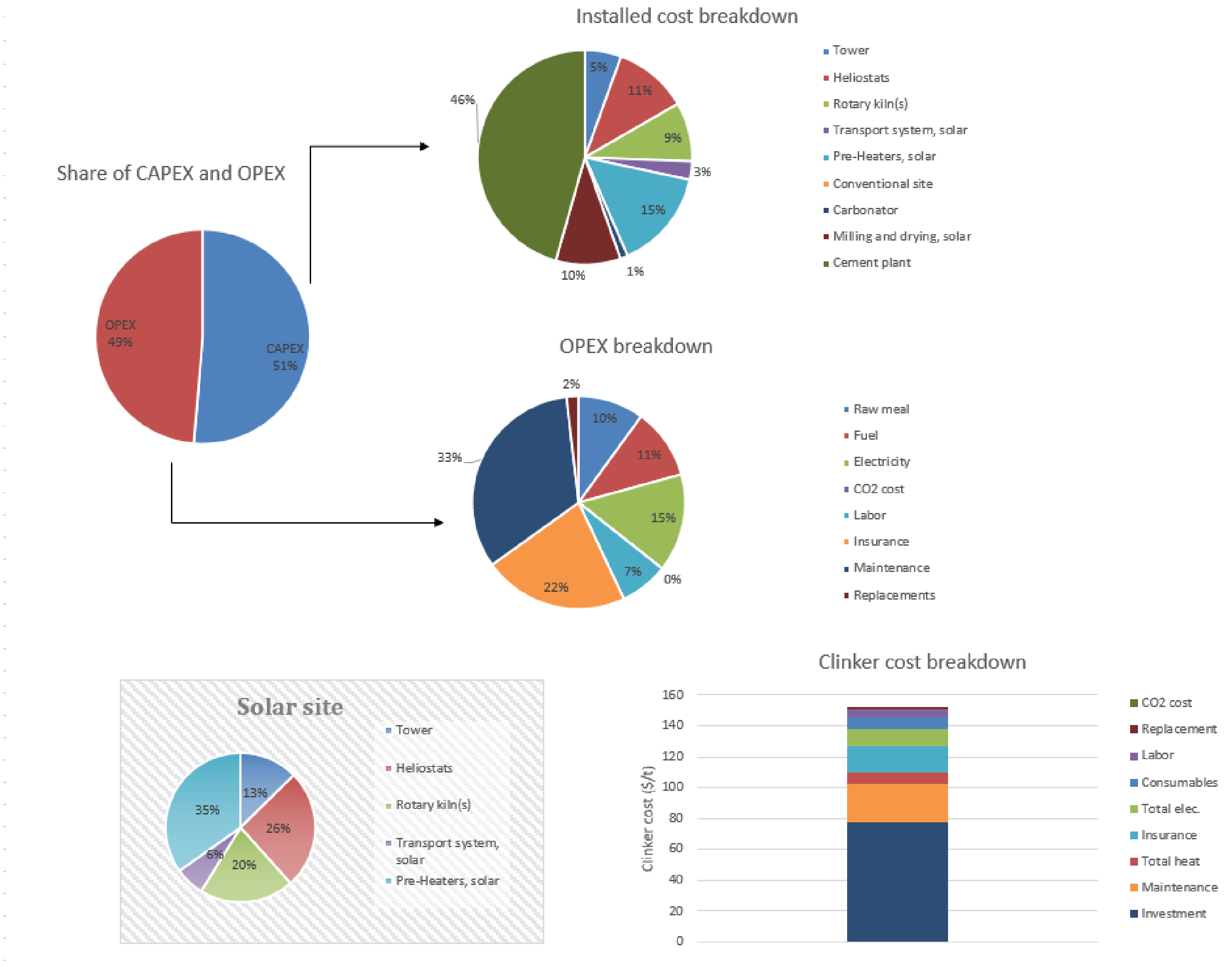

Figure 34. Capex and Opex for SM 3.25

8.1.5 Solar Multiple 3.5

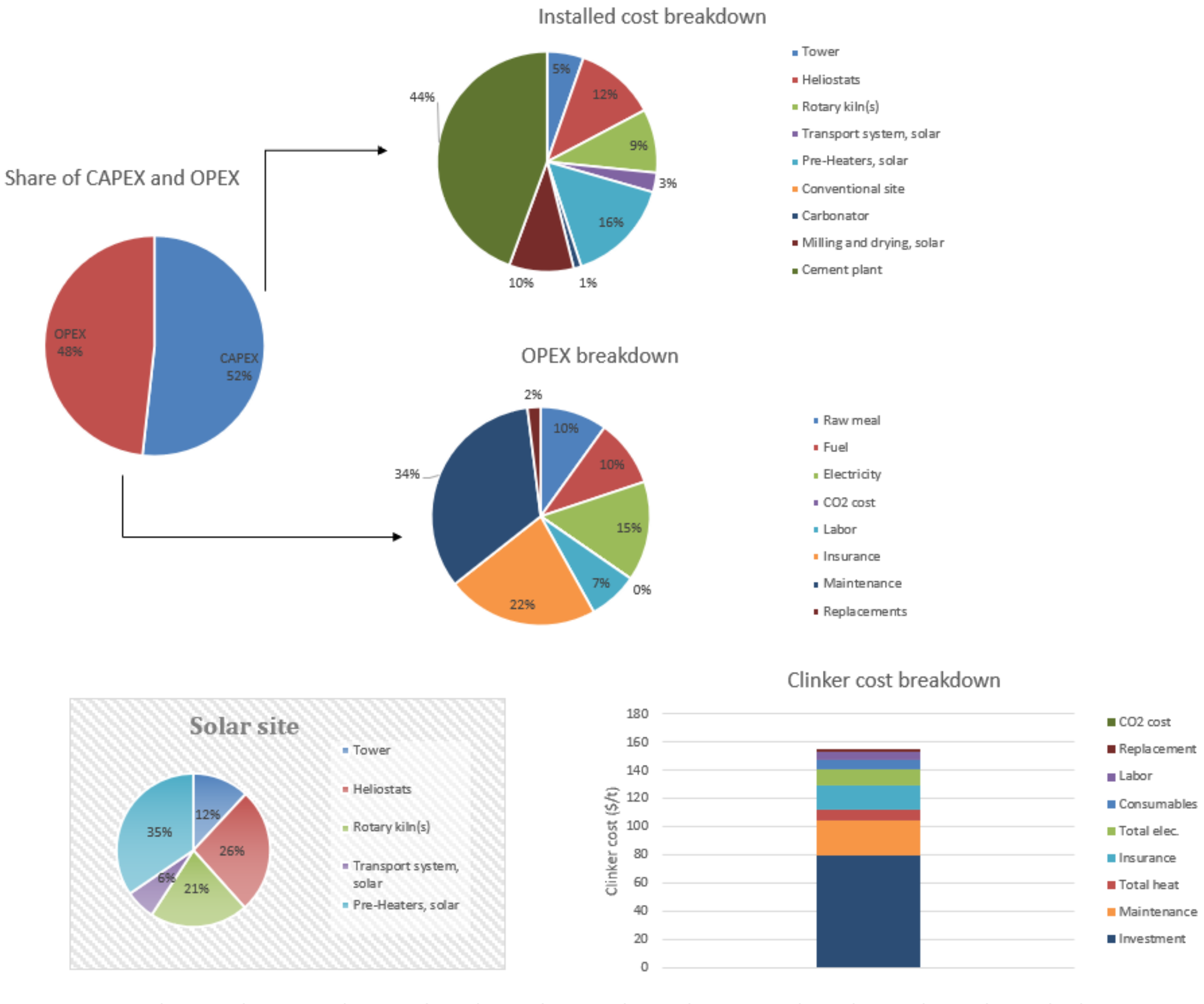

Figure 35. Capex and Opex for SM 3.5

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